2025 Annual Meeting

Seismological Society of America
Technical Sessions
14–18 April • Baltimore, Maryland

The SSA 2025 Annual Meeting will convene at the Hilton Baltimore Inner Harbor Hotel and feature more than 732 oral and poster technical presentations as well as plenary sessions, workshops and field seminars.

The schedule of events and abstracts contained in this program are valid until ____ and subject to change.

Where We Are Gathered

The land in Baltimore has a deep connection with the Piscataway Nation and the Susquehannock, who were forced to transfer their lands to English settlers in 1666 and 1652 respectively. In the centuries that followed, other indigenous cultures have since come to call the Baltimore area home, including the largest diasporic community of Lumbee people outside their traditional lands in present-day North Carolina. The ramifications of this past are profound and multifaceted, including components that are economic, environmental, legal and cultural. To learn more about the Baltimore-area indigenous communities, please visit the website of the Maryland State Arts Council, MSAC.org, and visit the Ashley Minner Collection in the Maryland Traditions Archives at the University of Maryland, Baltimore County. We encourage you to use this meeting to learn about and appreciate its land and people.

Annual Meeting Co-Chairs

The Society is grateful to SSA 2025 Co-Chairs Vedran Lekić of the University of Maryland and Victor Tsai of Brown University for leading the creation of this dynamic week of science.

Contact

info@seismosoc.org

SSA Meetings Code of Conduct

SSA is committed to fostering the exchange of scientific ideas by providing a safe, productive and welcoming environment for all SSA-sponsored meeting participants, including attendees, staff, volunteers and vendors. All participants at SSA meetings are expected to be considerate and collaborative, communicating openly with respect for others and critiquing ideas rather than individuals. Behavior that is acceptable to one person may not be acceptable to another, so use discretion to be sure that respect is communicated. For a detailed description of the ethics and code of conduct policies, please visit the SSA website: seismosoc.org/meetings/code-of-conduct.

Technical Program

Plenary Sessions

Keynote Address: What's Shaking, Eastern North America? The Continuing Quest to Understand Intraplate Quakes

Monday, 14 April, 6–7 PM

Susan Hough, U.S. Geological Survey (Pasadena), followed by panel discussion

The year 2025 marks the centennial anniversary of three moderately large North American earthquakes: Quebec, Montana and Santa Barbara. Before Richter's introduction of the magnitude scale, the differences in shaking distribution led credence to arguments that California did not face inordinately high earthquake hazard compared to the rest of the U.S. A century later, scientists understand the stark difference in wave propagation in eastern North America versus the west. But a half-century after plate tectonics provided an elegant paradigm to understand interplate earthquakes, a paradigm to explain intraplate quakes remains elusive. Detailed investigations have shed new light on key seismic zones, including New Madrid, Charlevoix (Quebec) and Charleston (South Carolina). Paleoliquefaction evidence confirms the existence of long-lived seismic zones, most convincingly at New Madrid. But why does stress (or strain) concentrate in a region subjected to broad, low-strain rate tectonic stresses? And how many unknown seismic zones might be lurking quietly, having remained mute during the short historical record? Hough will discuss the continuing quest to understand intraplate quakes, including the known knowns, the known unknowns and the unknown unknowns.

Plenary Address: The USGS Earthquake Hazards Program: Science to Support Decision-Making

Tuesday, 15 April, 6–7 PM

Gavin Hayes, U.S. Geological Survey (Golden), followed by panel discussion

Earthquakes are a national hazard, with recent analyses indicating that nearly 75% of the U.S. could experience damaging shaking. The USGS Earthquake Hazards Program (EHP) provides authoritative and impartial scientific information that can be successfully applied to reducing earthquake losses and improving resilience in the U.S. and its territories. The Program works under the Congressionally authorized National Earthquake Hazards Reduction Program and is a line item in annual USGS Federal Budget appropriation. Success in advancing earthquake risk reduction requires understanding of and working within existing guidelines and environments, while delivering actionable science to support decision-making. Partnerships are critical to support these efforts; the EHP funds the external community to collaborate in accomplishing its monitoring, hazard assessment and research goals. Hayes will discuss the work of the Program within the federal government, the new EHP decadal science strategy, and how partnerships with the external seismological community are critical to achieve an earthquake-ready nation.

Annual Business and Awards Luncheon

Wednesday, 16 April, Noon–2 PM

SSA President Susan Bilek (2025–26) will preside over the awards ceremony and provide an update on the Society. SSA President Heather DeShon (2024-25) will deliver her Presidential Address.

The 2025 honorees:

- Charles Langston, Harry Fielding Reid Medal
- Weiqiang Zhu, Charles F. Richter Early-Career Award
- Jeffrey Given, Frank Press Public Service Award
- James "Jim" Mori, Distinguished Service to SSA Award

Joyner Lecture: Risk and Reward: Working at the Boundaries of Earthquake Science

Wednesday, 16 April, 6–7 PM

Laurie Baise, Tufts University

Laurie Baise's Joyner Lecture will discuss working at the boundary of geology, seismology and earthquake engineering. In the lecture, she will highlight her work on bridging the gap between earthquake engineers and earthquake scientists through geospatial proxies for site effects and liquefaction and the importance of regionally informed models.

Workshops

SSA offers workshops for members to help advance their skills.

Building a High-Resolution Earthquake Catalog from Raw Waveforms: A Step-by-Step Guide

Monday 14 April, 1–5 PM

Instructors: Eric Beauce, Lamont-Doherty Earth Observatory, Columbia University; William Frank, MIT; Clara Yoon, U.S. Geological Survey; and Weiqian Zhu, University of California Berkeley

Earthquake catalogs provide deep insights into how the Earth works for our research and are a critical input to seismic hazard assessments. These readily available resources are the result of analyzing seismograms to detect earthquakes, identify wave arrivals and a series of inversions to produce estimates of hypocenters, magnitudes, moments and focal mechanisms. Understanding the strengths and uncertainties of each step is the key to doing excellent work.

Distributed Acoustic Sensing Open-source Software Workshop

Monday 14 April, 1–5 PM

Instructors: Hafiz Issah, Colorado School of Mines; Eileen Martin, Colorado School of Mines; Yida Song, Colorado School of Mines; and Shihao Yuan, Colorado School of Mines

As increasingly more seismologists have access to distributed acoustic sensing (DAS) instruments, either through purchase or through borrowing from community instrumentation facilities, many groups have 'reinvented the wheel' for basic DAS data management, visualization and processing software. To help more people use DAS data quickly, to reduce redundant coding effort, and to enable more flexible and reliable tools, we are building the Distributed Acoustic Sensing Data Analysis Ecosystem (DASDAE). The DASCore package is the flagship package of DASDAE, and contains basic utilities for reading many kinds of DAS data formats, objects to manage data with metadata about the experiments, and basic processing and visualization.

How to Open a Presentation and Foster a Great Q&A

Monday 14 April, 1–4:30 PM

Instructor: Ross S. Stein, Stanford University and Temblor, Inc.

The ability to present your research in a compelling, concise and engaging manner will enhance your professional career. Taught by communications expert Ross Stein, learn the best way to capture an audience in the opener, leaving a lasting impression in the first few minutes of a talk. Stein will also teach how to respond effectively to questions during and after your presentation.

Field Seminars

Pride of Baltimore

Monday, 14 April, 1–4 PM

Friday, 18 April, 9 AM–Noon

Trip Leaders: Vedran Lekić, University of Maryland; Mong-Han Huang, University of Maryland, College Park

Field trip participants will explore the Baltimore area aboard Pride of Baltimore II, a replica of the Baltimore Clipper vessels that played a key role in the War of 1812.

Smithsonian Private Tours and Washington Fault Lines Field Seminar

Friday, 18 April, 7 AM–5 PM

Trip Leaders: Ron Counts, University of Mississippi; Tom Pratt, U.S. Geological Survey

Scientists in the Department of Mineral Sciences at the Smithsonian National Museum of Natural History seek to understand the evolution of the Earth and Solar System by studying samples from environments ranging from the mantle to the surface, from volcanoes to the asteroid belt. The department is home to world-class collections of rocks, minerals, meteorites, and gems, as well as the laboratories used to simulate planetary processes and characterize specimens. Smithsonian staff are offering SSA a behind-the-scenes glimpse at some of these collections and laboratories. Following the Smithsonian, attendees will tour the Washington fault lines and learn about the Atlantic Coastal Plain sediments in the National Zoo area, and the fault beneath the White House and Washington Monument.

Technical Sessions

Accuracy and Variability of Physics-based Ground Motion Modeling

Accurate velocity and rupture models are essential to estimate realistic ground motions for seismic hazard and risk analysis. This session welcomes submissions assessing the importance of various model features on the accuracy of predicted ground motions through physics-based numerical modeling. Examples include dynamic and kinematic rupture models, development, calibration and validation of community seismic velocity models, and quantification of the contribution of various model features to the ground motions. In addition to guidance on model features required for accurate mean predictions, we welcome physics-based contributions that aim to model realistic variability of the ground motions. Finally, studies on mapping of uncertainty in velocity and source models into the resulting ground motions are encouraged.

Conveners: Evan Hirakawa, U.S. Geological Survey (ehirakawa@usgs.gov); Kim B. Olsen, San Diego State University (kbolsen@mail.sdsu.edu); William Stephenson, U.S. Geological Survey (wstephens@usgs.gov)

Advanced Geophysical Observations, Analytical Methods, and New Insights for Earthquake Swarms

Earthquake swarms are clusters of earthquakes that are localized in space and time but do not have a distinctive mainshock or a temporal decay of event rates characteristic of aftershocks. Earthquake swarms can trigger large, damaging earthquakes; however, their causality is not yet clear. In the last decade, there has been a remarkable surge in geophysical observations, such as dense seismic arrays, distributed acoustic sensing (DAS), borehole strainmeters, Global Navigation Satellite System (GNSS), and Interferometric Synthetic Aperture Radar (InSAR). This wealth of geophysical data provides an unprecedented opportunity to improve our understanding of the processes governing earthquake swarms and their hazards across various temporal and spatial scales, including tectonic, structural, geothermal, and anthropogenic conditions. Advances in the development of computing algorithms provide new opportunities to further probe earthquake sequence evolution within complex fault systems and to link these processes with improved observations.

The aim of this session is to explore innovative geophysical methodologies to observe and analyze earthquake swarms and to illuminate fresh perspectives on the underlying physics. We welcome contributions that encompass a wide range of topics, including but not limited to:

1. novel algorithms for constructing earthquake catalogs, incorporating state-of-the-art artificial intelligence tools,
2. advanced geospatial and statistical analyses and simulations of observed swarms,
3. hazard applications using seismology and other complementary geophysical data such as GNSS and InSAR.

Conveners: Kyren R. Bogolub, Nevada Seismological Laboratory, University of Nevada, Reno (kbogolub@unr.edu); Xiaowei Chen, Texas A&M University (xiaowei.chen@tamu.edu); Jeffrey L. Fox, Ohio Geological Survey (jeffrey.fox@dnr.ohio.gov); Yu Jiang, Nevada Seismological Laboratory, University of Nevada, Reno (yujiang@unr.edu); Andrea L. Llenos, U.S. Geological Survey (allenos@usgs.gov); Krittanon Sirorattanakul, Chevron (krittanon.pond@gmail.com); Elizabeth A. Vanacore, University of Puerto Rico Mayagüez, Puerto Rico Seismic Network (elizabeth.vanacore@upr.edu)

Advancements in Forensic Seismology and Explosion Monitoring

Geophysical signatures are crucial for enhancing the detection and characterization of anthropogenic activity. This session invites abstracts showcasing the latest advances in geophysical forensic analysis for global security and monitoring. Topics may encompass observation, modeling, and characterization of events that produce ground coupled signals including explosions, mining collapse, and bolides. We also seek to highlight advancements, physics-based and data-driven, in source, propagation, and signal analysis related to controlled source experiments. Submissions integrating multimodal observations and innovative instrumentation, such as distributed acoustic sensing, gradiometry, remote sensing, infrasound, and large-N arrays, are encouraged. This session aims to foster collaboration and discussion among experts to drive innovations in forensic seismology and explosion monitoring.

Conveners: Richard Alfaro-Diaz, Los Alamos National Laboratory (rad@lanl.gov); Louisa Barama, Lawrence Livermore National Lab (barama1@llnl.gov); Miles Bodmer, Sandia National Laboratories (mabodme@sandia.gov); Brandon Schmandt, University of New Mexico (bschmandt@unm.edu); Julien Thurin, University of Alaska Fairbanks (jthurin@alaska.edu); Cleat Zeiler, Nevada National Security Site (zeilercp@nv.doe.gov)

Advances in Reliable Earthquake Source Parameter Estimation

Reliable characterization of earthquake sources is fundamental to ground motion modeling, rupture simulation and statistical analyses. Estimates of earthquake source parameters such as location, magnitude, stress drop, and—or small and moderate earthquakes—their moment tensor components are used to describe and understand earthquake ruptures. Larger earthquakes may require a finite fault model to describe their source processes. Different procedures used in the estimation of source parameters may introduce variability in source, site, and path characterization intrinsic to the method used. These issues increase with the complexity of ruptures and require inversions with uncertainties that are difficult to quantify. The resulting artifacts may mask physical trends and lead to contradictory interpretations of earthquake scaling relationships and rupture processes. We encourage studies that aim to improve the reliability of earthquake source characterization, including ones that quantify the uncertainties of standard measurements, compare multiple methods or different datasets, and propose improved approaches to characterize complex sources and ruptures.

Conveners: Oliver S. Boyd, U.S. Geological Survey (olboyd@usgs.gov); Tom Garth, International Seismological Centre (tom.garth@isc.ac.uk); Keith McLaughlin, Leidos (mclaughlin0kl@gmail.com); Colin Pennington, Lawrence Livermore National Laboratory (pennington6@llnl.gov); Thanh-Son Pham, Australian National University (ThanhSon.Pham@anu.edu.au); Natalia Poiata, International Seismological Centre (Natalia.Poiata@isc.ac.uk); Adam Ringler, U.S. Geological Survey (aringler@usgs.gov); Boris Rösler, Ensenada Center for Scientific Research and Higher Education (boris@cicese.mx); William L. Yeck, U.S. Geological Survey (wyeck@usgs.gov); Clara Yoon, U.S. Geological Survey (cyoon@usgs.gov)

Advancing Seismic Hazard Models

This session welcomes contributions that enhance seismic hazard models and earthquake rupture forecasts through improved observational data, theoretical developments, and novel methodologies. We highlight research that refines or assesses ground motion predictions, fault behavior characterization, seismic source modeling, and uncertainty quantification.

Conveners: Vedran Lekic, University of Maryland, College Park (ved@umd.edu); Victor Tsai, Brown University (victor_tsai@brown.edu)

Advancing Time-dependent PSHA and Seismic Risk Assessment: Accounting for Short- to Medium-term Clustering

Traditional probabilistic seismic hazard and risk assessment often overlook the dynamic nature of earthquake clustering, including foreshocks, aftershocks, and extended sequences, as well as the damage accumulation from multiple earthquakes. Recent sequences, such as the 2010/2012 Canterbury earthquakes in New Zealand, the 2019 Ridgecrest earthquakes in the USA, and the 2023 Turkey-Syria earthquakes, highlight the need to refine our methodologies to better capture the dynamic nature of earthquake clustering. This session will focus on approaches to integrating time-dependent models into seismic hazard and risk assessments.

We invite contributions on advancements in time-dependent seismic hazard analysis and methods for incorporating earthquake clustering, including clustering-based models that address spatiotemporal variations, techniques for integrating aftershocks and foreshocks into hazard assessments, and vulnerability assessments that incorporate time-dependent fragility curves and damage accumulation. Additionally, we welcome studies that include real-world applications that assess the effectiveness of these analyses, or tackle current limitations and propose solutions. One of the goals of the session is to promote strategies for building capacity and upskilling end-users to effectively utilize these methodologies.

This session is targeted at seismologists, earthquake engineers, policymakers, insurance and re-insurance professionals, and academics in geosciences and structural engineering. The session will foster dialogue on the future of time-dependent seismic hazard and risk analysis. By embracing the complexities of earthquake behavior, we can enhance future risk assessments and strengthen community resilience.

Conveners: Edward Field, U.S. Geological Survey (field@usgs.gov); Matt Gerstenberger, GNS Science (m.gerstenberger@gns.cri.nz); Kenny Graham, GNS Science (k.graham@gns.cri.nz); Maximilian Werner, University of Bristol (max.werner@bristol.ac.uk)

Adventures in Social Seismology: Ethical Engagement, Earthquake Early Warnings, Operational Forecasts, and Beyond

In virtually every endeavor in which seismology is involved, there are considerations that warrant the participation of other disciplines. Social science and social scientists comprise one of these disciplinary areas and practitioners. As applied to real world issues, including earthquake hazard warnings, general and public education regarding earthquake hazards, establishing institutional trust and credibility, and other areas involving communication with various publics, social scientists are increasingly called upon to provide insights based on empirical studies and theoretical orientations. The social and behavioral sciences can provide valuable information on the social and culture environments in which scientific developments are shared with community residents and various institutional sectors.

A recent example is the effort to understand how, as earthquake early warning (EEW) systems expand globally, this relatively new technology is being used: whether the recommended drop, cover and hold on self-protection strategy is being implemented by those who receive alerts; user assessments of the value of EEW; perceptions regarding threshold levels for alerting; alert message content and post-alert information; and whether users understand how EEW systems work. In short, social scientists are playing a productive role between scientific discovery and technological advances, and implementation for public benefit. Social scientists may also have a role in operational earthquake forecasting in the identification of actions that can be taken in situations involving a low probability forecast with very serious potential consequences as well as high probability forecasts for aftershocks.

The example above, involving earthquake hazard warnings, is just one example of how the social sciences intersect with seismology and we invite social scientists and seismologists with an interest in the social and economic applications of earth science developments to join this session.

Conveners: Lindsay Davis, U.S. Geological Survey (ldavis@usgs.gov); Roby Douilly, University of California, Riverside (robyd@ucr.edu); James D Goltz, Disaster Prevention Research Institute, Kyoto University, (jamesgoltz@gmail.com); Susan E. Hough, U.S. Geological Survey (hough@usgs.gov); Maggie Ortiz-Millan, Earthquake Engineering Research Institute (maggie@eeri.org)

Building and Decoding High-resolution Earthquake Catalogs With Statistical and Machine-learning Tools

Recent application of advanced earthquake detection techniques such as template matching and machine learning (ML) have produced exponential growth in the quantity of earthquakes listed in next-generation high-resolution catalogs around the world. These improved catalogs can include relocated seismicity on the order of tens of thousands to a few million individual events, making it challenging to use standard analysis and modeling tools such as the Epidemic Type Aftershock Sequence (ETAS) model or the nearest neighbor algorithm for de-clustering, to extract key features and forecast seismicity. This session welcomes contributions on recent efforts to build high-resolution earthquake catalogs using waveform-based and ML methods such as transformers or foundation models. We also solicit presentations on innovative methods to decode these high-resolution catalogs using statistical analyses and advancing our understanding of earthquake interactions, swarms, fault geometries or localization processes, as well as predictive modeling approaches including neural and Bayesian point processes, deep Gaussian process models, and other generative models. We especially encourage submissions that compare new results with benchmarks, e.g. with respect to standard catalogs, or to model benchmarks such as statistical ETAS models or physics-based models such as Coulomb Rate-and-State (CRS) models to forecast seismicity.

Conveners: Xu Si, Georgia Institute of Technology (xsi33@gatech.edu); Maximilian J. Werner, University of Bristol (max.werner@bristol.ac.uk); Shixiang Zhu, Carnegie Mellon University (shixianz@andrew.cmu.edu)

Challenges and Opportunities in Constraining Ground-motion Models from Physics-based Ground-motion Simulations

Ground-motion models (GMMs) are an integral part of a seismic hazard analysis; moreover, they are crucial for earthquake early warning, shake maps and earthquake rapid response applications. In the last two decades, the abundance of instrumentally recorded data at regional and national scales has allowed recent developments in partially and fully non-ergodic GMMs in certain regions across the globe. However, constraining such path and site-specific effects in data-scarce regions (or sites) remains a challenge in addition to constraining the scaling of Ground motions for larger magnitude and complex ruptures. Moreover, empirical GMMs face major limitations when evaluating ground motions in regions/locations with dominant 2D/3D site effects.

Thanks to the rapid advancement of high-performance enabled, exascale parallelized simulation methods, deterministic physics-based ground motion modeling has been gradually integrated into seismic hazard analysis, with a specific focus on near-source complexity and site-specific considerations (e.g., basin response modeling). The ongoing development in source modeling approaches and in high-resolution regional 3D velocity models is a crucial component in improving the accuracy and predictive power of physics-based ground motion modeling simulations.

This session is targeted at studies focused on integrating such simulations into empirical ground-motion models. It includes regional scale ground-motion simulations, basin, site and source-specific simulations. Topics related to calibration of simulations with observed data, data formats and dissemination of such simulations results are also encouraged. Studies focused on the use of ground-motion simulations in constraining regionally varying GMMs, partially and fully non-ergodic GMMs are of particular interest. The session also welcomes studies related to advanced empirical approaches for ground-motion modeling.

Conveners: Sanjay Singh Bora, GNS Science (s.bora@gns.cri.nz); Asako Iwaki, National Research Institute for Earth Science and Disaster Resilience (iwaki@bosai.go.jp); Duo Li, GNS Science (d.li@gns.cri.nz); Chih-Hsuan Sung, University of California Berkeley (karensung@berkeley.edu); Graeme Weatherill, GFZ Potsdam (gweather@gfz-potsdam.de); Shihao Yuan, Colorado School of Mines (syuan@mines.edu)

Community Efforts in Distributed Acoustic Sensing (DAS)

Over the past decade, distributed acoustic sensing (DAS) has undergone significant technological advances and overcome many challenges. DAS turns fiber-optic cables into dense arrays of seismic sensors that span the length of the cable, collecting data across spatial and temporal scales that were not previously possible with traditional seismic instrumentation. These recent advances have enabled detailed understanding and active monitoring of earthquakes, glaciers, volcanoes, oceans, rivers, urban centers, and more. Despite considerable progress, a wider adoption of DAS technology still faces challenges. The lack of data and metadata standards, large quantity of data, cost of instrumentation, power consumption for field deployments, ambiguous instrument to instrument responses, and relatively small software ecosystems are prohibitive. We invite contributions focused on, but not limited to, data and metadata standardization, efficient data storage and transport, dataset discovery and exchange mechanisms, software ecosystems, instrumentation comparisons, and general best practices for field deployments.

Conveners: Matt Briggs, EarthScope Consortium, (matt.briggs@earthscope.org); Christopher M Calvelage, EarthScope Consortium (chris.calvelage@earthscope.org); Kathleen Hodgkinson, Sandia National Laboratories (kmhodgk@sandia.gov); Gizem Karslioglu, EarthScope Consortium, (gizem.karslioglu@earthscope.org); Christian Stanciu, Sandia National Laboratories, (astanci@sandia.gov)

Compiling Active Faults for Improved Hazard Modeling from Cascadia to Alaska

Active faults refer to faults which are believed to be capable of rupturing again in the future, generally meaning they have demonstrated activity in the Late Quaternary. Identifying these faults is crucial for understanding seismic hazard, particularly at near-source distances. Unfortunately, identification is thwarted in regions with low strain rates, dense vegetation, recent glaciation, extensive anthropogenic reworking, and/or other complicating factors. This is particularly true in the forearc of the Cascadia subduction zone, Alaskan subduction zone, and intervening North American crust of British Columbia and the Yukon. Nonetheless, many recent studies have sought to better constrain the crustal faulting potential from the offshore region all the way to the eastern edge of the cordillera, as part of research within academia and industry.

This session seeks to bring together recent studies on active faults or their implications for seismic hazard and risk, including contributions in the field of paleoseismology, geodesy, seismology, marine acoustics, geochronology, and seismic hazard and risk modeling. Negative results and methodological submissions are welcomed, to contribute to a robust discussion on the difficulties of assembling a complete crustal fault map across this remote and rugged swath of western North America.

Conveners: Tiegan E Hobbs, Natural Resources Canada (thobbs@eoas.ubc.ca); Richard Styron, The Global Earthquake Model Foundation (richard.styron@globalquakemodel.org); Martin Zaleski, BGC Engineering (mzaleski@bgcengineering.ca)

Data-driven and Computational Characterization of Non-earthquake Seismoacoustic Sources

Non-earthquake seismoacoustic sources, such as landslides, avalanches, volcanoes, glacial calving, utilities and industrial blasts, bolide airburst and their impacts on Earth, are commonly recorded by seismoacoustic monitoring networks. This session focuses on data-driven and computational methods and algorithms that aim to better understand and characterize these non-earthquake sources, and to ultimately better monitor and mitigate their associated hazards. We encourage contributions from studies that include, but are not limited to, seismoacoustic, geodetic, and remote sensing techniques at all relevant spatiotemporal scales with emphasis on multisensors Bayesian & Dempster-Shafer statistical data integration and fusion, high-performance deterministic and stochastic computational modeling and simulation, and AI-driven and physics-informed ML techniques. We solicit studies that include, but are not limited to, source detection, location, characterization, modeling, classification, monitoring, and hazard mitigation.

Conveners: Souheil M Ezzedine, Lawrence Livermore National Laboratory (ezzedine1@llnl.gov); Benjamin L Moyer, University of Maryland, College Park (blmoyer@umd.edu)

Earthquakes, Lithospheric Structure, and Dynamics in Stable Continental Regions

Damaging earthquakes can occur far from tectonic plate boundaries, where shaking impacts large areas because of low seismic attenuation in bedrock and amplification by sedimentary deposits. Long time intervals between earthquakes, low strain rates, and human development pose challenges to understanding seismic hazard in intraplate areas such as central and eastern North America, northern Europe, central Asia, and Australia. Geophysical imaging, geodynamic modeling, and geologic studies indicate that features inherited from prior tectonism such as intraplate basins, rifts, faults, arches, and domes can be reactivated seismogenically by the modern stress field. This session seeks diverse contributions related to intraplate seismic hazards, lithospheric structure, and dynamics. Studies of recent earthquakes (e.g., 2024 M4.8 Tewksbury, NJ, USA; 2019 M4.9 Le Teil, France) are especially encouraged, as are those of historical seismicity, paleoseismic features, seismic attenuation and ground motions, and constraints on ground shaking ranging from balanced rocks to railroads. We welcome approaches that cross spatial and temporal scales and the disciplinary boundaries between structural geology, geophysics, geochronology, rock physics, and geodynamics.

Conveners: Oluwaseyifunmi Adeboboye, Georgia Institute of Technology (oadeboboye3@gatech.edu); Oliver S Boyd, U.S. Geological Survey, (olboyd@usgs.gov); John E. Ebel, Weston Observatory, Boston College (ebel@bc.edu); Susan Hough, U.S. Geological Survey (hough@usgs.gov); Jessica T Jobe, U.S. Geological Survey(jjobe@usgs.gov); Will Levandowski, Tetra Tech, Inc. (will.levandowski@tetratech.com); Anjana Shah, U.S. Geological Survey (ashah@usgs.gov); Xiaotao Yang, Purdue University (xtyang@purdue.edu)

Earthquake Shaking and the Geologic Record: Triggered Phenomena and Preserved Fragile Geologic Features

The geologic record includes evidence of strong shaking from earthquakes, including shaking intensity and timing, with their distribution sometimes allowing earthquake locations to be inferred. Evidence of strong shaking intensities can also be due to ruptures of blind faults, providing further evidence for areas with less understood seismic occurrence. Some geologic shaking evidence is unique, preserving the rarest and most intense earthquake shaking over millennial timescales, which until recently have largely gone undocumented by seismometers. The geologic record of shaking includes turbidites, landslides, paleo liquefaction, speleothems, and fault-plane slickenlines. In addition, preserved fragile geologic features provide negative evidence for maximum shaking intensities. In this session, we welcome presentations that: 1) use geologic features to identify past strong ground motions, and infer the timing of such motions; 2) characterize the distribution of past strong ground shaking and recognize seismogenic sources through regional evidence; 3) estimate the likely maximum strengths of past ground motions permitted by the presence of fragile geologic features; 4) develop methodologies to locate and constrain ages of geologic features indicative of past ground motions; and 5) directly relate past strong ground motions to seismic hazard assessments.

Conveners: Paula Marques Figueiredo, North Carolina State University (paula_figueiredo@ncsu.edu); Devin F. McPhillips, U.S. Geological Survey, Earthquake Science Center (dmcphillips@usgs.gov); Thomas L. Pratt, U.S. Geological Survey (tpratt@usgs.gov); Mark W. Stirling, University of Otago (mark.stirling@otago.ac.nz)

Earthquake-triggered Ground Failure: Data, Hazards, Impacts and Models

Landslides and liquefaction triggered by earthquakes are a diverse set of phenomena that can cause widespread and significant impacts during and after earthquake shaking. Advances in our ability to model the initiation, extent, and impacts of ground failure are needed to improve our ability to quantify the magnitude and uncertainty of hazard and risk, as well as predict near-real-time losses for emergency response. Models of earthquake-triggered ground failure should consider the complex spatial-temporal variations (e.g., spatial heterogeneity of material properties, climate change, wildfire, anthropogenic changes to the landscape and groundwater levels) on hazard and risk. However, the complete physics of earthquake-triggered ground failure is often impossible to capture at any scale, and simplified probabilistic, regionalized, and or time-dependent modeling of ground failure, as well as the development of detailed inventory and case-history data, are essential to building practical models of ground failure susceptibility, hazard, and loss.

We welcome all submissions relating to earthquake-triggered ground failure, including but not limited to: regional scale susceptibility and hazard assessment; characterizing uncertainty, or developing ensemble model predictions; studies on the impacts, losses, and risk modeling for coseismic ground failure; new or revised inventories, or case histories, from recent and historic earthquakes; as well as advances in information or communication products for earthquake-triggered ground failure.

Conveners: Laurie Baise, Tufts University (laurie.baise@tufts.edu); Alex Grant, U.S. Geological Survey (agrant@usgs.gov); Meera Kota, University of California, Los Angeles (meerakota@g.ucla.edu); Andrew Makdisi, U.S. Geological Survey (amakdisi@usgs.gov)

Earth's Structure from the Crust to the Core

This session will cover all aspects of "structural seismology" and highlight new contributions to research of core and mantle dynamics, the role of the mantle transition zone in mantle convection, volcanism in different settings around the world, the structure of subducting slabs, deep lithospheric deformation and processes, lithosphere-asthenosphere interactions, and their feedbacks into geohazards. We encourage submissions that introduce new datasets or new combinations of seismological data types, advances in global and regional-scale seismic tomography, 3-D waveform modeling, array-based approaches, and the analysis of correlation wavefields.

Conveners: Ebru Bozdag, Colorado School of Mines (bozdag@mines.edu); Gatut Daniarsyad, Agency for Meteorology, Climatology and Geophysics (gatut.daniarsyad@bmkg.go.id); Daryono Daryono, Agency for Meteorology, Climatology and Geophysics (daryonobmkg@gmail.com); Jan Dettmer, University of Calgary (jan.dettmer@ucalgary.ca); Theron Finley, University of Victoria (tfinley@uvic.ca); Jeremy M. Gosselin, Natural Resources Canada, Sidney (jeremy.gosselin@nrcan-rncan.gc.ca); Indra Gunawan, Agency for Meteorology, Climatology and Geophysics (indra.gunawan@bmkg.go.id); Nicolas Harrichhausen, University of Alaska, Anchorage (njharrichhausen@alaska.edu); Hao Hu, University of Oklahoma, (huhaoletitbe@gmail.com); Lorraine J. Hwang, University of California, Davis (ljhwang@ucdavis.edu); Keith Koper, University of Utah (kkoper@gmail.com); Andrew Lloyd, Lamont-Doherty Earth Observatory, Columbia University (andrewl@ldeo.columbia.edu); Walter D Mooney, U.S. Geological Survey (mooney@usgs.gov); Nelly F Riama, Agency for Meterology, Climatology and Geophysics (nelly.florida@bmkg.go.id); Jeroen Ritsema, University of Michigan (jritsema@umich.edu); Vera Schulte-Pelkum, University of Colorado (vera.schulte-pelkum@colorado.edu); Derek Schutt, Colorado State University (derek.schutt@colostate.edu); Ying Zhang, University of Oklahoma, (yingzhang3.geo@gmail.com)

ESC-SSA Joint Session: Seismology in the Global Oceans: Advances in Methods and Observations

Seismological studies beneath the global oceans, which cover 70% of Earth's surface, provide key insights into tectonic processes. These investigations have advanced our understanding of fundamental topics such as the differences between oceanic and continental lithosphere-asthenosphere systems, the evolution of oceanic plates from mid-ocean ridges to subduction zones, and the influence of mantle plumes in these processes. Seismic imaging of subduction zones and transform faults has also been instrumental in improving our understanding of earthquake hazards and volcanic activity.

This session invites contributions that showcase recent advancements in overcoming the challenges of collecting, processing, and interpreting oceanic seismic data. Topics may include but are not limited to, innovations in noise reduction (e.g., reverberations, tilt, compliance, bottom currents), the use of probabilistic and machine learning methods for modeling wave reflections and conversions, and novel approaches to imaging oceanic plate structures. We welcome studies utilizing ocean-bottom and land-based seismic data to investigate oceanic features, such as SS precursors, ambient noise, and surface wave tomography. Contributions highlighting new geophysical experiments, seismic deployments, and instrumentation are also encouraged, along with any research offering new insights into tectonic processes beneath the global oceans.

This session is jointly organized by the European Seismological Commission and SSA

Conveners: Takeshi Akuhara, University of Tokyo (akuhara@eri.u-tokyo.ac.jp); William Ellsworth, Stanford University (wellsworth@stanford.edu); Margaret Hellweg, University of California, Berkeley (hellweg@berkeley.edu); Tolulope Olugboji, University of Rochester (tolulope.olugboji@rochester.edu); Matteo Picozzi, University of Naples Federico II (matteo.picozzi@unina.it); Karin Sigloch, Géoazur Laboratory (karin.sigloch@geoazur.unice.fr); Youqiang Yu, Tongji University (yuyouqiang@tongji.edu.cn); Ziqi Zhang, University of Maryland, College Park (evan.z.0920@gmail.com)

Exploring Planetary Interiors and Seismology: Observations, Models, Experiments and Future Missions

Advancing our understanding of planetary interiors requires the integration of geophysical observations, quantitative models, and experimental studies. This session aims to promote discussions on how recent geophysical measurements from various planetary missions, combined with new numerical and experimental constraints, illuminate the internal structures and dynamics of planetary bodies. Topics will include the implications of these findings for the density, fluid content, and temperature variations from crust to core. Contributions that incorporate recent mission data, constraints, and their implications for the interior dynamics of the Moon, Mars, and other planetary bodies are particularly encouraged, along with Earth-based seismological approaches that inform comparative planetology.

Conveners: Andrea Bryant, Brown University (andrea_bryant@brown.edu); Doyeon Kim, Imperial College London (doyeon.kim@imperial.ac.uk); Jiaqi Li, Peking University (lijiaqi315@gmail.com); Nicholas Schmerr, University of Maryland (nschmerr@umd.edu)

Exploring the Complexity of Fault Discontinuities

How is deformation accommodated in structurally immature, discontinuous fault zones? Strain accommodation is rarely limited to kinematically and/or geometrically homogeneous fault segments, and often involves strain partitioning between systems of faults that work together to release seismogenic strain. This is especially true in young or structurally immature zones such as fault tips, stepovers, transfer zones, fault relays, or other along-strike discontinuities, but may also occur on mature faults. Deformation in these zones is also often spatially or temporally variable over multiple earthquake cycles, challenging our seismic hazard assessments. We invite contributions that aim to characterize these complex zones, including the spatiotemporal expression of slip, both at depth and at the surface. Approaches from neotectonic mapping, paleoseismology, geodesy, modeling, and novel techniques are welcome.

Conveners: Catherine Hanagan, U.S. Geological Survey (chanagan@usgs.gov); Aubrey LaPlante, Northern Arizona University (aal382@nau.edu); Emerson M Lynch, U.S. Geological Survey (elynch@usgs.gov)

Fiber-optic Sensing Applications in Seismology

Fiber-optic sensing methods, such as Distributed Acoustic Sensing (DAS), Distributed Temperature Sensing (DTS), and Distributed Strain Sensing (DSS), are transforming seismology by advancing our understanding of seismic sources and Earth's structure. These innovative technologies convert fiber-optic cables into dense sensor arrays capable of capturing seismic and deformation signals across the solid Earth, oceans, and glaciers with unprecedented resolution. We invite contributions on recent developments in fiber-optic seismology applications, including but not limited to the detection and characterization of various seismic sources (e.g., earthquakes, icequakes, volcanic activities, ocean processes, atmospheric phenomena, energy extraction and storage activities, and anthropogenic signals), Earth's structure imaging (e.g., urban setting, offshore, and cryosphere), environmental monitoring (e.g., the dynamics of oceans, rivers, lakes, critical zones, soil moisture, groundwater, permafrost, and glaciers), and natural hazard mitigation (e.g., earthquake, tsunami, and volcanic eruption monitoring and early warning). We also welcome recent engineering advancements in the theoretical, methodological, and instrumental aspects of fiber-optic sensing for future Earth and planetary applications. Contributions from the computational and data science communities focused on exploring fiber-optic data are encouraged, including areas such as machine learning, advanced signal processing techniques, data compression, high-performance computing, and cloud computing and storage. We aim to bring together researchers from diverse fields, including Earth science, computational and data science, and fiber-optic sensing engineering to open a discussion on the future opportunities enabled by these new technologies.

Conveners: Ettore Biondi, Stanford University, California Institute of Technology (ebiondi@caltech.edu); Xiaowei Chen, Texas A&M University (xiaowei.chen@tamu.edu); Jiaxuan Li, University of Houston (jli74@uh.edu); Yan Yang, University of California, San Diego (yanyang@ucsd.edu); Qiushi Zhai, California Institute of Technology (qzhai@caltech.edu)

Fifty Years and Beyond of Broadband Seismic Instrumentation: Performance, Precision and Uncertainties

Inertial broadband seismometers, introduced five decades ago, are now standard measuring tools for seismology. These feedback instruments permit high quality ground motion measurements over four to five decades of frequency, while resolving them with astonishingly high resolution, from the order of cm/s down to nm/s. They provide high dynamic range, digital measurement of 3 components of ground motion, and linear, well described response functions allowing the original ground motion to be reconstructed. Thus, it is important to be able to document the precisions and uncertainties of the measurements of these instruments, and of other seismic sensors like accelerometers and geophones, and to assess and manage their performance over time.

One example of such documentation is linking the precision of seismometer measurements to the international system of units (SI) and tracking it over the lifetime of a broadband seismometer or seismic station. An effort is currently underway to develop such a link and thereby introduce seismometers to standardized procedures common in the world of metrology. At the same time, instrument manufacturers deploy a variety of individual techniques to calibrate their wares before they are sold, while network operators deploy clever procedures to remotely monitor the performance of their instruments during their lifetime in the field. With the advent of the use of optical fibers and other innovative seismic measuring devices, the question of procedures and tools to describe, assess and monitor performance becomes broader.

We invite everybody interested in seismic instrumentation to submit abstracts to this session. Topics of interest include calibration techniques; long term assessment of instrument performance; precision and uncertainties and their influence in interpreting seismic data; and comparison of high precision measurements of ground motion from inertial seismometers with observations from optical fibers and other techniques.

Conveners: Akobuije Chijioke, National Institute of Standards and Technology (akobuije.chijioke@nist.gov); Margaret Hellweg, University of California, Berkeley (hellweg@berkeley.edu); John Merchant, Sandia National Laboratories (bjmerch@sandia.gov); Xyoli Pérez-Campos, Comprehensive Test Ban Treaty Organization (xyoli.perez.campos@ctbto.org)

From Physics to Forecasts: Advancements and Future Directions of Induced Seismicity Research

Induced seismicity has been associated with many anthropogenic activities involving fluid mobilization in subsurface formations such as hydraulic fracturing, waste-water injection, geothermal exploitation, and carbon sequestration. Research on this topic has matured over recent decades, and dominant controls of induced seismicity have been identified. The spatiotemporal evolution of these earthquakes is mostly modulated by the fluid volumes, flow rates, hydromechanical properties of the subsurface, regional geological conditions, and proximity and orientation of existing fault structures. However, it is often hard to reconstruct the complex interplay between these factors that led to the earthquakes.

New technologies and multidisciplinary approaches to subsurface modeling advance our knowledge of the underlying physics of these events and quantify the remaining stochastic variability. Ongoing induced seismicity research addresses such questions as: How can the likelihood of future large seismic events be reduced during these anthropogenic activities? How can the physics of induced earthquakes guide hazard assessment over short and long timescales? Do we have better success at forecasting earthquake hazards in induced vs tectonic settings – and how should the public and/or regulatory agencies utilize these forecasts?

We invite contributions that present new modeling technologies, resulting datasets, that update, or present new, models of the processes leading to induced seismicity. We particularly welcome multi- and interdisciplinary studies, and we encourage contributions across a broad range of geoscientific disciplines including, but not limited to Earth imaging, numerical modeling, seismicity, and earthquake source processes. We also welcome challenging case studies where the induced seismicity is difficult to model, the model results propagate to time-dependent seismic hazard assessment and forecasting, and recommendations for future directions for this field.

Conveners: Stanislav Glubokovskikh, Lawrence Berkeley National Laboratory (sglubokovskikh@lbl.gov); Jeremy Gosselin, Natural Resources Canada, Geological Survey of Canada – Pacific (jeremy.gosselin@nrcanrncan.gc.ca); Ian Main, University of Edinburgh (Ian.Main@ed.ac.uk); Alexandros Savvaidis, University of Texas at Austin (alexandros.savvaidis@beg.utexas.edu); Jake Walter, Oklahoma Geological Survey, University of Oklahoma (jwalter@ou.edu)

Geophysics in a Changing World: Monitoring Applications from Seismology and Beyond

Recent developments in environmental monitoring with geophysical tools demonstrate their utility for mapping small-scale changes in the shallow subsurface. Such innovative applications are becoming increasingly relevant as society faces challenges related to sustainability in the context of changing environments. Passive seismic investigations have used recordings of ambient noise to resolve groundwater fluctuations on the basin scale, and to monitor and characterize fluvial system bedload transport and flood response. Resistivity and electromagnetic techniques have been used for soil characterization and to map saltwater intrusion, with implications in hazards, resource mapping, and climate change. Microgravity and passive-seismic surveys have been used independently and jointly to assess dam stability, to detect karst, and for other near-surface applications. Moreover, seismic and infrasonic data have become useful for real-time landslide detection and have shown potential for detecting severe weather phenomena such as tornadoes and hurricanes. While focusing on seismology, this session invites presentations from a wide range of geophysical applications to study Earth's surface and near-surface processes, and other aspects of the emerging fields of environmental seismology and geophysics.

Conveners: Jochen Braunmiller, University of South Florida (jbraunmiller@usf.edu); Seth Carpenter, Kentucky Geological Survey, University of Kentucky (seth.carpenter@uky.edu); Felix Rodriguez Cardozo, University of South Florida (felixr1@usf.edu); Glenn Thompson, University of South Florida (thompsong@usf.edu)

Improving the State of the Art of Earthquake Forecasting Through Models, Testing and Communication

Current earthquake forecasting models utilize only a fraction of the existing knowledge about earthquakes, thereby lacking important information on seismogenesis. With the advent of increased computational power and high-resolution geophysical datasets, including fault information, interseismic strain data, highly detailed machine-learning-based catalogs, laboratory observations of microseismicity, etc., our understanding of the physical processes involved in earthquake nucleation is continuously growing. Yet, translating this theoretical knowledge into practical, informative earthquake forecasts remains a significant hurdle. Furthermore, testing these forecasts against observations and communicating them to non-scientific audiences similarly require innovative solutions so earthquake forecasts can realize their potential for seismic risk reduction.

In this session, we welcome contributions that seek to improve the state of the art of earthquake forecasting by bridging the gap between theoretical advancements and real-world applications. We invite submissions that integrate our growing understanding of earthquake processes with the creation of generalizable, statistically robust and interdisciplinary models that are more informative than the currently widely used empirical clustering models—both for natural and induced seismicity, and across scales from micro-scale in the laboratory to continental catalog analysis. Complementarily, we seek contributions that explore tests or metrics that better characterize model performance and thus identify promising areas for their improvement. We also encourage the submission of new communication and visualization strategies that turn earthquake probability estimates into practical, actionable and societally relevant information.

Conveners: José A. Bayona, University of Bristol (jose.bayona@bristol.ac.uk); Kélian Dascher-Cousineau, University of California, Berkeley (kdascher@berkeley.edu); Pablo Iturrieta, GFZ German Research Centre for Geosciences (pciturri@gfz-potsdam.de); Leila Mizrahi, ETH Zurich (leila.mizrahi@sed.ethz.ch); Berman Neri, Tel Aviv University (neriberman@gmail.com); Max Schneider, U.S. Geological Survey (mschneider@usgs.gov)

Innovative Applications of Seismic Nodal Technology for Hazard Mitigation and Earth System Monitoring

Seismic Nodal arrays have revolutionized the way we monitor and study geodynamic Earth processes such as earthquakes, volcanic activity, landslides, ocean dynamics and anthropogenic activity. Their flexibility, dense spatial coverage, and ease of deployment allow for unprecedented high-resolution seismic data collection across a range of environments and scales. These portable and autonomous sensors provide detailed insights into subsurface structures, fault zone mechanics, and volcanic systems.

In this session, we seek to explore the cutting-edge advancements in seismic nodal technology and their applications. We invite contributions that focus on innovative field deployments, novel data analysis techniques, and case studies showcasing the impact of nodal arrays on our understanding of tectonic phenomena. We encourage researchers from all disciplines within the geoscience community to submit abstracts and share their latest findings and experiences using seismic nodal arrays and other related knowledge.

Conveners: Andy Barbour, U.S. Geological Survey (abarbour@usgs.gov); Paul Bodin, University of Washington (bodin@uw.edu); Nahomy Campos, Volcanological and Seismological Observatory of Costa Rica (nahomy.campos.salas@est.una.ac.cr); Esteban J Chaves, Volcanological and Seismological Observatory of Costa Rica (esteban.j.chaves@una.ac.cr); Joan Gomberg, U.S. Geological Survey (gomberg@usgs.gov); Sonia Hajaji, Volcanological and Seismological Observatory of Costa Rica (soniahajaji@gmail.com); Marino Protti, Volcanological and Seismological Observatory of Costa Rica (marino.protti.quesada@una.cr)

The Landscape Record of Earthquakes and Faulting

Recent earthquakes have left vastly different records in the landscape, from coastal uplift in the 2024 Mw7.5 Noto, Japan, earthquake to large lateral surface rupture in the 2023 Mw7.8 and Mw7.5 Türkiye earthquakes, and subtle or blind displacement in the 2024 Mw7.0 Aykol, China, earthquake. How long the earthquake record remains in the landscape depends on the surface rupture (or lack thereof) and shaking signatures of the earthquake as well as the lithology and climate of the region. Field and remote sensing observations of recent and past ruptures highlight the variable rupture geometries, surface slip distributions, damage zones, distributed or off-fault deformation, and ground shaking. The extent to which the complex and heterogenous patterns are consistent or variable between earthquakes is a fundamental question in earthquake science, critical for hazard modeling, and remains largely unknown. Meanwhile, advances in numerical and physical models and laboratory experiments expand the ability to study strain accumulation and release and the landscape response through multiple earthquake cycles. In this session, we encourage abstracts that investigate spatial and temporal patterns in strain accumulation and release spanning coseismic to geologic timescales, including their causes and uncertainties. We welcome contributions from geodesy, earthquake geology, tectonic geomorphology, lacustrine paleoseismology, numerical modeling, analog experiments, and especially contributions with novel approaches integrating multiple data sources to further our understanding of how strain accumulation and release are stored in, interpreted from, and alter the landscape.

Conveners: Solène Antoine, California Institute of Technology (santoine@caltech.edu); Sean Bemis, Virginia Tech (sbemis@vt.edu); Ron Counts, University of Mississippi (rcounts@olemiss.edu); Hanna Elston, Smith College (helston@smith.edu); Nadine Reitman, U.S. Geological Survey (nreitman@usgs.gov); Jessica Thompson Jobe, U.S. Geological Survey (jjobe@usgs.gov)

Late-breaking on Recent and Future Large Earthquakes

This session features preliminary research results on the latest sequences around the world, including the 2024 Mw 7.5 Noto Peninsula Earthquake, the ongoing earthquake swarm near Ethiopia, and the 2025 M 7.1 Southern Tibetan Plateau earthquake.

Conveners: Hongfeng Yang, The Chinese University of Hong Kong, (hyang@cuhk.edu.hk); Shengji Wei, Nanyang Technological University Singapore, (shjwei@ntu.edu.sg); Aitaro Kato, Earthquake Research Institute, the University of Tokyo, (akato@eri.u-tokyo.ac.jp)

Macroseismic Intensity: Past, Present and Future

Macroseismic intensity (MI) observations and analyses connect our collective seismological past with the present and the present to the future. MI facilitates estimating earthquake hazards and communicating the effects of ground shaking to a wide variety of audiences, across the ages. Invaluable ground-shaking and building damage information is gained through standardized, systematic approaches for assigning MI values and, importantly, sharing and archiving those assignments in a reproducible form. Traditional macroseismic surveys provide vital constraints on critical aspects of earthquakes and their impacts on society, whereas internet-based macroseismic datasets are extremely valuable for real-time earthquake situational awareness and contribute to subsequent engineering loss and risk analyses. These important applications of MI observations require us to revisit traditional macroseismic surveys for modern environments, standardize internet-based collection strategies, and assure compatibility between traditional and internet-based approaches of macroseismic data collection.

This session aims to connect researchers and practitioners in earthquake seismology, earthquake engineering, and macroseismology. Accordingly, we encourage contributions related to historical and modern MI collection, including internet macroseismology, recent and historical MI analyses, intensity prediction equation and ground-motion conversion equation development, assigning higher intensities with rigorous building damage data collection, and developments related to the International Macroseismic Scale (IMS; a recent update to the European Macroseismic Scale, EMS-98).

Conveners: Ayse Hortacsu, Applied Technology Council (ayse@atcouncil.org); Susan E. Hough, U.S. Geological Survey (hough@usgs.gov); Jessie Saunders, California Institute of Technology (jsaunder@caltech.edu); Paola Sbarra, National Institute of Geophysics and Volcanology (paola.sbarra@ingv.it); David J. Wald, U.S. Geological Survey (wald@usgs.gov)

Mechanistic Insights into Fluid-induced Earthquakes from the Laboratory to the Field

Fluid-induced earthquakes, including those that are triggered, occur both naturally and anthropogenically and are fundamentally connected to fluid-fault and/or fluid-fracture mechanical interactions. Fluid-induced seismicity has become a significant phenomenon and concern during natural fluid migration or human-made fluid injection and extraction activities, such as hydraulic flows, slab dehydration, hydrocarbon or hydrogen production, wastewater and CO_2 injection, and geothermal production. The physical mechanisms driving the seismicity have been extensively studied and include pore-pressure diffusion, poroelastic stress changes, fluid-driven aseismic slip, and shear stress transfer. However, understanding these mechanisms is challenging due to their context-specific nature and because there is a lack of high-quality geophysical measurements that quantify subsurface and fault zone properties and in-situ stress evolutions. This complexity necessitates comprehensive studies that explore the effects of heterogeneous fault or fracture properties, varying host materials, and environmental conditions on the generation and evolution of triggered or induced seismicity. Such research will help clarify the intricate physical processes underlying the complex spatiotemporal distribution and behavior of the seismicity. Moreover, these insights will enhance the characterization and mitigation of seismic hazards.

We invite submissions of studies, ranging from laboratory experiments to field observations, that offer new perspectives on the underlying physics of fluid-fault and/or fluid-fracture interactions. We welcome contributions from national labs, academics, regulators and industry members, focusing on : 1) studies using laboratory experiments and numerical simulations to explore the physical processes that control fluid-induced seismicity, and 2) studies of spatiotemporal behavior of fluid-induced seismicity across various natural scales and settings, particularly those that offer new insights into the mechanisms driving fluid-induced seismicity in the field.

Conveners: David Chas Bolton, University of Texas at Austin (chasbolton19@gmail.com); Xiaowei Chen, Texas A&M University (xiaowei.chen@exchange.tamu.edu); Thomas H. Goebel, University of Memphis (thgoebel@memphis.edu); Congcong Yuan, Cornell University (cy547@cornell.edu)

Modern Waveform Processing and Engineering Datasets - Accessibility, Quality Control, and Metadata

Open access to seismic waveform datasets across a variety of geographic terrains on Earth and beyond offer the opportunity to evaluate ground motions with increased resolution and depth. Workflows can be tailored towards different applications, but generally aim towards reducing uncertainty and maximizing signal quality. Increasing data quality is a universal goal, regardless of application. Here we aim to discuss topics broadly related to ground motion processing, such as new approaches and techniques (both automatic and manual) for ground motion processing and quality assurance. We also encourage presentations that highlight newly developed ground motion datasets using strong-motion and/or broadband data from permanent as well as temporary networks and arrays, as well as hybrid (empirical and simulated) or simulated datasets. We welcome work on new use cases from analyzing ground motion datasets, improving quality control, and on the integration and development of both basic and advanced station metadata (including housing and site characterization). Inspired by the notion of data FAIRness (Findability, Accessibility, Interoperability, and Reuse) of digital assets, we also welcome discussion regarding open data access for seismic data, associated products and metrics related to signal processing and associated site metadata.

Conveners: Carlo Cauzzi, Swiss Seismological Service (SED) at ETH Zürich (carlo.cauzzi@sed.ethz.ch); Lijam Hagos, California Geological Survey (Lijam.Hagos@conservation.ca.gov); Olga-Joan Ktenidou, National Observatory of Athens (olga.ktenidou@noa.gr); Albert Kottke, Pacific Gas and Electric (arkk@pge.com); Lucia Luzi, National Institute of Geophysics and Volcanology (lucia.luzi@ingv.it); Lisa S. Schleicher, U. S. Geological Survey (lschleicher@usgs.gov)

Network Seismology: Recent Developments, Challenges and Lessons Learned

Seismic monitoring is not only an essential component of earthquake response but also forms the backbone of a substantial amount of research into seismic hazards, the earthquake process and seismotectonics. To ensure networks best serve the public, media, government, and academic communities, it is important to continue to develop monitoring networks' abilities to accurately and rapidly catalog earthquakes. Due to the operational environment of seismic monitoring, seismic networks encounter many unique challenges not seen by the research community. In this session, we highlight the unique observations and challenges of monitoring agencies and look to developments that may improve networks' ability to fulfill their missions. Seismic operation centers play a crucial role in collecting seismic data and generating earthquake products, including catalogs, warnings, and maps of ground shaking. The purpose of the session is to foster collaboration between network operators, inform the wider seismological community of the interesting and challenging problems within network seismology and look to the future on how to improve monitoring capabilities. This session is not only an opportunity for monitoring agencies to highlight new developments in their capabilities, but we also encourage submissions describing new instrumentation, methods, and techniques that would benefit network operations for detecting, locating and characterizing earthquakes, particularly in a near real-time environment.

Conveners: Blaine M Bockholt, Idaho National Laboratory (Blaine.bockholt@inl.gov); J. Renate Hartog, University of Washington (jrhartog@uw.edu); Kristine L. Pankow, University of Utah (pankowseis2@gmail.com); Dmitry Storchak, International Seismological Centre (dmitry@isc.ac.uk); William Yeck, U.S. Geological Survey (wyeck@usgs.gov)

New Directions in Environmental, Seismic Hazard and Mineral Resource Exploration Studies

The identification and assessment of ground displacement hazards, their environmental and social impacts, and mineral resource exploration targets are of growing importance for populations near industrial settings and in urbanized areas. As infrastructure development accelerates, multi-hazard assessments are needed to ensure the safety and sustainability of these regions. New approaches for collecting high-resolution geophysical and geological datasets and advances in methodologies allow us to image the subsurface at increasingly higher resolution. Advances in time-lapse imaging and event detection provide new opportunities for monitoring underground storage sites, changes in aquifer systems, and fault zone properties over time. These advances are key for improving community preparedness and resilience.

This session focuses on new directions in subsurface research for environmental studies, mineral resource exploration, and seismic hazard evaluation, including data collection, methodologies, and the application of dense seismic arrays and other instrumentation. Such studies create new avenues for interdisciplinary research, enabling geoscientists, engineers, and environmental scientists to collaborate and integrate findings across fields. We invite submissions on potential unidentified hazards and environmental impacts in well-researched and in understudied geographic areas. We encourage submissions from early-career researchers, cross-disciplinary approaches, and studies using innovative methodologies such as machine learning and distributed acoustic sensing (DAS).

Conveners: Claire Doody, Lawrence Livermore National Laboratory (doody1@llnl.gov); Md Mohimanul Islam, University of Missouri (mibhk@missouri.edu); Chiara Nardoni, University of Bologna (chiara.nardoni4@unibo.it); Shujuan Mao, University of Texas at Austin(smao@jsg.utexas.edu); Patricia Persaud, University of Arizona (ppersaud@arizona.edu); Valeria Villa, California Institute of Technology (vvilla@caltech.edu); Xin Wang, Chinese Academy of Sciences (wangxin@mail.iggcas.ac.cn)

Numerical Modeling in Seismology: Theory, Algorithms and Applications

Progress in seismology is unthinkable without continuous developments of theory and numerical-modeling methods. Recent advances in finite-difference, discontinuous-Galerkin, spectral-element and distributional finite-difference methods prove the irreplaceable role of numerical modeling in investigation of earthquake source, earthquake ground motion, seismic ambient noise, and Earth's structure.

We equally invite contributions to numerical-modeling methods and efficient computational algorithms, both in all dimensions, and applications to earthquake phenomena and specific sites of interest. We invite contributors to share their advances in the numerical modeling and understanding of seismic wave propagation, earthquake rupture, earthquake ground motion, and seismic ambient noise. Better understanding of physics of these phenomena based on new observations, seismic data from dedicated networks, and efficient numerical modeling should eventually help to progress in predicting earthquake ground motion.

Recent developments in numerical modeling of seismic waves, earthquake ground motion and rupture propagation aim to account for more realistic rheology as well as geometrical complexity of material interfaces and faults. They also address discretization in time and space and their relations to accuracy and computational efficiency. Remarkable progress in the efficiency and accuracy of finite-difference modeling in seismic exploration poses a useful challenge for numerical modeling in earthquake seismology.

We especially welcome applications to compelling observational issues in seismology.

Conveners: Alice-Agnes Gabriel, Scripps Institution of Oceanography, University of California, San Diego (algabriel@ucsd.edu); Martin Galis, Comenius University Bratislava (martin.galis@uniba.sk); Jozef Kristek, Comenius University Bratislava (kristek@fmph.uniba.sk); Peter Moczo, Comenius University Bratislava (moczo@fmph.uniba.sk); Arben Pitarka, Lawrence Livermore National Laboratory, Livermore (pitarka1@llnl.gov); Wei Zhang, Southern University of Science and Technology, Shenzhen (zhangwei@sustech.edu.cn)

Performance and Progress of Earthquake Early Warning Systems Around the World

Earthquake early warning (EEW) systems aim to rapidly detect that an earthquake is happening and issue alerts for incoming shaking. Such systems can provide crucial seconds for people and automated systems to take protective actions before shaking arrives, potentially mitigating the impacts of damaging ground motions. The development and operation of EEW systems is a multidisciplinary effort at the intersection of seismology, engineering, and social science. Timely alerting requires both sophisticated network engineering to provide real-time seismic and geodetic observations as well as earthquake characterization algorithms that use small portions of these data to rapidly detect earthquake shaking and estimate ground motion distributions. Social science and emergency management research help determine what alert messages should say and illuminate public perception of the system's performance. Selecting alerting strategies that balance tradeoffs among prediction accuracy, available warning time, and the level of shaking for which users desire alerts requires insight from all disciplines.

There are many EEW systems around the world that are in various stages of operation and development. The details of a given EEW system vary, but system operators look to each other for new ideas and lessons learned from recent earthquakes. This session welcomes contributions across all disciplines of EEW science, including abstracts that discuss the performance of current EEW systems, the development of new EEW approaches, and education and outreach efforts to encourage adoption of these systems.

Conveners: Glenn Biasi, U.S. Geological Survey (gbiasi@usgs.gov); Angela Lux, University of California Berkeley (angie.lux@berkeley.edu); Jessica Murray, U.S. Geological Survey (jrmurray@usgs.gov); Jessie K Saunders, California Institute of Technology (jsaunder@caltech.edu); Alan Yong, U.S. Geological Survey (yong@usgs.gov)

Predictability of Seismic and Aseismic Slip: From Basic Science to Operational Forecasts

A central problem of earthquake seismology is time-dependent earthquake forecasting. We are currently unable to reliably predict damaging earthquakes—or the lack thereof—within relatively short and therefore actionable space and timeframes. It may be that the earthquake nucleation process is complex enough that such prediction is impractical. However, new pieces of the forecasting puzzle continue to accumulate from lab and field experiments, multidisciplinary observations, theory, physical modeling, advanced computing and machine learning.

This session welcomes approaches to evaluate constraints on short-timescale forecasting as well as opportunities for the predictability of seismic and aseismic fault slip, fracturing, and their associated processes, such as crustal deformation, aftershocks, fluid flow or geochemical alterations. If the old, central problem of earthquake prediction is too ill-conditioned, how do we integrate across disciplinary boundaries to make progress on more predictable variables and processes?

We welcome a broad range of contributions that provide new perspectives on the predictability of seismic and aseismic slip and associated phenomena. These may include new insights from: lab and field experiments, analyses of aseismic slip or low-frequency earthquakes and their interaction with fast earthquakes, models of fault slip, evaluations of seismicity forecasting models including machine learning models, enhanced earthquake catalogs, advanced computing and machine learning techniques, or integrated predictive modeling of a broad spectrum of phenomena beyond purely seismic slip.

Conveners: Jessica Hawthorne, University of Oxford (jessica.hawthorne@earth.ox.ac.uk); Maximilian J. Werner, University of Bristol (max.werner@bristol.ac.uk)

Recent Advances in Modeling Near-source Ground Motions for Seismic Hazard Applications

In recent years, modeling efforts that characterize the earthquake source in greater detail have enabled a better understanding of earthquake behavior and resulting broadband ground motion. For example, modeling the geometry of fault surfaces and propagation of rupture has helped map source properties into ground motion amplification patterns and variability. This improved accuracy from modeling finite-fault effects can be influential in studies investigating predictions of earthquake ground motions and other downstream efforts involving seismic hazard assessment. Here, we invite studies that model earthquake source processes targeting improved ground shaking via either empirical or simulation-based approaches. Example topics of interest include observations of azimuthally varying ground motion, rupture directivity from both small and large events, polarization of ground motion records, complex source modeling using kinematic or dynamic ruptures, and near-source efforts that study median and ground motion variability terms, isolated in terms of either intra- or inter-event standard deviation. Studies using machine learning methods, utilizing both empirical and synthetic datasets are welcomed as well.

Conveners: Jeff Bayless, AECOM (jeff.bayless@aecom.com); Nick Gregor, Consultant (nick@ngregor.com); Evan Hirakawa, U.S. Geological Survey (ehirakawa@usgs.gov); Grace Parker, U.S. Geological Survey (gparker@usgs.gov); Badie Rowshandel, California Earthquake Authority (browshandel@calquake.com); Kyle B. Withers, U.S. Geological Survey (kwithers@usgs.gov)

Scientific Machine Learning for Forward and Inverse Wave Equation Problems

The synergy between scientific machine learning (SciML) and computational mechanics is transforming our approach to forward and inverse problems governed by complex partial differential equations, particularly in seismic wave propagation. This session brings together experts from various disciplines—including seismology, computational geomechanics and dynamics, and the broader SciML community—to explore cutting-edge methods and real-world applications in this interdisciplinary arena. The goal is to bridge the gap between traditional computational approaches and emerging AI-driven techniques in the modeling and analysis of wave phenomena. We welcome contributions that leverage data-driven and physics-inspired machine-learning techniques to enhance the modeling, simulation, and interpretation of seismic wave phenomena across different fields. Topics of interest include but are not limited to: (1) Applications of PINNs in solving forward and inverse wave problems, handling complex boundary conditions and subsurface velocity models; (2) Advancements in neural operators, such as Deep Operator Networks and Fourier Neural Operators for efficient and accurate wavefield simulations; and (3) Innovative uses of SciML in related fields such as acoustics and ultrasound imaging, elastodynamics, structural health monitoring, planetary seismology, environmental monitoring, and natural hazard assessment. We particularly encourage submissions highlighting how SciML techniques applied to wave equation problems can be adapted or inspire solutions in adjacent fields, fostering the exchange of ideas and methodologies. This session provides a dynamic forum for attendees to discuss theoretical developments, share practical experiences, and identify future research directions that transcend traditional domain boundaries. Through these interactive exchanges, we aim to advance the capabilities of computational models and unlock new potentials in scientific research and engineering applications.

Conveners: Tariq Alkhalifah, King Abdullah University of Science and Technology (tariq.alkhalifah@kaust.edu.sa); Arash Fathi, ExxonMobil Technology and Engineering (arash.fathi@exxonmobil.com); Lu Lu, Yale University (lu.lu@yale.edu); Kami Mohammadi, University of Utah (kami.mohammadi@utah.edu); Harpreet Sethi, NVIDIA (hasethi@nvidia.com)

Seismology for the Energy Transition

As the energy transition accelerates toward low- and zero-carbon sources, technologies such as geothermal and hydrogen energy, alongside geologic carbon storage, will be essential to achieving the net-zero emissions goal by 2050. The success of this transformation relies on advanced seismic and non-seismic technologies to optimize the exploration and development of geothermal and hydrogen energy, as well as to ensure safe, long-term geologic carbon storage.

This session invites cutting-edge research on site and reservoir characterization and monitoring, utilizing techniques such as passive and active seismic methods, distributed acoustic sensing (DAS), ambient noise analysis, induced seismicity, advanced sensors, other emerging approaches, and non-seismic techniques. We encourage contributions that explore applications of these techniques in geothermal energy (including hydrothermal, enhanced geothermal systems and superhot geothermal), hydrogen energy development, hydrogen and geothermal storage, and geologic carbon storage. We welcome abstracts on laboratory experiments, numerical modeling, AI and machine learning innovations, and field-scale studies.

Conveners: Erkan Ay, Shell (Erkan.Ay@shell.com); Hiroshi Hiroshi, National Institute of Advanced Industrial Science and Technology (h.asanuma@aist.go.jp); Lianjie Huang, Los Alamos National Laboratory (ljh@lanl.gov); Yingcai Zheng, University of Houston (yzheng24@central.uh.edu)

Station Installations and Site Conditions, a Quest for Improved Strong Motion Database

This session emphasizes the practical challenges related to how seismic data is recorded and to the factors that introduce uncertainties in ground motion databases. Ground Motion Models (GMMs) used in seismic hazard assessment (SHA) often rely on proxies to model site effects. These proxies are often estimated indirectly because of the lack of site characterization of the seismic station used to develop the strong-motion database. Either directly or indirectly assessed, the use of proxies introduce uncertainty in GMMs predictions. Moreover, in empirical GMMs it is often assumed that the earthquakes are recorded at the free surface of the earth, that sensor installation conditions and seasonal effects can be neglected, and that all instruments provide recordings with reliable amplitudes. In practice, many seismic stations are located at depth (e.g., in boreholes or in tunnels) or in an urban environment, errors in the metadata can be found, and detailed site characterization and site-effect assessment are performed only on a limited subset of stations.

With this background, this session welcomes contributions highlighting any effects (from station installation conditions to complex site-effects) that could affect the recorded ground motion, with consequent implications for GMMs, especially at high frequencies. Topics of interest include data processing and data quality control, soil-instrument coupling, soil-structure interactions, depth effects (down-going waves), seasonal variations, topography effects, site effects, site characterization, regional and local attenuation, and small-scale heterogeneity and scattering. Studies demonstrating the value of site instrumentation and characterization in improving site-specific SHA are also encouraged. Studies focusing on improving our current practices in earthquake database implementation or on the enhanced understanding of the high-frequency content of seismic records are particularly welcome.

Conveners: Fabrice Hollender, CEA Cadarache (fabrice.hollender@cea.fr); Vincent Perron, CEA Cadarache (vincent.perron@cea.fr); Zafeiria Roumelioti, University of Patras (zroumelioti@upatras.gr); Paola Traversa, Electricity of France (paola.traversa@edf.fr)

Temporally Variable Records of Earthquake Behavior and Considerations for Seismic Hazard Analyses

Geologic data used to constrain past earthquakes – geologic slip rates and paleoseismic chronologies – are inherently time-variable data streams due to irregular earthquake occurrence through time. While time-varying by their nature, these records are used to extrapolate and infer long-term fault behavior, most notably in time-independent seismic hazard analyses. We seek submissions discussing new contributions in the field of earthquake geology, particularly studies geared to address time-dependence of geologic slip rates, paleoseismic chronologies and recurrence intervals, regional geologic deformation models, and displacement and/or surface rupture variability at a point through time. We also welcome contributions comparing geologic data to geodetic deformation models to further assess discrepancies rooted in sampling decadal (geodetic) vs. longer (geologic) time scales. We encourage submissions that pose ideas for the implementation of these geologic data in future time-independent and time-dependent seismic hazard model development.

Conveners: Alexandra E Hatem, U.S. Geological Survey (ahatem@usgs.gov); Belle Philibosian, U.S. Geological Survey (bphilibosian@usgs.gov); Ashley Streig, Portland State University (streig@pdx.edu)

Testing, Testing 1 2 3: Appropriate Evaluation of New Seismic Hazard and Risk Models

Many models used in earthquake science have societal impact, whether directly, such as through insurance premiums calculated on the basis of hazard maps, or indirectly, such as the fault rupture sets which underpin these maps. Frequently, such models are developed initially from a perspective of scientific curiosity rather than downstream application. This session seeks to explore the question of what constitutes appropriate testing and evaluation of models with potential life-safety impact, whether by design or in terms of their future potential. In particular, as observations of earthquakes have become more numerous, more detailed and more precise, the range of earthquake phenomena understood to be possible has continued to expand. In this context, how can we develop methods of evaluation which require models to be both consistent with our (limited) observations to date, and not overly constrained by observation bias? We invite contributions on all aspects of testing and evaluation of models with societal applications, and would particularly welcome speakers interested in these questions as applied to multi-fault, multi-cycle earthquake simulators.

Conveners: Kirsty Bayliss, GEM Foundation, (kirsty.bayliss@globalquakemodel.org); Bill Fry, GNS Science, (b.fry@gns.cri.nz); Matthew Gerstenberger, GNS Science, (m.gerstenberger@gns.cri.nz); Andrew Nicol, University of Canterbury(andy.nicol@canterbury.ac.nz); Bruno Pace, Gabriele d'Annunzio University Chieti-Pescara (bruno.pace@unich.it); Camilla Penney, University of Canterbury(camilla.penney@canterbury.ac.nz)

Unusual Earthquakes and Their Implications

Many earthquakes challenge paradigms about earth mechanics and pose troubling implications for hazard and risk. Earthquakes can occur in unexpected regions: low shear-stress stable continental interiors; deep in subduction zones where high pressures and temperatures should inhibit brittle failure; and even on the Moon, Mars and other planets. Earthquakes can behave in unusual ways: ruptures can slip "backwards" or propagate in unexpected directions; large earthquakes can happen in rapid succession; or they can happen with multiple slip episodes with rupture speeds faster or slower than expected. Such events often require new physical explanations that push the boundaries of our understanding of seismogenesis and rupture propagation. They also complicate hazard and risk analyses, requiring those models to go beyond standard statistical and physical approaches. We welcome contributions on any unusual or thought-provoking earthquakes.

Conveners: Zhe Jia, University of Texas at Austin (zjia@ig.utexas.edu); Chris Rollins, GNS Science (c.rollins@gns.cri.nz); Alice R. Turner, University of Texas at Austin (alice.turner@jsg.utexas.edu)

Visualization and Sonification in Solid Earth Geosciences, What's Next?

The integration of visualization and sonification techniques, leveraging the human auditory and visual systems in tandem, has opened new avenues for understanding complex solid Earth processes and presenting them to a general audience. However, as the volume and complexity of geophysical data continue to grow, traditional high-level methods often fall short in conveying the significance of underlying patterns and insights. This session aims to explore developments in these areas, highlighting innovative methods and applications that enhance data interpretation, accessibility, and communication within and beyond the geoscience community.

We invite contributions that address the following topics:

- Novel visualization/sonification techniques for exploration of basic or high-resolution catalog data, multiparameter timeseries, or multidisciplinary data.
- Case studies showcasing the impact of visualization/sonification on research, education and outreach.
- Applications of machine learning (ML) and artificial intelligence (AI) in enhancing visualization and sonification processes, applications in which ML/AI algorithms are developed through use of sonification/visualization, and other novel algorithms for mapping data to soundscapes.
- Future directions and challenges in the integration of these techniques in active research, citizen science projects, and public outreach.

Conveners: Julien Chaput, University of Texas, El Paso (jachaput@utep.edu); Debi Kilb, University of California, San Diego (dkilb@ucsd.edu); Leif Karlstrom, University of Oregon (leif@uoregon.edu); Zhigang Peng, Georgia Institute of Technology (zpeng@gatech.edu)

Why Ignore the Structure? Soil-structure Interaction and Site Response at Local and Regional Scales

In regions prone to seismic activity, the execution of reliable site response analyses stands out as a cost-efficient measure during the design phase of critical infrastructure such as buildings, rail and tunneling systems, and power plants and utility networks. The dynamic interactions between structural components and underlying soil layers, known as soil-structure interaction (SSI), impact the overall seismic performance and safety of structures, and are relevant at both site-specific and regional scales.

In this session, we invite researchers and practitioners to contribute to a cohesive understanding of SSI and local site effects, two essential components of seismic design. This session seeks fostering of cutting-edge methodologies and innovative approaches in areas including but not limited to site response analysis (e.g., nonlinear 1D/3D site effects), kinematic and inertial effects of SSI (e.g., numerical and experimental modeling), and their effects on structures with deeply embedded foundations and large footprints (e.g., nuclear power plants). Additionally, we welcome studies investigating the role of physics-based simulations in improving our understanding of SRA and SSI, the complexities of SSI in urban and regional settings, and risk assessments of portfolios of infrastructure assets, such as densely built environments or pipeline networks.

Conveners: Sean K. Ahdi, ARUP US, Inc., (sean.ahdi@arup.com); Mohammad Yazdi, Mott MacDonald, (m_yazdi@nevada.unr.edu); Peiman Zogh, ARUP US, Inc. (peiman.zogh@arup.com)

Overview of Technical Program

Monday 14 April

1–4 PM
Pride of Baltimore Field Seminar

1–4:30 PM
How to Open a Presentation and Foster a Great Q&A Workshop
Peale A-C

1–5 PM
Building a High-Resolution Earthquake Catalog from Raw Waveforms: A Step-by-Step Guide Workshop
Key Ballroom 10

1–5 PM
Distributed Acoustic Sensing Open-source Software Workshop
Key Ballroom 11

3–7:30 PM
Registration Opens
East Foyer

5–6 PM
Opening Reception and Exhibits
Exhibit Hall, Key Ballroom 1-8

6–7 PM
Plenary
Holiday Ballroom 4-6

Tuesday 15 April

7 AM–5 PM
Registration
East Foyer

8–9:15 AM
Technical Sessions

9:15–10:30 AM
Exhibits, Posters Break
Key Ballroom 1-8

10:30–11:45 AM
Technical Sessions

11:45 AM–2 PM
Lunch Break

2–3:15 PM
Technical Sessions

3:15–4:30 PM
Exhibits, Posters Break
Key Ballroom 1-8

4:30–5:45 PM
Technical Sessions

6–7 PM
Plenary
Holiday Ballroom 4-6

7–8 PM
Student/Early-Career Reception*
Holiday Ballroom 2-3

Wednesday 16 April

7:30 AM–5 PM
Registration
East Foyer

8–9:15 AM
Technical Sessions

9:15–10:30 AM
Exhibits, Posters Break
Key Ballroom 1-8

10:30–11:45 AM
Technical Sessions

Noon–2 PM
Annual Business and Awards Luncheon
Holiday Ballroom 4-6

2–3:15 PM
Technical Sessions

3:15–4:30 PM
Exhibits, Posters Break
Key Ballroom 1-8

4:30–5:45 PM
Technical Sessions

6–7 PM
Joyner Lecture
Holiday Ballroom 4-6

7–8 PM
Joyner Reception
Exhibit Hall, Key Ballroom 1-8

Thursday 17 April

7:30 AM–5 PM
Registration
East Foyer

8–9:15 AM
Technical Sessions

9:15–10:30 AM
Exhibits, Posters Break
Key Ballroom 1-8

10:30–11:45 AM
Technical Sessions

11:45 AM–2 PM
Lunch Break

2–3:15 PM
Technical Sessions

3:15–4:30 PM
Exhibits, Posters Break
Key Ballroom 1-8

4:30–5:45 PM
Technical Sessions

Friday 18 April

7 AM–5 PM
Smithsonian Private Tours and Washington Fault Lines Field Seminar

9 AM–Noon
Pride of Baltimore Field Seminar

* Invite only event

Tuesday, 15 April

Oral Sessions

Time	*Holiday Ballroom 1*	*Holiday Ballroom 4–6*	*Key Ballroom 9*
8:00–9:15 AM	Adventures in Social Seismology: Ethical Engagement, Earthquake Early Warnings, Operational Forecasts, and Beyond	Network Seismology: Recent Developments, Challenges and Lessons Learned	Fiber-optic Sensing Applications in Seismology
9:15–10:30 AM	Poster Break		
10:30–11:45 AM	Adventures in Social Seismology: Ethical Engagement, Earthquake Early Warnings, Operational Forecasts, and Beyond	Network Seismology: Recent Developments, Challenges and Lessons Learned	Fiber-optic Sensing Applications in Seismology
11:45 AM–2:00 PM	Lunch Break		
2:00–3:15 PM	Improving the State of the Art of Earthquake Forecasting Through Models, Testing and Communication	Network Seismology: Recent Developments, Challenges and Lessons Learned	Innovative Applications of Seismic Nodal Technology for Hazard Mitigation and Earth System Monitoring
3:15–4:30 PM	Poster Break		
4:30–5:45 PM	Building and Decoding High-resolution Earthquake Catalogs With Statistical and Machine-learning Tools	ESC-SSA Joint Session:Seismology in the Global Oceans: Advances in Methods and Observations	Geophysics in a Changing World: Monitoring Applications from Seismology and Beyond
6:00–7:00 PM	Plenary Address: The USGS Earthquake Hazards Program: Science to Support Decision-Making		
7:00–8:00 PM	Student/Early-Career Reception		

Time	*Key Ballroom 10*	*Key Ballroom 11*	*Key Ballroom 12*
8:00–9:15 AM	Late-breaking on Recent and Future Large Earthquakes	Testing, Testing 1 2 3: Appropriate Evaluation of New Seismic Hazard and Risk Models	From Physics to Forecasts: Advancements and Future Directions of Induced Seismicity Research
9:15–10:30 AM	Poster Break		
10:30–11:45 AM	Late-breaking on Recent and Future Large Earthquakes	Advancing Time-dependent PSHA and Seismic Risk Assessment: Accounting for Short- to Medium-term Clustering	From Physics to Forecasts: Advancements and Future Directions of Induced Seismicity Research
11:45 AM–2:00 PM	Lunch Break		
2:00–3:15 PM	Advanced Geophysical Observations, Analytical Methods, and New Insights for Earthquake Swarms	Accuracy and Variability of Physics-based Ground Motion Modeling	Mechanistic Insights into Fluid-induced Earthquakes from the Laboratory to the Field
3:15–4:30 PM	Poster Break		
4:30–5:45 PM	Scientific Machine Learning for Forward and Inverse Wave Equation Problems	Accuracy and Variability of Physics-based Ground Motion Modeling	Mechanistic Insights into Fluid-induced Earthquakes from the Laboratory to the Field
6:00–7:00 PM	Plenary Address: The USGS Earthquake Hazards Program: Science to Support Decision-Making		
7:00–8:00 PM	Student/Early-Career Reception		

Poster Sessions

- Accuracy and Variability of Physics-based Ground Motion Modeling
- Advanced Geophysical Observations, Analytical Methods, and New Insights for Earthquake Swarms
- Advancing Time-dependent PSHA and Seismic Risk Assessment: Accounting for Short- to Medium-term Clustering
- Adventures in Social Seismology: Ethical Engagement, Earthquake Early Warnings, Operational Forecasts, and Beyond
- Building and Decoding High-resolution Earthquake Catalogs With Statistical and Machine-learning Tools
- ESC-SSA Joint Session:Seismology in the Global Oceans: Advances in Methods and Observations
- Fiber-optic Sensing Applications in Seismology
- From Physics to Forecasts: Advancements and Future Directions of Induced Seismicity Research
- Geophysics in a Changing World: Monitoring Applications from Seismology and Beyond
- Improving the State of the Art of Earthquake Forecasting Through Models, Testing and Communication
- Innovative Applications of Seismic Nodal Technology for Hazard Mitigation and Earth System Monitoring
- Late-breaking on Recent and Future Large Earthquakes
- Mechanistic Insights into Fluid-induced Earthquakes from the Laboratory to the Field
- Network Seismology: Recent Developments, Challenges and Lessons Learned
- Scientific Machine Learning for Forward and Inverse Wave Equation Problems
- Testing, Testing 1 2 3: Appropriate Evaluation of New Seismic Hazard and Risk Models

Wednesday, 16 April

Oral Sessions

Time	*Holiday Ballroom 1*	*Holiday Ballroom 4–6*	*Key Ballroom 9*
8:00–9:15 AM	Performance and Progress of Earthquake Early Warning Systems Around the World		Earth's Structure from the Crust to the Core
9:15–10:30 AM	Poster Break		
10:30–11:45 AM	Performance and Progress of Earthquake Early Warning Systems Around the World		Earth's Structure from the Crust to the Core
11:45 AM–2:00 PM	Annual Business and Awards Luncheon		
2:00–3:15 PM	Data-driven and Computational Characterization of Non-earthquake Seismoacoustic Sources		Earth's Structure from the Crust to the Core
3:15–4:30 PM	Poster Break		
4:30–5:45 PM	Fifty Years and Beyond of Broadband Seismic Instrumentation: Performance, Precision and Uncertainties		Earth's Structure from the Crust to the Core
6:00–7:00 PM	Joyner Lecture: Risk and Reward: Working at the Boundaries of Earthquake Science		
7:00–8:00 PM	Joyner Reception		

Time	*Key Ballroom 10*	*Key Ballroom 11*	*Key Ballroom 12*
8:00–9:15 AM	The Landscape Record of Earthquakes and Faulting	Recent Advances in Modeling Near-source Ground Motions for Seismic Hazard Applications	Advances in Reliable Earthquake Source Parameter Estimation
9:15–10:30 AM	Poster Break		
10:30–11:45 AM	The Landscape Record of Earthquakes and Faulting	Recent Advances in Modeling Near-source Ground Motions for Seismic Hazard Applications	Advances in Reliable Earthquake Source Parameter Estimation
11:45 AM–2:00 PM	Annual Business and Awards Luncheon		
2:00–3:15 PM	Unusual Earthquakes and Their Implications	Station Installations and Site Conditions, a Quest for Improved Strong Motion Database	Advances in Reliable Earthquake Source Parameter Estimation
3:15–4:30 PM	Poster Break		
4:30–5:45 PM	Predictability of Seismic and Aseismic Slip: From Basic Science to Operational Forecasts	Station Installations and Site Conditions, a Quest for Improved Strong Motion Database	Seismology for the Energy Transition
6:00–7:00 PM	Joyner Lecture: Risk and Reward: Working at the Boundaries of Earthquake Science		
7:00–8:00 PM	Joyner Reception		

Poster Sessions

- Advances in Reliable Earthquake Source Parameter Estimation
- Data-driven and Computational Characterization of Non-earthquake Seismoacoustic Sources
- Earth's Structure from the Crust to the Core
- Fifty Years and Beyond of Broadband Seismic Instrumentation: Performance, Precision and Uncertainties
- The Landscape Record of Earthquakes and Faulting
- Performance and Progress of Earthquake Early Warning Systems Around the World
- Predictability of Seismic and Aseismic Slip: From Basic Science to Operational Forecasts
- Recent Advances in Modeling Near-source Ground Motions for Seismic Hazard Applications
- Seismology for the Energy Transition
- Station Installations and Site Conditions, a Quest for Improved Strong Motion Database
- Unusual Earthquakes and Their Implications

Thursday, 17 April

Oral Sessions

Time	*Holiday Ballroom 1*	*Holiday Ballroom 4–6*	*Key Ballroom 9*
8:00–9:15 AM	Exploring Planetary Interiors and Seismology: Observations, Models, Experiments and Future Missions	Advancements in Forensic Seismology and Explosion Monitoring	Numerical Modeling in Seismology: Theory, Algorithms and Applications
9:15–10:30 AM	Poster Break		
10:30–11:45 AM	Visualization and Sonification in Solid Earth Geosciences, What's Next?	Advancements in Forensic Seismology and Explosion Monitoring	Numerical Modeling in Seismology: Theory, Algorithms and Applications
11:45 AM–2:00 PM	Lunch Break		
2:00–3:15 PM	Earthquake Shaking and the Geologic Record: Triggered Phenomena and Preserved Fragile Geologic Features	Advancements in Forensic Seismology and Explosion Monitoring	New Directions in Environmental, Seismic Hazard and Mineral Resource Exploration Studies
3:15–4:30 PM	Poster Break		
4:30–5:45 PM		Advancements in Forensic Seismology and Explosion Monitoring	New Directions in Environmental, Seismic Hazard and Mineral Resource Exploration Studies

Time	*Key Ballroom 10*	*Key Ballroom 11*	*Key Ballroom 12*
8:00–9:15 AM	Earthquakes, Lithospheric Structure, and Dynamics in Stable Continental Region	Challenges and Opportunities in Constraining Ground-motion Models from Physics-based Ground-motion Simulations	Earthquake-triggered Ground Failure: Data, Hazards, Impacts and Models
9:15–10:30 AM	Poster Break		
10:30–11:45 AM	Earthquakes, Lithospheric Structure, and Dynamics in Stable Continental Region	Challenges and Opportunities in Constraining Ground-motion Models from Physics-based Ground-motion Simulations	Why Ignore the Structure? Soil-structure Interaction and Site Response at Local and Regional Scales
11:45 AM–2:00 PM	Lunch Break		
2:00–3:15 PM	Exploring the Complexity of Fault Discontinuities	Challenges and Opportunities in Constraining Ground-motion Models from Physics-based Ground-motion Simulations	Macroseismic Intensity: Past, Present and Future
3:15–4:30 PM	Poster Break		
4:30–5:45 PM	Compiling Active Faults for Improved Hazard Modeling from Cascadia to Alaska	Modern Waveform Processing and Engineering Datasets - Accessibility, Quality Control, and Metadata	

Poster Sessions

- Advancements in Forensic Seismology and Explosion Monitoring
- Advancing Seismic Hazard Models
- Challenges and Opportunities in Constraining Ground-motion Models from Physics-based Ground-motion Simulations
- Compiling Active Faults for Improved Hazard Modeling from Cascadia to Alaska
- Earthquake Shaking and the Geologic Record: Triggered Phenomena and Preserved Fragile Geologic Features
- Earthquake-triggered Ground Failure: Data, Hazards, Impacts and Models
- Earthquakes, Lithospheric Structure, and Dynamics in Stable Continental Region
- Exploring Planetary Interiors and Seismology: Observations, Models, Experiments and Future Missions
- Exploring the Complexity of Fault Discontinuities
- Macroseismic Intensity: Past, Present and Future
- Modern Waveform Processing and Engineering Datasets - Accessibility, Quality Control, and Metadata
- New Directions in Environmental, Seismic Hazard and Mineral Resource Exploration Studies
- Numerical Modeling in Seismology: Theory, Algorithms and Applications
- Temporally Variable Records of Earthquake Behavior and Considerations for Seismic Hazard Analyses
- Why Ignore the Structure? Soil-structure Interaction and Site Response at Local and Regional Scales

Tuesday, 15 April 2025—Oral Sessions

Presenting author is indicated in bold.

Time	*Holiday Ballroom 1*	*Holiday Ballroom 4–6*	*Key Ballroom 9*
	Adventures in Social Seismology: Ethical Engagement, Earthquake Early Warnings, Operational Forecasts, and Beyond (see page 1337).	**Network Seismology: Recent Developments, Challenges and Lessons Learned** (see page 1429).	**Fiber-optic Sensing Applications in Seismology** (see page 1388).
8:00 AM	Invited: Geosciences in Dangerous Area: The Case of Haiti. **Symithe, S. J.**, Calais, E.	Evolution and Optimization of the Raspberry Shake Data Center: Managing the World's Largest Real-time Seismic Network. **Christensen, B.**, Boaz, R.	Applications of Distributed Acoustic Sensing Using Dark Fiber in Dallas, Texas. **Sharma, J.**, Arrowsmith, S., Hayward, C., DeShon, H. R.
8:15 AM	Student: The Large-enrollment Seismology Skill Building Workshop Is an Inclusive and Effective Geoscience Recruiting Tool. **Ventura-Valentin, W. A.**, Brudzinski, M. R., Haberli, G., Hubenthal, M., Meyer, E. H.	ISC: Supplementary Services for Seismology. **Storchak, D. A.**, Harris, J., Di Giacomo, D., Lieser, K.	Invited: Student: Daily Groundwater Monitoring Using Vehicle-DAS Elastic Full-waveform Inversion. **Li, H.**, Liu, J., Mao, S., Yuan, S., Clapp, R., Biondi, B.
8:30 AM	Invited: Navigating Earthquake News in the Age of AI. **Stanley, S. M.**, Wardle, C.	Station Statistics Derived from the ISC Bulletin. Harris, J., Gallacher, R., **Garth, T.**, Storchak, D. A.	Detection and Source Characterisation of Crevasse Icequakes at an Alpine Glacier Using Distributed Acoustic Sensing. Hudson, T. S., Noe, S., Walter, F., Kendall, M., **Fichtner, A.**
8:45 AM	Invited: Centering Users When Designing Earthquake and Aftershock Products. **Schneider, M.**, Artigas, B., Wein, A. M., van der Elst, N., McBride, S. K., Becker, J., Castro, R., Diaz, M., Gonzalez-Huizar, H., Hardebeck, J., Michael, A. J., Mixco, L., Page, M.	Geophysical and Sea-level Monitoring in Puerto Rico: Recent Developments, Challenges and Lessons Learned. **Huerfano, V. A.**, Martinez-Cruzado, J. A., Rivera, J.	Englacial Ice Quake Cascades in the Northeast Greenland Ice Stream - DAS Observations and Implications for Ice Stream Dynamics. **Fichtner, A.**, Hofstede, C., Kennett, B., Svensson, A., Westhoff, J., Walter, F., Ampuero, J., Cook, E., Zigone, D., Jansen, D., Eisen, O.
9:00 AM	Reflections on the Role of the International Community for the Promotion of Global Risk Reduction. **Hough, S. E.**	In the Pursuit of 99% Data Return - Case Study of the Italian National Accelerometric Network. **Franke, M.**, Filippi, L., Zambonelli, E., Ammirati, A., Radman, S.	Monitoring of Tele-seismic Events Using Multiple Trans-oceanic Telecom Cables and Distributed Fiber Sensing. **Mazur, M.**, Karrenbach, M., Fontaine, N. K., Ryf, R., Kamalov, V., Williams, E. F., Dallachiesa, L., Gunnarsson, A. I., Jonsson, O., Hlynsson, A. A., Hlynsson, S., Chen, H., Winter, D., Neilson, D. T., Ruiz-Angulo, A., Hjorleifsdottir, V.
9:15–10:30 AM	Poster Break		

Time	*Key Ballroom 10*	*Key Ballroom 11*	*Key Ballroom 12*
		Testing, Testing 1 2 3: Appropriate Evaluation of New Seismic Hazard and Risk Models (see page 1472).	**From Physics to Forecasts: Advancements and Future Directions of Induced Seismicity Research** (see page 1395).
8:00 AM		Testing and Evaluation of Earthquake Simulations for Natural Hazards and Risk Modelling. **Gerstenberger, M. C.**, Penney, C., Nicol, A., Fry, B., Pace, B., Bayliss, K.	Invited: Interpretable Deep Learning Framework for Forecasting Induced Seismicity in Geothermal Fields. **Nakata, N.**, Bi, Z.
8:15 AM		Evaluating the Impact of 3D Fault Geometry on Surface Rupture Probabilities Using Earthquake-cycle Simulations. **Gómez-Novell, O.**, Visini, F., Álvarez-Gómez, J. A., Pace, B.	Modeling and Forecasting Wastewater Disposal Induced Seismicity in the Delaware Basin. **Sirorattanakul, K.**, Fang, Z., An, J., Ruby, N., Tavakoli, R., Palmer, J., Comiskey, C.
8:30 AM		Invited: At the Testing Frontier. **Page, M.**	Managing Induced Earthquake Potential with Deep Graph Neural Networks. **Liu, B.**, Ellsworth, W. L., Howe, G., Eimon, B., Gebara, M., Murphy, O., Beroza, G. C.
8:45 AM		Student: Modeling Synthetic Catalogues of Earthquake Ruptures in Complex Interacting Fault Systems: A Case Study in Central Apennines, Italy. **Saghatforoush, K.**, Pace, B., Verdecchia, A., Visini, F., Peruzza, L., Zielke, O.	Modeling and Forecasting Induced Seismicity in the Midland Basin, Texas and Oklahoma. **Marty, S. B.**, Avouac, J., Curry, B., Hussenoeder, S. A., Yuan, Y., Jin, L.
9:00 AM		Invited: Guidelines for the Evaluation Process of a NSHM: The Italian MPS19 Legacy. **Marzocchi, W.**, Meletti, C., D'Amico, V., Lanzano, G., Luzi, L., Martinelli, F., Pace, B., Rovida, A., Taroni, M., Visini, F.	Advanced Deep Learning for Distinguishing the Quarry Blasts from Induced Seismicity. Yang, L., **Chen, Y.**, Siervo, D., Vallejo, K., Savvaidis, A.
9:15–10:30 AM	Poster Break		

Time	*Holiday Ballroom 1*	*Holiday Ballroom 4–6*	*Key Ballroom 9*
	Adventures in Social Seismology: Ethical Engagement, Earthquake Early Warnings, Operational Forecasts, and Beyond (see page 1337).	**Network Seismology: Recent Developments, Challenges and Lessons Learned** (see page 1429).	**Fiber-optic Sensing Applications in Seismology** (see page 1388).
10:30 AM	The December 5, 2024 Offshore Cape Mendocino Earthquake: Response to Earthquake Early Warning in an Earthquake Experienced Region. **Goltz, J. D.**	Advancing Operational Earthquake Monitoring at Local and Regional Scales With Machine Learning-enhanced SeisComP Tools - as Demonstrated in Switzerland. **Jozinović, D.**, Clinton, J. F., Massin, F., Diehl, T., Saul, J.	Invited: Student: Characterizing Microearthquakes and Shallow Attenuation With Downhole Optical Fibers in the Cape Modern Geothermal Field. **Chang, H.**, Nakata, N., Abercrombie, R. E., Dadi, S., Titov, A.
10:45 AM	Student: Scientific Storytelling to Improve Earthquake Shaking and Impact Communication. **Pope, I. E.**, Macias, M. A., Stoian, C. B., McBride, S. K., Lin, K., Earle, P. S., Wald, D. J.	Using Machine Learning for Near Real-time Monitoring in Utah and Yellowstone. **Baker, B.**, Armstrong, A. D., Pankow, K. L.	Rapid Earthquake Magnitude Estimation From P-wave Strains: Comparing Borehole Strain Meters and DAS. **Sawi, T.**, McGuire, J. J., Barbour, A. J., Yoon, C. E., Yartsev, V., Karrenbach, M., Stewart, C., Hemphill-Haley, M., McPherson, R., Stockdale, K.
11:00 AM	Deaf University Student Experiences With Earthquake Early Warning. **Cooke, M. L.**, Cooper, A., Takayama, K., Sumy, D., McBride, S. K.	An Explainable Phase-picking Model That Imitates Human Workflow. **Park, Y.**, Armstrong, A. D., Yeck, W. L., Shelly, D. R., Beroza, G. C.	Detecting and Locating Earthquakes using Machine Learning Workflow and Offshore Distributed Acoustic Sensing. **Shi, Q.**, Denolle, M. A., Lipovsky, B. P., Williams, E. F., Ni, Y., Wilcock, W. S. D.
11:15 AM	Student: Public Feedback and Actions During EEW Alerts: Lessons From Central America. **Orihuela, B.**, Clinton, J. F., Massin, F., Burgoa, B., Boese, M., Protti, M., Yani, R., Marroquin, G.	Towards Consistent Event Classification at Mount Baker Volcano, Washington, USA. **Stevens, N. T.**, Poobua, S., Hartog, J., Malone, S., Thelen, W., Wright, A. K., Johnson, B., O'Rourke, C. T.	Coherence-based Earthquake Location Using Integrated Fiber-optic and Conventional Seismic Networks. **Bozzi, E.**, Pascucci, G., Gaviano, S., Saccorotti, G., Bocchini, G., Harrington, R., Ugalde, A., Martins, H. F., Grigoli, F.
11:30 AM	Just Because We Can, Does That Mean We Should? An Ethical Discussion and Case Studies of International Aftershock Forecast by the U.S. Geological Survey. **McBride, S. K.**, Schneider, M., van der Elst, N., Michael, A. J., Page, M., Hardebeck, J., Llenos, A. L., Wein, A. M.	Implementation of AI/ML Detection of Seismicity as a Real-time SeisComP Module. **Muñoz Lopez, C. E.**, Salles, V., Skevofilax, C. G., Chen, Y., Savvaidis, A.	Deep Learning for Distributed Acoustic Sensing Data Compression. **Chen, Y.**, Saad, O., Chen, Y., Savvaidis, A.
11:45 AM–2:00 PM	Lunch Break		

Time	*Key Ballroom 10*	*Key Ballroom 11*	*Key Ballroom 12*
	Late-breaking on Recent and Future Large Earthquakes (see page 1414).	**Advancing Time-dependent PSHA and Seismic Risk Assessment: Accounting for Short- to Medium-term Clustering** (see page 1334).	**From Physics to Forecasts: Advancements and Future Directions of Induced Seismicity Research** (see page 1398).
10:30 AM	Student: The Multi-segment Complexity of the 2024 Mw 7.5 Noto Peninsula Earthquake Governs Tsunami Generation. **Kutschera, F.**, Jia, Z., Oryan, B., Wong, J., Fan, W., Gabriel, A.	Invited: Exploring Long and Short-term Time Dependencies in Earthquake Risk Modeling. Iacoletti, S., **Cremen, G.**, Galasso, C.	Invited: Mitigation and Optimization of Induced Seismicity Using Physics-based Forecasting. **Hill, R. G.**, Weingarten, M., Langenbruch, C., Fialko, Y.
10:45 AM	Analysis of the Magnitude 5.7 Parker Butte Earthquake Near Yerington Nevada, Using High Precision Relocation, InSAR, GPS, and Strong Motion Data. **Bogolub, K. R.**, Trugman, D. T., Hammond, W. C., Jiang, Y., Koehler, R. D., Rowe, C. D., Smith, K. D.	Invited: Who Needs ETAS-based Seismic Hazard? **Iervolino, I.**, Cito, P., Chioccarelli, E., Vitale, A., Giorgio, M.	The Prinos CO_2 Storage Site (Greece): Seismotectonic Setting and Monitoring Challenges. **Kiratzi, A. A.**, Vavlas, N., Cotton, F., Pilz, M., Ktenidou, O. J., Sokos, E., Kiomourtzi, P., De Marchi, N., Marras, C., Bracciamà, V., Albani, Y., Papadopoulos, A., Caccamo, C.
11:00 AM	The 2025 Ms6.8 (Mw 7.1) Dingri Earthquake Sequence and Seismogenic Structure. **Wang, D.**, Yao, D., Chen, F., Wang, Z.	Risk Implications of Poisson Assumptions and Declustering Inferred From a Fully Time-Dependent Earthquake Forecast. **Field, E. H.**, Milner, K. R., Porter, K. A.	Transient Rate-dependent Forecast for Induced Earthquakes in Carbon Sequestration. Wang, C., Geffers, G., Sherman, C. S., **Kroll, K. A.**
11:15 AM	Sampling the Earthquake Cycle in a Graben System: Insights from the 2025 Mw7.1 Dingri Earthquake in the Southern Tibetan Plateau. **Wei, S.**, Ma, Z., Zeng, H., Li, C., Chen, H., Shan, X.,	Student: Accounting for Earthquake Sequences in Probabilistic Seismic Hazard Assessment. **Pane, A.**, Visini, F., Marzocchi, W.	Efficient Physics-based Modelling of Induced Seismicity Decatur CCS Project and Upscaling to the Illinois Basin. **Acosta, M.**, Salha, G., Forestier, C., Wang, G., Avouac, J.
11:30 AM	Two Days, Three Earthquakes, Three Provinces. Mulder, T., Bird, A., **Bent, A. L.**, Brillon, C., Paul, C., Ackerley, N., Boucher, C., Kao, H., Cassidy, J., Smith, B., Schaeffer, A., Kolaj, M., Crane, S.	Seismic Models for the Taiwan Probabilistic Seismic Hazard Assessment: Tradition and Innovation. **Chan, C.**	Site-specific Seismic Hazard Analyses in Oklahoma Addressing Both Tectonic and Induced Seismicity. **Wong, I. G.**, Thomas, P., Lewandowski, N., Hartleb, R., Lindvall, S., Zandieh, A., Darragh, B., Kayastha, M., Yenihayat, N., Levish, D., Gutierrez, A.
11:45 AM–2:00 PM	Lunch Break		

Time	*Holiday Ballroom 1*	*Holiday Ballroom 4–6*	*Key Ballroom 9*
	Improving the State of the Art of Earthquake Forecasting Through Models, Testing and Communication (see page 1402).	**Network Seismology: Recent Developments, Challenges and Lessons Learned** (see page 1429).	**Innovative Applications of Seismic Nodal Technology for Hazard Mitigation and Earth System Monitoring** (see page 1405).
2:00 PM	STUDENT: ETAS With Anisotropy in the Spatial Distribution of Aftershocks. **Han, M.**, Mizrahi, L., Wiemer, S.	MAXI3D: A Novel Offshore Earthquake Location Workflow for the Endeavour Segment of the Juan De Fuca Ridge. **Hutchinson, J.**, Heesemann, M., Krauss, Z., Wilcock, W. S. D., Zhang, M.	Probing the Seismicity and Magmatic Plumbing System of Erebus Volcano Using Machine Learning Techniques and a Dense Near Summit Seismic Array. **Pena Castro, A. F.**, Schmandt, B., Garza Giron, R., Aster, R. C.
2:15 PM	Stress Shadows in Physics-based Forecasts of Aftershock Locations. **Hardebeck, J.**, Harris, R.	A Virtual Experiment to Quantify Gains in Explosion Monitoring Techniques. **Carmichael, J. D.**, Berg, E. M., Sarathi, R., Price, A., Young, C. J., Eras, S. J., Hodgkinson, K. M., Barno, J. G.	Nodal Deployment and Characterization of Microseismicity and Structure at Cape Modern Geothermal Field, Utah. **Nakata, N.**, Wu, S., Bi, Z., Chen, L., Soom, F., Titov, A., Dadi, S.
2:30 PM	Evaluation of 10 Years of UCERF3-ETAS Next-day Forecasts. **Serafini, F.**, Werner, M. J., Silva, F., Maechling, P. J., Milner, K., Field, E.	Local Magnitude Practices in the United States of America. **Hartog, J.**, Morton, E. A., Earle, P. S., Tepp, G., West, M. E., Savran, W. H., Marty, J., Walter, J., Chang, J. C., Vanacore, E., Savvaidis, A., Withers, M.	Nodal Arrays for Improved Tomography Imaging of the Ecuadorian Forearc and Insights Into Slip Behavior Controlling Process. **Wickham, A.**, Meltzer, A., Beck, S. L., Ponce, G., Roecker, S., Ruiz, M., Segovia, M., Hernandez, S., Garcia, A., Andramuno, M.
2:45 PM	ETAS-positive Parameter Sets for Three Southern California Earthquake Catalogs. **van der Elst, N.**	Revamping the Oklahoma Geological Survey Statewide Seismic Network for the Next Generation of Earthquake Monitoring. **Ogwari, P. O.**, Walter, J., Thiel, A., Gregg, N., Mase, B., Woelfel, I.	STUDENT: High-resolution Imaging of Fault Damage Zones Based on Multiple Ultra-dense Arrays in the Aftershock Zone of the 2023 Kahramanmaras Earthquake Sequence in Southern Türkiye. **Snook, M.**, Si, X., Mach, P., Adeboboye, O., Zor, E., Ergin, M., Cengiz Tapırdamaz, M., Açıkgöz, C., Büyük, E., Tarancıoglu, A., Sevim, F., Xu, H., Zhang, X., Wen, J., Song, X., Chen, J., Liang, C., Sandvol, E., Peng, Z.
3:00 PM	Challenges in Hazard and Risk Assessment for Seismicity in Volcanic Regions: Cases for Guadeloupe and Italy. **Velasquez, J.**, Crume, H. R., Woessner, J.	Network Design for Seismic Activity Monitoring in an Unconventional Oil Reservoir Exploitation Context. **Sánchez, G.**, García, R., Moreno, M., Moreno, S., Andújar, L., Gaitán, M., Sifón, R., Nicolía, V., Pirri, J., Aguiar, J. P.	Fault Geometry in the 2023-05-11 Mw 5.5 Lake Almanor, California, Earthquake Sequence, Revealed by Precise Aftershock Locations and Focal Mechanisms From a Nodal Deployment. **Yoon, C. E.**, Skoumal, R., Hardebeck, J., Catchings, R. D., Goldman, M., Chan, J. H., Sickler, R.
3:15– 4:30 PM	Poster Break		

Time	*Key Ballroom 10*	*Key Ballroom 11*	*Key Ballroom 12*
	Advanced Geophysical Observations, Analytical Methods, and New Insights for Earthquake Swarms (see page 1312).	**Accuracy and Variability of Physics-based Ground Motion Modeling** (see page 1307).	**Mechanistic Insights into Fluid-induced Earthquakes from the Laboratory to the Field** (see page 1421).
2:00 PM	INVITED: The 2024 Mw7.5 Noto Peninsula Earthquake and Recent Earthquake Swarms in Japan Triggered by the Upward Migration of Deep Crustal Fluids. **Yoshida, K.**	Toward a Multi-scale Community Velocity Model for California. **Olsen, K. B.**, Yeh, T.	INVITED: Injection-induced Slow Slip Events in the Canadian Rockies. **van der baan, M.**, Samsonov, S. V., Vasyura-Bathke, H., Eaton, D. W., Han, H., Pradisti, R., Rojas Parra, J.
2:15 PM	STUDENT: Intermediate-depth Earthquakes Driven by Migrating Strain Localization in the Bucaramanga Earthquake Nest. **Tsuchiyama, A.**, Frank, W. B., Prieto, G. A.	Development of a Data-driven Near-surface Velocity Models for the San Francisco Bay Area: Stationary and Spatially Varying Approaches. **Lavrentiadis, G.**, Seylabi, E., Xia, F., Tehrani, H., Asimaki, D., McCallen, D.	STUDENT: Insights Into Fault Behavior in Southern Kansas From Stress Evolution Modeling of Multiple Induced Earthquake Sequences. **Ries, R.**, Beroza, G. C., Ellsworth, W. L.
2:30 PM	Benchmarking Remote Seismic Monitoring Against Local Seismic Monitoring of Hazardous Volcanoes: Application to the May 2021 Nyiragongo Eruption. **Deane, C. A.**, Yeck, W. L., Pesicek, J. D., Prejean, S. G., Earle, P. S., Shelly, D. R.	STUDENT: Velocity and Attenuation Models of a 18km Section of Mississippi Embayment Sediments. **Islam, S.**, Langston, C. A.	Importance of In-situ Stress Estimation in the Understanding of Induced Seismicity. **Han, H.**, van der baan, M.
2:45 PM	INVITED: Spatio-temporal Evolution of Seismicity Controlled by Damage Zone Architecture. **Cattania, C.**	SPE Rock-valley-direct-comparison Chemical Explosions Near-field 3D Ground Motion Simulations and Predictions. **Ezzedine, S. M.**, Vorobiev, O., Walter, W. R., Working Group, M.	Geomechanical Insights Into the Recent Mw 5+ Earthquakes in the Delaware Basin, West Texas. **Jin, L.**, Curry, W. J., Bolton, D. C., Hussenoeder, S. A.
3:00 PM	STUDENT: Characterization of Seismicity Rates on the Megathrust and Sliver Fault in Southern Mexico With Potential Relationships to Aseismic Slip. **Ventura-Valentin, W. A.**, Brudzinski, M. R., Fasola, S., Szucs, E., Graham, S.	STUDENT: Are Empirical Models Adequate for Risk Estimation? **Sharp, B. J.**, Olsen, K. B., Callaghan, S., Milner, K. R., Wang, Y.	Probing Frictional Properties of Delaware Basin Formations: Insights From Laboratory Experiments. **Magnani, M.**, Volpe, G., Mauro, M., Scuderi, M., Collettini, C.
3:15– 4:30 PM	Poster Break		

Time	*Holiday Ballroom 1*	*Holiday Ballroom 4–6*	*Key Ballroom 9*
	Building and Decoding High-resolution Earthquake Catalogs With Statistical and Machine-learning Tools (see page 1343).	**ESC-SSA Joint Session:Seismology in the Global Oceans: Advances in Methods and Observations** (see page 1380).	**Geophysics in a Changing World: Monitoring Applications from Seismology and Beyond** (see page 1398).
4:30 PM	INVITED: EarthquakeNPP: Benchmarking Neural Point Processes in California and China. **Stockman, S.**, Tian, W., Zhang, Y., Lawson, D. J., Werner, M. J.	The Cascadia Offshore Subduction Zone Observatory Infrastructure Project: A Year 2 Update. **Thompson, M.**, Wilcock, W. S. D., Harrington, M. J., Schmidt, D. A., Kelley, D. S., Tobin, H., Denolle, M. A., Khoo, M. S., Cram, G. S., Labrado, A. L., Manalang, D. A., McGuire, C., Tilley, J. W., Zumberge, M. A., Sasagawa, G. S.	Real-time Detection and Insights From the September 2024 Surprise Glacier, Alaska, Landslide Sequence. **Karasozen, E.**, West, M. E., Barnhart, K. R., Lyons, J., Nichols, T., Ohlendorf, S. J., Schaefer, L. N., Staley, D. M., Wolken, G. J.
4:45 PM	INVITED: Denoising Score Matching for Online Change Point Detection. Zhou, W., **Xie, L.**, Peng, Z., Zhu, S.	PACSAFE: Preliminary Results from Deployment of Ocean Bottom Seismometers Off Canada's West Coast. **Hobbs, T. E.**, Schaeffer, A., Sun, T., Bostock, M., Nedimovic, M., Stacey, C., Cairns, G., Bosman, K., Thibodeau, J., Eville, V., Plourde, A., Dave, R., Finley, T., Oliva, S. J., Parkinson, F., Podhorodeski, A., Hughes, A., Yakuden, L., Carson, T., Kung, R., Lintern, G., Wang, K., Rohr, K., Kao, H., Nissen, E., Peacock, S., Zhang, M., Cassidy, J., Paul, C., Brillon, C.	Characterizing Analog Instrument Responses Relevant to Long-term Oceanic Microseism Analyses. **Lee, T. A.**, Aster, R. C., Ishii, M., Ishii, H., Simons, F. J.
5:00 PM	Fault Geometries of the 2024 Mw 7.5 Noto Peninsula Earthquake From Hypocenter Clustering. Sawaki, Y., Shiina, T., Sagae, K., Sato, Y., Horikawa, H., Miyakawa, A., Imanishi, K., **Uchide, T.**	Detection, Characterization and Interpretation of Diverse Seismic Signals in Submarine Hotspot-ridge Interaction Settings. **Waldhauser, F.**, Wang, K., Wilcock, W. S. D., Zhang, M., Tolstoy, M., Tan, Y., Wang, P.	Global Frequency-dependent Primary and Secondary Band Microseism Change Since the Late 20th Century. **Aster, R. C.**, Ringler, A. T., Anthony, R. E., Lee, T. A., Simons, F. J.
5:15 PM	STUDENT: Exploring the Origin of Temporal b-Value Variation: Insights From the 2016/17 Central Italy Sequence. **Corrado, P.**, Piegari, E., Herrmann, M., Marzocchi, W.	Seismotectonics of the Puerto Rico Subduction Zone: Leveraging Machine Learning Analysis of Ocean Bottom Seismometers. **Aziz Zanjani, A.**, DeShon, H. R.	Seismic and Gravity Imaging for Dam Design in a Complex Geologic Setting. **Levandowski, W.**, Clark, J., Scharnhorst, V., O'Connell, C. R. H., Steele, L., Mirzanejad, M.
5:30 PM	STUDENT: Insights Into the 2020 Monte Cristo Range Earthquake Sequence From a Near-source Aftershock Deployment. **Zhang, M.**, Trugman, D. T., Scalise, M., Eckert, E., Zeiler, C. P.	Innovative Approaches to Subsea Orientation of Seismic Instrumentation. **Bainbridge, G.**, Li, Y., Dovlo, E., Perlin, M., Somerville, T., Pelyk, N.	Optical Detection of Modal Frequencies of Structures. **Castellaro, S.**
6:00–7:00 PM	Plenary Address: The USGS Earthquake Hazards Program: Science to Support Decision-Making		

Time	*Key Ballroom 10*	*Key Ballroom 11*	*Key Ballroom 12*
	Scientific Machine Learning for Forward and Inverse Wave Equation Problems (see page 1460).	**Accuracy and Variability of Physics-based Ground Motion Modeling** (see page 1307).	**Mechanistic Insights into Fluid-induced Earthquakes from the Laboratory to the Field** (see page 1421).
4:30 PM	Helmholtz Neural Operator for Full Waveform Inversion Tomography of California. **Rodgers, A. J.**, Doody, C., Kong, Q., Zou, C., Azizzadenesheli, K., Ross, Z., Clayton, R.	STUDENT: Evaluating Bias in Simulated Ground Motions for Moderate Magnitude Earthquakes in Southern California: A Study Using the Graves-Pitarka Method. **K C, S.**, Nweke, C. C., Stewart, J. P., Graves, R.	INVITED: Studying Fluid-induced Earthquakes in the Bedretto Lab. **Wiemer, S.**
4:45 PM	Simulating Seismic Wavefields Using Generative Artificial Intelligence. **Nakata, N.**, Nakata, R., Ren, P., Bi, Z., Lacour, M., Erichson, B., Mahoney, M. W.	STUDENT: 3D Broadband (0-25 Hz) Ground Motion Simulations for Statewide California. **Xu, K.**, Olsen, K. B.	Aftershocks and Ongoing Evolution of Seismicity Surrounding the Damaging 2024 M5.1 Prague Earthquake in Oklahoma. **Walter, J.**, Ogwari, P. O., Woo, J., Thiel, A., Mace, B., Gregg, N., Woelfel, I., Xiao, H., Ellsworth, W. L.
5:00 PM	STUDENT: Efficient Solutions to the Acoustic Wave Equation Using Extreme Learning Machines With Domain Decomposition. **Ojoboh, E. P.**, Jingyi, C.	Simulation of Ground Motions for the November 11, 2019, Mw 4.9, Le Teil, France Earthquake Using a Hybrid Approach. **Li, W.**, Fatehi, A., Rizzo, P. C., Gutierrez, J. J.	On the Link Between Glacial Ablation in the Gongga Mountain, Southeastern Tibetan Plateau and the Aftershocks of the 2022 Moxi Earthquake (M6.8). Sun, Y., **Liu, M.**, Zhang, H., Shi, Y.
5:15 PM	STUDENT: An End-to-end Physics-based Deep Learning Approach for Robust Seismic Inversion. **Wasih, M.**, Almekkawy, M.	How Many Earthquake-rupture Simulations Are Required to Quantify Epistemic Ground-Motion Variability? **Castro-Cruz, D.**, Anwar Aquib, T., Mai, P.	Geological CO2 Storage in Swiss Saline Aquifers: Numerical Simulations at Triemli and Insights From the Citru Pilot Project. **Gunatilake, T.**, Zappone, A., Zhang, Y., Zbinden, D., Schulz, R., Wiemer, S.
5:30 PM	Seismic Geotechnical Imaging Using Full-waveform Inversion and Physics-informed Neural Networks. **Mohammadi, K.**, Pu, Y.	Repeatable Source, Path and Site Effects on Ground Motion Variability Based on Dataset From the Central and Eastern United States. **Davatgari Tafreshi, M.**, Pezeshk, S.	Mechanical and Acoustic Response of Laboratory Fault-valve Media to Fluid Injections. **Yuan, C.**, Bell, A., Saló-Salgado, L., Du, Y., Denolle, M. A., Xiao, L., Weitz, D.
6:00–7:00 PM	Plenary Address: The USGS Earthquake Hazards Program: Science to Support Decision-Making		

Poster Sessions

ESC-SSA Joint Session:Seismology in the Global Oceans: Advances in Methods and Observations (see page 1382).

1. Measurement of Seafloor Rayleigh Ellipticity From Unoriented Seismic Data and Its Significance for Seismic Imaging in the Ocean. **Ai, S.**, Akuhara, T.
2. Exploring Local Seafloor Pressure Changes Along the Nankai Trough: Insights Into Fluid Reservoir Dynamics. **Ariyoshi, K.**, Nagano, A., Hasegawa, T., Matsumoto, H., Takahashi, N., Hori, T., Aso, T.
3. Potential Tectonic Tremor Detected on a Single Ocean Bottom Seismometer Offshore Cascadia. **Krauss, Z.**, Wilcock, W. S. D., Creager, K.
4. From Autonomous Deployments to SMART Cables: Challenges and Innovations in Ocean Bottom Sensing. **Somerville, T.**, Jusko, M., Bainbridge, G., Laporte, M.
5. Student: Localizing Very Long Period (VLP) Enigmatic Microseismic Sources and Associated Gliding Tremors in the Gulf of Guinea Using Numerical Matched Field Processing. **Soni, Y.**, Pulliam, J.
6. Imaging of the Global Oceanic Lithospheric Structure With Probabilistic Deconvolution of SS Waves. **Zhang, Z.**, Olugboji, T.
7. Guralp Ocean Bottom Monitoring Solutions: Autonomous Nodes, Cabled Observatories and SMART. **Lindsey, J. C.**, Watkiss, N. R., Hill, P., Restelli, F.

Innovative Applications of Seismic Nodal Technology for Hazard Mitigation and Earth System Monitoring (see page 1406).

8. Guralp Artius: A Revolutionary Broadband Node to Further Enable Passive Seismology. **Lindsey, J. C.**, Watkiss, N. R., Hill, P., Restelli, F.
9. Using Nodal Arrays for Fluvial Seismology Applications: Tracking Flow Fronts, Rockfalls and Bedload Transport. **Bilek, S.**, McLaughlin, J. M., Luong, L., Cadol, D., Laronne, J.
10. Apparent Large Seismic Velocity Variations Across the East Anatolian Fault, Turkiye. **Catchings, R. D.**, Goldman, M., Celebi, M. K., Chan, J. H., Sickler, R., Alver, F., Kilicarslan, O.
11. Revealing 3D Subsurface Structure of Paliki Peninsula, Kefalonia, Greece. **Garcia-Fernandez, M.**, Van Noten, K., Jiménez, M., Sakellariou, N., De Plaen, R., Kouskouna, V., Lecocq, T., Rodriguez-Diaz, S., Galanos, N.
12. Student: Urban Seismology in Cartago, Costa Rica Using Seismic Nodal Arrays to Uncover Faults. **Hajaji, S.**, Protti, M., Campos, N. A., Bodin, P., Nuñez, E.
13. Student: Unsupervised Spectral Clustering and Spectral Ratio Analysis of Earthquakes in Cushing, Oklahoma. **Hoefer, B. A.**, Chen, X., Ratre, P.
14. The Antics Large-N Seismic Deployment in Albania. **Rietbrock, A.**, Agurto-Detzel, H., Tilmann, F., Dushi, E., Frietsch, M., Heit, B., Kufner, S., Lindner, M., Rama, B., Schurr, B., Yuan, X.
15. An Initial Dense Seismic Array Study of Magmatic System Structure and Seismicity of the Three Sisters Volcanic Complex. **Schmandt, B.**, Herr, B., Zhou, Y., Lee, T.
16. Volcanic Tsunami and Its Prediction for Early Warning. **Song, Y.**

Network Seismology: Recent Developments, Challenges and Lessons Learned (see page 1433).

17. The Minimus Digitizer Platform: A User-friendly Ecosystem for Efficient Network Management and Seismic Station Configuration. **Lindsey, J. C.**, Watkiss, N. R., Hill, P., Restelli, F.
18. Improvements in Seismic Station Noise Levels Through Budget Boreholes. **Anthony, R. E.**, Litherland, M., Bainbridge, G., Parker, T., Johnson, W., Armendariz, K.
20. Orfeus-coordinated Seismological Datasets in the Euro-mediterranean Region and Beyond. **Cauzzi, C.**, Clinton, J. F., Crawford, W., D'Amico, S., Evangelidis, C., Haberland, C., Kiratzi, A. A., Luzi, L., Kolínský, P., Roumelioti, Z., Schaeffer, J., Sigloch, K., Sleeman, R., Strollo, A.
21. Upgrading the Liubeshka Station of the Ukrainian National Seismic Network: Modernization and Integration. **Farfuliak, L.**, Amashukeli, T., Mackey, K., Chiang, A., Burk, D., Kasey, A., Haniiev, O., Kuplovskyi, B., Prokopyshyn, V., Petrenko, K., Levon, D.
22. Implementing a Regional 1-D Velocity Model for Locating Earthquakes for Southern Texas. **Huang, D.**, Salles, V., Vallejo, K., Savvaidis, A.
23. AdriaArray – a Passive Seismic Experiment to Study Structure, Geodynamics and Geohazards of the Adriatic Plate. **Kolínský, P.**, Meier, T., AdriaArray Seismology Group, .
24. Next Generation Multidisciplinary Geophysical Monitoring Station. **Laporte, M.**, Perlin, M., Easton, D., Jusko, M., Pelyk, N., Somerville, T.
25. Station Operators Perspective as Input on the Development of the International Monitoring System Sustainment Strategy. **Pérez-Campos, X.**, Grobbelaar, M., Rocco, G.
26. Student: The Utility of Small Aperture Arrays for Assessing Subduction Zone Earthquakes: Insights From Temporary Nodal Deployments. **Quigley, C.**, West, M. E.
28. Evaluating the Performance of the Guralp Radian Posthole Seismometer Across Variable Tilt and Orientation Conditions. **Sandru, J.**, Bockholt, B.

30. System Monitoring, Telemetry Quality Control and DAS Testing at SCSN. **Stubailo, I.**, Biondi, E., Bhadha, R., Biasi, G., Alvarez, M., Watkins, M., Husker, A. L.
31. Challenges and Lessons Learned from Applying Machine Learning Models to Seismic Monitoring Across Diverse Tectonic Settings. Wang, K., **Waldhauser, F.**, Wang, H., Zhu, W.
32. The Southern California Seismic Network Earthquake Catalog: Completeness, Event Quality and Recent Improvements. Tepp, G., **Yu, E.**, Chen, S., Bhaskaran, A., Scheckel, N., Newman, Z., Jaski, E., Tam, R.

Building and Decoding High-resolution Earthquake Catalogs With Statistical and Machine-learning Tools (see page 1344).

33. Developing Machine-learning-based Seismic Data Processing Tools for a Carbon Storage Site. **Chai, C.**, Maceira, M.
34. Student: Improving Earthquake Detection and Localization in Hawaii With Deep Learning and High-performance Computation. **Cheng, Z.**, Shen, Y.
35. Student: Towards a Deep Learning Approach for Short-term Data-driven Spatiotemporal Seismicity Rate Forecasting Using Standard and High-resolution Earthquake Catalogues. **Dervisi, F.**, Segou, M., Baptie, B., Poli, P., Main, I., Curtis, A.
36. Earthquake Source Depth Determination Using Single Station Waveforms and Deep Learning. **Li, W.**, Zhang, M.
37. Using Lossy Compression to Speed Up Seismic Event and Ambient Noise Analysis. **Martin, E. R.**, Issah, A. S., Brooks, G.
38. Student: Seasonal Variations in the Magnitude-frequency Distribution of California Earthquakes. **Petschek, E. R.**, Ebel, J. E.
39. High-resolution Aftershock Catalog of the 2023 Kahramanmaraş Earthquake Sequence Reveals Detailed Fault Structures in Southeastern Türkiye. **Si, X.**, Mach, P., Adeboboye, O., Gao, H., Sandvol, E., Zor, E., Ergin, M., Yalvac, O., Tapirdamaz, M., Tarancioglu, A., Sevim, F., Peng, Z.
40. Automatic Phase Picking Model for Ocean Bottom Seismic Data: Phasenet Model Trained Using Japanese S-net Data. **Uchide, T.**
41. Investigating Complex Seismogenic Structures in the Northern Longitudinal Valley, Eastern Taiwan Through an AI-based Catalog of the April 3, 2024 Mw 7.3 Hualien Earthquake. **Yang, H.**, Wu, E., Chen, H., Liu, C., Hsu, Y., Huang, H.
42. Student: Denoising Score Matching for Online Change Point Detection. **Zhou, W.**, Si, X., Xie, L., Peng, Z., Zhu, S.

Geophysics in a Changing World: Monitoring Applications from Seismology and Beyond (see page 1400).

43. Visualizing Cyclical Variations in Seismoacoustic Activity Using Circular Spectrograms. **Bowman, D. C.**, Malach, A. K., PE1 Experiment Team.
44. Cost-effective Groundwater Monitoring Using Nodal Geophones: Updates From a Case Study in the Upper Mississippi Embayment. **Carpenter, S.**, Rodriguez Cardozo, F. R., Schmidt, J. P., Braunmiller, J., Woolery, E. W., Wang, Z.
45. Seismic Site Characterization and Basin Depth Estimation Using Seismic Ambient Noises: An Example From the Hetauda Dun Valley, Nepal. **Chamlagain, D.**, Acharya, S., Dhakal, N. R., Neupane, P., DeShon, H. R.
46. Using Horizontal-to-vertical Spectral Ratio to Characterize Landslides in Complex Terrain. **Collins, E.**, Allstadt, K., Coe, J.
47. Rapid Seismic and Infrasonic Assessment of a Large Landslide in Denali National Park (Alaska) Aided by Aerial and Satellite Imagery and Numerical Flow Modeling. Toney, L., West, M. E., Karasozen, E., Staley, D. M., Capps, D., **Collins, E.**, Allstadt, K., McFarlin, H., Bellini, J., Haney, M., Fee, D., Lyons, J., Mangeney, A.
48. Joint Inversion of MASW and Ambient-noise HVSR Data for Estimating Shear Wave Velocity Profile in Warm Permafrost: A Case Study at Northway Airport, Alaska. **Dutta, U.**, Zhao, Y., Yang, Z.
49. Identification of Cavities in Karst Areas Using Seismic Ambient Noise. **Kristekova, M.**, Kristek, J., Moczo, P.
50. Student: Exploring Possible Tornado Seismic Signals From the December 10-11, 2021, Tornado Outbreak in the Central U.S. **Thompson, S. C.**, Carpenter, S., Wang, Z.
51. Student: High and Low Noise Models for Geophone Deployments: Toward Global Denoising Strategies and Enhanced Global Monitoring Capabilities. **Toro-Acosta, C.**, Gochenour, J. A., Zeiler, C. P.

Fiber-optic Sensing Applications in Seismology (see page 1391).

52. Detection and Characterization of Ice-related Seismic Signals Using Distributed Acoustic Sensing Offshore Beaufort Sea, Alaska. **Aerts, J.**, Stanciu, C., Frederick, J., Herr, B., Baker, M., Abbott, R. E.
53. Subsurface Source Characterization Using Distributed Acoustic Sensing. **Cunningham, E.**, Marcillo, O., Chai, C., Maceira, M., Fratta, D., Wang, H.
54. Mapping Fault Dynamics: Very High Seismicity Detected Along the Kefalonia Transform Faul With DAS and Template Matching. Wang, Y., **Fichtner, A.**
55. Chirped-pulse DAS for Ambient Noise Tomography. Canudo, J., **Gella, D.**, Perciado-Garbayo, J., Sevillano, P.,

Subias, J., Gonzalez-Herraez, M., Martins, H. F., Gaite-Castrillo, B., Bravo-Monge, J. B., de Maria, I., Rodriguez-Plaza, M.

56. STUDENT: Submarine Volcano Monitoring With Distributed Acoustic Sensing at Kolumbo, Greece. **Klaasen, S. A.**, Hudson, T. S., Nomikou, P., Fichtner, A.
58. Aquifer Monitoring With DAS: A Case Study From Lyon Water Catchment. **Nziengui Bâ, D.**, Coutant, O., Lanticq, V.
59. A Hybrid Deep Learning Framework for Denoising Distributed Acoustic Sensing Data. **Oboue, Y. A. S. I.**, Chen, Y., Chen, Y.
60. Preliminary Shallow Seismic Imaging at Los Alamos National Laboratory Using Distributed Acoustic Sensing. **Rodriguez, E. E.**, Donahue, C. M., Maier, N.
61. STUDENT: Bayesian Inversion of Microseismic Events at the FORGE Geothermal Site. **Song, Y.**, Yuan, S., Martin, E. R.
62. STUDENT: Preliminary Analyses of Source Mechanism Effects on Fracture Dynamics in Mines Using Distributed Acoustic Sensing. **Vite Sanchez, R.**, Martin, E. R., Tourei, A., Shragge, J., Westman, E., Walton, G., Chapman, M. C., Ankamah, A.
63. STUDENT: Imaging the Fault Zone Structure of the Shanchio Fault in Taipei Metropolis Using Dark Fiber Distributed Acoustic Sensing. **Wang, C.**, Huang, H., Ha, V., Ku, C., Chen, P.
64. Fiber-optic Sensing of Repeating Icequakes and Firnquake Swarms at the South Pole. **Zhai, Q.**, Li, J., Yang, Y., Zhan, Z.

Testing, Testing 1 2 3: Appropriate Evaluation of New Seismic Hazard and Risk Models (see page 1474).

66. A New Empirical Probability Model for Surface Faulting Utilizing Width-rupture Ratio for Crustal Earthquakes. **Huang, J.**, Abrahamson, N.
67. Refining Seismogenic Source Models: Revisiting the Alboran Sea for an Updated Zesis Framework. Perea, H., **Jiménez, M.**, García-Fernández, M., García Mayordomo, J., Martínez Loriente, S., Canari, A.
68. STUDENT: Earthquake Source Modelling for Hazard Assessment of the Tonga and Vanuatu Subduction Zones. **Liao, Y.**, Fry, B., Williams, C. A., Howell, A., Nicol, A.
69. Significance of Non-ergodic Ground Motion Models in Seismic Loss Assessment. Wu, C., Cao, Y., **Seyhan, E.**
70. SIGMA3: A Further Step for the Reduction of Epistemic Uncertainties in PSHA. Daniel, G., Alsokhon, A., Alvarez-Sanchez, L. G., Arroucau, P., El Haber, E., Javelaud, E., Lefevre, M., Perron, V., **Traversa, P.**, Zentner, I.

Advancing Time-dependent PSHA and Seismic Risk Assessment: Accounting for Short- to Medium-term Clustering (see page 1335).

71. A Comparison of Earthquake Risk in the Western U.S.: Time-independent vs. Time-dependent Approaches. **Apel, T.**, Neely, J., Gupta, N.
72. What If? – A Look at How Partial Ruptures and Stress Transfer Can Be Incorporated Into Time-dependent PSHA. **Apel, T.**, Neely, J., Gupta, N.
73. Clustering in PSHA: A Study on Short Return Period Risk Assessments. **Crume, H. R.**, Velasquez, J., Farghal, N. S., Papadopoulos, A., Woessner, J.
74. Integrating Earthquake Clustering Into Probabilistic Seismic Hazard and Risk Assessments. **Graham, K.**, Gerstenberger, M. C., Christophersen, A., Rhoades, D.
75. Seismic Hazards in the Makran Accretionary Wedge, Pakistan. **Lisa, M.**
76. STUDENT: Probabilistic Seismic Hazard Analysis of the Shillong Plateau, Northeast India, Using Multiple Source Models and Logic Tree Approach. **Shahabuddin, M.**, Mohanty, W. K.
77. The U.S. Geological Survey's 2025 National Seismic Hazard Model for Puerto Rico and the U.S. Virgin Islands. **Shumway, A. M.**, Milner, K. R., Powers, P. M., Moschetti, M. P., Altekruse, J. M., Aagaard, B. T., Jobe, J. A. T., Briggs, R., Hatem, A. E., Llenos, A. L., Michael, A. J., Withers, K. B., Haynie, K. L., Herrick, J. A., Zeng, Y., Rezaeian, S., Jaiswal, K., Field, E. H., Pratt, T.
78. Time-lapse Study of Earthquake Focus as an Additional Risk Control System. **Zimin, M.**, Zimina, S., Zimin, M.

Accuracy and Variability of Physics-based Ground Motion Modeling (see page 1309).

79. Developing International Standards and Guidelines for Curating, Validating and Disseminating Simulated Ground-motion Data. **Aagaard, B. T.**, Askan, A., Rezaeian, S.
80. Sensitivity of Focal Mechanism and Depth of the 2024 M4.8 Tewksbury Earthquake to Seismic Velocity Model and the Impacts on Earthquake Ground Motions. **Boyd, O. S.**, Bozdag, E., Kehoe, H. L., Moschetti, M. P.
81. A New Ground Motion Model for Coastal Plain Region of the U.S Considering Sediment Thickness. Akhani Senejani, M., **Davatgari Tafreshi, M.**, Pezeshk, S.
82. Nonergodic Ground Motion Model for the Central and Eastern United States. **Davatgari Tafreshi, M.**, Pezeshk, S.
83. STUDENT: Linked Earthquake and Tsunami Hazard Modeling on Puget Sound's Crustal Faults. **Grossman, J. B.**, Wirth, E. A., Dunham, A., Stone, I., LeVeque, R. J., Adams, L. M., Wei, Y., Moore, C.

84. Strong Ground Motions From Large Earthquakes on the Creeping Hayward, Rodgers Creek and Calaveras Faults, California. **Harris, R. A.**, Barall, M., Parker, G., Hirakawa, E.
85. STUDENT: Development of a Peak Spectral Displacement Ground-motion Model Using Global HR-GNSS Observations. **Hensley, B.**, Sahakian, V. J., DeGrande, J., Crowell, B. W., Melgar, D.
86. Preliminary Results of 3D Site Response Analysis in the Norcia (Italy) Sedimentary Basin. **Linsalata, F.**, Puglia, R., Costanzo, A., Massa, M., Lovati, S., Smerzini, C., Pischiutta, M., Vanini, M., Parolai, S., d'Onofrio, A., Silvestri, F.
87. Ground Motion Characterization in Regions of "Intermediate" Attenuation. **Onur, T.**, Herrera, C., Chiang, A., Gok, R.
88. STUDENT: Region-specific Spatial Correlation Models for Ground Motion Intensity Measures in South Korea. **Ryu, B.**, Kwak, D.
89. Analysis of Seismic Waves Amplification in Sedimentary Basins Using 3D Wavefield Simulation. **Tian, Y.**, Tape, C.
90. Near-fault Strong-motion of the 2023 Mw7.8 Kahramanmaraş Earthquake: Insights Into High-frequency Radiation Mechanisms. **Wu, B.**, Li, B., Zhang, H., Huang, S., Li, G., Gabriel, A.
91. STUDENT: Validation of Shallow Crustal Structure in Northern California and Community Velocity Model Validation Using Ambient-noise-derived Rayleigh Wave Ellipticity and Receiver Functions. **Zaldivar Andrade, G. A.**, Kim, H., Lin, F., Taira, T.

Mechanistic Insights into Fluid-induced Earthquakes from the Laboratory to the Field (see page 1423).

92. Factors That Can Influence the Fault Activation Process: Examples From Wastewater-induced Sequences in Oklahoma and Geothermal Fields in Utah. **Chen, X.**, Mohammadi, A., Abercrombie, R. E., Asirifi, R., Nakata, N., Dadi, S.
93. Reassessing the North Texas Earthquake Catalog Using Machine Learning. **DeShon, H. R.**, Seldon, Y.
94. STUDENT: Relocating Induced Seismic Events to Evaluate the 2022 Hydraulic Stimulation Stages at Utah FORGE. **Goecker, A. M.**, Pankow, K. L., Karvounis, D., Dyer, B., Whidden, K.
95. A General Probabilistic Trans-dimensional Approach to Estimate Spatiotemporal Variations of Recorded Seismicity. **Gosselin, J. M.**, Kao, H., Dokht, R., Visser, R.
97. STUDENT: Improving Our Understanding of Seismogenic Faults and Operations That Have Induced Seismicity in the Eagle Ford Basin, Texas. **Kirchenwitz, J.**, Brudzinski, M. R.
98. Dynamic Triggering in the Geysers Geothermal Field by Two Recent Large Earthquakes. **Li, L.**, Yu, Y., Beroza, G. C., Ellsworth, W. L.
100. Investigating the Influence of Seasonal Groundwater Level Fluctuations on Localized Seismic Activity in Southwestern Taiwan. **Phoa, F.**, Sun, Y.
101. STUDENT: Linking Spatiotemporal b-Value Evolution to Physical Mechanisms Influencing EGS Induced Seismicity. **Salinas, M. P.**, Huang, Y.
102. Characterization of Shallow Seismic Sources in the Neuquén Province, Argentina. **Sánchez, G.**, Venerdini, A., García, R., Goebel, T., Pérez, I., López, L., Rufino, C., Kaufmann, C., Peña, M., Goubat, R., Romero, M., Guevara, J. M.
103. STUDENT: Understanding Rupture Directivity of Injection-induced Earthquakes: A Numerical Study Coupling Poroelastic Model With Rate-and-state Earthquake Cycle Simulator. **Tan, X.**, Lui, S. K. Y.
104. Repeating Earthquake Sequences in Induced Seismicity in West Texas. **Turner, A. R.**, Bolton, D. C.

From Physics to Forecasts: Advancements and Future Directions of Induced Seismicity Research (see page 1398).

105. STUDENT: Development of a Machine Learning-based Ground Motion Model for Induced Earthquakes in the Central and Eastern United States. **Alidadi, N.**, Pezeshk, S.
106. High-Resolution Seismic Monitoring Reveals the State of Stress in the Delaware Basin. **Baig, A. M.**
108. STUDENT: Seismicity in Sichuan, Southwestern China, 2009-2019: Interaction of Hydraulic Fracturing Induced Earthquakes Characterized by the Nearest-Neighbor Distance Approach. **Zhou, Y. Y.**, Niu, F. F.

Advanced Geophysical Observations, Analytical Methods, and New Insights for Earthquake Swarms (see page 1313).

109. STUDENT: Reexamining Historical Yellowstone Swarms Using a Relocated Earthquake Catalog From 1995-2023. **Czech, T. L.**, Farrell, J., Lomax, A.
111. Investigating an Earthquake Swarm in Ohio: Reactivation of a Large Precambrian Fault With a Destructive Past? **Fox, J.**
112. STUDENT: Seismic Swarm Dynamics in the Atacames Region, Ecuador. **Garcia, A.**, Meltzer, A., Wickham, A., Hernandez, S., Ruiz, M., Ponce, G., Segovia, M., Vaca, S., Andramuno, M., Beck, S. L.
113. STUDENT: Improved Characterization of Earthquake Sequence Patterns in the Mexican Subduction Zone Using Seismogram Correlation to Enhance Detection of Smaller Seismicity. **Khalkhali, M.**, Brudzinski, M. R., Ventura-Valentin, W. A., Fasola, S.

114. Student: Microseismicity and Fault Structure in the Daliangshan Subblock within the Southeastern Tibetan Plateau. **Ma, J.**, Meng, L., Ding, L., Ai, Y.
115. Student: Automated Detection and Characterization of Swarms and Mainshock-aftershock Sequences in Nicaragua and Costa Rica. **Miesse, L.**, Brudzinski, M. R., Ventura-Valentin, W. A.
116. Seismicity Characterisation in the Mount Cameroon Region. **Ndibi Etoundi, D.**, Mbossi, E., Taki-Eddine Rahmani, S., Ateba, B.
117. Student: Rapid Migration of Seismic Swarms in the Central-north Ecuadorian Subduction Zone Revealed by Deep Learning and Dense Seismic Arrays. **Ponce, G.**, Meltzer, A., Wickham, A., Beck, S. L., Ruiz, M., Hernandez, S., Garcia, A., Andramuno, M.
118. Student: Geophysical Case Studies of Buildings in Tehran Against Earthquakes. **Shahshahani, S. S. S.**
119. Student: Investigating Potential Relationships Between Rates of Seismicity, Strain Accumulation, and Slow Slip in the Oaxaca Region of Mexico. **Szucs, E.**, Brudzinski, M. R., Graham, S., Cabral-Cano, E., Ventura-Valentin, W. A., Khalkhali, M.

Adventures in Social Seismology: Ethical Engagement, Earthquake Early Warnings, Operational Forecasts, and Beyond (see page 1340).

120. Schoolshake: Inspiring the Next Generation, Increasing Community Resilience and Conducting Research Through a School-based Seismograph Network. **Brillon, C.**, Schaeffer, A., Nissen, E.
121. Preliminary Multilingual Survey Results on Earthquake Early Warning and San Diego County's SD Emergency Multi-hazards App to Improve Equity in Disaster Risk Reduction. **Brudzinski, M. R.**, Sumy, D., Gomez, K., Olds, S., Briceno, Y., Jordan, P., Robles, M., Rea, S.
122. The Propagation of Seismic Waves, Misinformation and Disinformation From the 2024-10-05 M 4.5 Iran Earthquake. **Fernando, B.**, Maguire, R. R., Fernandez, B., Karimi, S., Koenck, E., Ekström, G., Rivlin, T., Labedz, C.
123. Self-developed Low-cost Shaking Table and Other Educational Tools as an Itinerant Laboratory for Seismic Engineering Educational Purposes: The Case of the LabIt. Pozos-Estrada, A., **García-Soto, A.**, Nava-Gónzalez, R., Hernández-Martínez, M., Cortes-Portillo, D., Nuñez-Matos, J., Gómez-Castillo, A., Cortez-Loreto, J., Barba-Zárate, D., García-Rodríguez, C.
124. Assessing the Usability of Near-Real-Time Earthquake Information for Supporting Impacted Communities. **Macías, M. A.**, Loos, S., Reddy, E., Wald, D. J., Knodel, E., McGowan, S., Marano, K.
125. ShakeAlert's Contribution to Social and Behavioral Sciences: A Retrospective. **McBride, S. K.**, deGroot, R., Terbush, B., Vinnell, L., Stanley, S. M.
126. Student: Defining Aspects of the Seismology Learning Ecosystem by Exploring Introductory Seismology Courses and the Seismology Skill Building Workshop. **Meyer, E. H.**, Hubenthal, M., Haberli, G., Brudzinski, M. R., Ventura-Valentin, W. A.
127. Student: Intercultural Praxis: A Tool for Engaging With Misinformation on Earthquake Risk. **Pope, I. E.**
128. What "Did You Feel It?" Data Can Tell Us About Earthquake Early Warning Performance. **Saunders, J. K.**, Wald, D. J., McBride, S. K., Quitoriano, V.
129. Student: Navigating Healthcare, Family Well-Being and Cultural Adaptation: The Experiences of South Asian Mothers on F1/F2 Visas in Urban U.S. Communities. **Sikder, P.**
131. Long-term Communication of Aftershock Forecasts: the Canterbury Earthquake Sequence in New Zealand. **Wein, A. M.**, McBride, S. K., Christophersen, A., Becker, J. C., Doyle, E. E. H., Gerstenberger, M. C., Potter, S. H.

Improving the State of the Art of Earthquake Forecasting Through Models, Testing and Communication (see page 1403).

132. Forecasting Ground Motion Intensity Time Series with a Generative Pre-trained Transformer. **Clements, T.**, Cochran, E., Baltay, A., Yoon, C. E., Minson, S., Schneider, M.
133. A Deep Learning Application to Model the Full Distribution of Higher-order Aftershock Numbers in the ETAS Framework. **Mizrahi, L.**, Jozinović, D.
134. Towards Operational Earthquake Forecasting in Switzerland. **Mizrahi, L.**
135. The Influence of Magnitude Determinations on b-Values. **Mizrahi, L.**, Schorlemmer, D.
136. Evaluating the Forecasting Performance of U.S. Geological Survey Aftershock Forecasts. **Schneider, M.**, Barall, M., Hardebeck, J., Michael, A. J., Page, M., van der Elst, N.

Scientific Machine Learning for Forward and Inverse Wave Equation Problems (see page 1461).

137. Auto-linear: A Self-supervised Framework for Robust Subsurface Imaging Through Latent Space Correlations. Feng, Y., Chen, Y., **Lin, Y.**
138. Extensions for the Reversibility of First-arrival Travel-times using PINNs. **Nowack, R. L.**
139. Methods for Preemptively Optimizing Geophone Array Size for Measurement of Subsurface Volumes using Machine Learning and Synthetic Data From Numerical Simulations. **Welsh, D. W.**, Heylmun, J., Cardenas, D. P.
140. Akinet: A Physics Informed Neural Network for Building a Short-period Global Dispersion Model. **Xue, S.**, Swar, S. K., Olugboji, T.

Late-breaking on Recent and Future Large Earthquakes (see page 1415).

141. Student: Sequence Analysis of the M7.1 South Halmahera Earthquake on July 14, 2019: Hypocenter Relocation, Moment Tensor and Static Stress Changes. **Ali, Y. H.**, Priyobudi, P., Daryono, D.
142. Student: Local Magnitude (Ml) Calibration and Seismic Attenuation in the Ethiopian Rift Valley: Implications for the 2024–2025 Earthquake Swarm. **Aregawi, A. B.**
143. Detailed Analysis of the February 21, 2025 Sechelt Mw 4.7 Earthquake. **Brillon, C.**, Mulder, T., Schaeffer, A., Paul, C., Kao, H., MacLeod, R., Cassidy, J., Bent, A. L.
144. Satellite Geodetic Measurement of the Coseismic and Postseismic Displacements from the January 2025 Mw 7.1 South Tibet Earthquake. **Fielding, E. J.**, Zinke, R., Peltzer, G., Speed, C., Bato, G. M.
145. Remote Observations of Surface Rupture and Fault Kinematics in the January 7, 2025, Southern Tibet Plateau Earthquake. Reitman, N., **Jobe, J. A. T.**, Barnhart, W., Briggs, R., DuRoss, C., Goldberg, D., Hanagan, C., Hatem, A., Lynch, E., Nicovich, S., Powell, J.
146. The 2024 M7.0 Offshore Cape Mendocino Sequence: Insights from Enhanced Catalogs of Earthquake Locations, Focal Mechanisms and Repeating Events. **Song, J.**, Rong, B., Taira, T., Zhu, W.
147. Sequence Characteristics and Seismogenic Structure of the 2025 Xizang Dingri M6.8 Earthquake. An, Y., Zhang, Y., **Yang, H.**
148. Source and Impact Characterization of the M7.3 2024 Port Vila, Vanuatu, Earthquake. **Yeck, W. L.**, Goldberg, D., Allstadt, K., Cerovski-Darriau, C., Fry, B., Massey, C., Wald, D. J., Earle, P. S., Jaiswal, K., Barnhart, W., van der Elst, N., Shelly, D. R.

Wednesday, 16 April 2025—Oral Sessions

Presenting author is indicated in bold.

Time	*Holiday Ballroom 1*	*Holiday Ballroom 4–6*	*Key Ballroom 9*
	Performance and Progress of Earthquake Early Warning Systems Around the World (see page 1446).		**Earth's Structure from the Crust to the Core** (see page 1359).
8:00 AM	INVITED: Shakealert Version 3, Current Status and Future Possibilities. **McGuire, J. J.**		STUDENT: Investigating Along-strike Differences in Crust and Upper Mantle Structure of the Central Andes Through High-resolution Receiver Functions. **Bradford, J. M.**, Beck, S. L., Mahanti, S., Kiser, E., Howe, H., Tauber, S., Porter, R., Fernandez, M., Trad, M., Saez, M., Leon-Rios, S., Comte, D., Roecker, S.
8:15 AM	Shakealert Earthquake Early Warning: Testing New Vs30 With Population Weighted Values, New Epic With Bayesian Priors, and Finder Triggering With CE Stations. **Smith, D. E.**, McGuire, J. J., Jha, S., Lux, A. I.		Seismic Imaging of the Ecuadorian Margin Lithosphere Using Teleseismic Receiver Functions Analysis and Ambient Noise Tomography. **Li, C.**, Beck, S. L., Delph, J., Ericksen, B., Meltzer, A., Lynner, C., Ruiz, M., Hernandez, S., Segovia, M., Vaca, S.
8:30 AM	EEW Station Connectivity (Latency) Is Shockingly Low. Here's How We Know. **Terra, F.**, Stubailo, I.		Upper Mantle Structure Beneath the Mongolian Region From Multimode Surface Waves: Implications for the Western Margin of Amurian Plate. **Ganbat, B.**, Yoshizawa, K., Sodnomsambuu, D., Munkhuu, U.
8:45 AM	Development and Testing of an Alaska Earthquake Testsuite Within Epic. **Williamson, A. L.**, Lux, A. I., Henson, I., Akimov, A., Allen, R. M.		The Wave Gradiometry Method: Theory and Applications for Imaging 3D Velocity, Anisotropy and Attenuation. **Liang, C.**, Cao, F.
9:00 AM	From Shakealert to Post-earthquake Assessment – Applied Technologies to Improve Situation Awareness in Buildings. **Franke, M.**, Parrott, B., Skolnik, D. A.		Unraveling Serpentinite Distribution in the Subduction Zone of NW South America. **Vargas, C. A.**, Caneva, A.
9:15–10:30 AM	Poster Break		

Time	*Key Ballroom 10*	*Key Ballroom 11*	*Key Ballroom 12*
	The Landscape Record of Earthquakes and Faulting (see page 1408).	**Recent Advances in Modeling Near-source Ground Motions for Seismic Hazard Applications** (see page 1455).	**Advances in Reliable Earthquake Source Parameter Estimation** (see page 1324).
8:00 AM	Quantifying the Erasure of Earthquakes From Desert Landscapes: Implications for Interpreting the Geomorphic Record of Faulting in Hazard Assessment. **Rodriguez Padilla, A. M.**, Zuckerman, M., Arrowsmith, R.	Orientation Dependence of Probabilistic Seismic Hazard Results From Physics-Based Simulations. **Poulos, A.**, Hirakawa, E., Parker, G. A., Baltay, A.	Revising the Iaspei Ground Truth List. Gallacher, R., **Garth, T.**, Harris, J., Bondár, I., McLaughlin, K. L., Storchak, D. A.
8:15 AM	Rock, River, Record: Reading the Geomorphic Record of Seismic Cycles Through Bayesian Inversion of River-incised Landscapes. **Oryan, B.**, Gailleton, B., Olive, J., Malatesta, L. C., Jolivet, R.	Modeling of Ground-motion Amplitude Saturation at Large Magnitudes and Short Distances. **Pinilla Ramos, C.**, Abrahamson, N., Graves, R., Ben-Zion, Y., Sung, C., Bayless, J.	Importance of Accurate Earth Models and Network Geometry for Earthquake Location. **Savvaidis, A.**, Lomax, A., Parastatidis, E., Dommisee, R., Huang, D.
8:30 AM	INVITED: Using Mapped Tectonic Faults as a Record of Past Earthquakes to Predict Future Surface Rupture Location. **Scott, C. P.**, Madugo, C., Arrowsmith, R., Zuckerman, M.	Ground Motion Variability and Near-fault Amplification: Insights From Modeling of the Central Italy Earthquake Sequences. **Akinci, A.**, Pitarka, A., Artale Harris, P., De Gori, P.	INVITED: Improving First-order Seismic Characterization Through Calibrated Earthquake Locations. **Karasozen, E.**, Bergman, E. A., Benz, H. M.
8:45 AM	STUDENT: Lacustrine and Terrestrial Paleoseismic Records of the Twin Lakes Fault Near Mt Hood, Oregon, USA. **Culhane, N. K.**, Streig, A. R., Bennett, S. E. K., Gavin, D., Peterson, J. V., Metens, A., Lally, K., Henderson, C., Schwarzbart, S., Wagner, B., Murphy, M.	Developing a Near-fault Non-ergodic Ground Motion Model for the Ridgecrest, CA, Area. **Meng, X.**, Pinilla Ramos, C., Kottke, A. R., Ben-Zion, Y.	INVITED: The Body-wave Magnitude mb: An Attempt to Rationalize the Distance-depth Correction Q(delta, H). **Okal, E. A.**, Saloor, N.
9:00 AM	Constraining Past Earthquakes in the NMSZ Using Sediment Records of Three Separate Lakes. **Rodysill, J.**, Carter, M., Seidenstein, J.	A Slip-based Directivity Model. **Rowshandel, B.**	Extending Coda Envelope Moment Magnitudes to Remote Regions of Canada for Improved Hazard Assessment. **Bent, A. L.**, Mayeda, K., Roman-Nieves, J. I., Barno, J. G.
9:15–10:30 AM	Poster Break		

Time	*Holiday Ballroom 1*	*Holiday Ballroom 4–6*	*Key Ballroom 9*
	Performance and Progress of Earthquake Early Warning Systems Around the World (see page 1446).		**Earth's Structure from the Crust to the Core** (see page 1359).
10:30 AM	INVITED: How Did People React to the Early Warning During the M7.8 Kahramanmaras-Pazarcik (Türkiye) Earthquake? **Bossu, R.**, Finazzi, F., Fallou, L., Cotton, F.		chinalgq_v1.0: Seismic Lg-wave Attenuation Model in China. **He, X.**, Zhao, L., Xie, X., Zhang, L., Liu, Z., Yao, Z.
10:45 AM	Earthquake Impacts on Traffic Safety Using Crowdsourced and Police Reported Accident Data. **Chupp, W. L.**, Daniel, D., Fox, E., McGuire, J. J., McBride, S. K., deGroot, R.		INVITED: Surface Wave Constraints on Crustal Structure Beneath Elysium Planitia. **Maguire, R. R.**, Kim, D.
11:00 AM	Real Time Characterization of Earthquakes in the Mexican Subduction Zone Based on a Seismogeodetic Network. **Suarez, G.**, Santiago, J., Espinosa, D.		An Overview of the Crustal and Uppermost Mantle Structure and Tectonics of Asia. **Mooney, W. D.**
11:15 AM	Enhancing Earthquake Early Warning With Real-time Ground Motion Assimilation for Rupture Directivity Effects via Kalman Filter. **Huang, Y.**, Huang, H.		Imaging the Crustal Structure of Fiji and Its Surrounding Regions From Seismic Receiver Functions. **Zhang, Y.**, Mooney, W. D., Hu, H.
11:30 AM	Improving Detections by Reducing Problematic Triggers in the Epic Earthquake Early Warning Algorithm. **Lux, A. I.**, Henson, I., Akimov, A., Allen, R. M.		STUDENT: Three-dimensional Least-squares Migration of Teleseismic Receiver Functions and Its Application to the Qaidam Basin. **Zuo, P.**, Chen, Y., Wu, L., Cao, F.
Noon–2:00 PM	Annual Business and Awards Luncheon		

Time	*Key Ballroom 10*	*Key Ballroom 11*	*Key Ballroom 12*
	The Landscape Record of Earthquakes and Faulting (see page 1408).	**Recent Advances in Modeling Near-source Ground Motions for Seismic Hazard Applications** (see page 1455).	**Advances in Reliable Earthquake Source Parameter Estimation** (see page 1324).
10:30 AM	Geodetic Imaging of Strain Partitioning Between the Megathrust and Crustal Faults in Cascadia. **Elston, H. M.**, Loveless, J. P., Crowell, B. W.	STUDENT: Beyond -1 Geometric Spreading in the Near-field: Insights From Theory and Simulation. **Marcou, S.**, Dreger, D. S.	Sparse Fault Representation Based on Moment Tensor Interpolation. **Thurin, J.**
10:45 AM	INVITED: STUDENT: Insights From 3D DEM Models Into Along-strike Variability of Ground Surface Ruptures Observed in Thrust and Reverse Fault Earthquakes. **Chiama, K.**, Plesch, A., Shaw, J. H.	Physically-based Non-ergodic Event Terms in the 2023 U.S. National Seismic Hazard Research and Development Model. **Petersen, M. D.**, Zeng, Y., Abrahamson, N., Sung, C., Rukstales, K., Moschetti, M. P., Baltay, A.	Numerical Simulations Reproduce Characteristics of Distributions of Non-double-couple Components in Global Moment Tensor Catalogs. **Rösler, B.**, Stein, S., Ringler, A. T., Vackář, J.
11:00 AM	Constraints on Geometry of the San Joaquin Hills Blind Thrust Fault, Orange County California U.S.A, From Quaternary Geology and Recent Earthquakes. **Grant Ludwig, L.**	Modeling the Rupture Dynamics of Strong Ground Motion (> 1 g) in Fault Stepovers. **Lozos, J.**, Akçiz, S., Ladage, H.	Moment Tensor Uncertainty Analysis for the 2017 Hojedk, Central Iran, Earthquakes Using 1D and 3D Green's Function. **Rodriguez Cardozo, F. R.**, Braunmiller, J., Ghods, A., Sawade, L., Orsvuran, R., Bozdag, E.
11:15 AM	Unearthing Slickenlines on the 2016 Rupture of the Kekerengu Fault and Paleosurface Ruptures of the Alpine Fault, New Zealand: Testing the Veracity and Utility of the Rupture-propagation-direction / Curved-slickenline Hypothesis. **Van Dissen, R. J.**, Kearse, J., Barth, N., Little, T. A., Kaneko, Y., Howarth, J.	Ground-motion Processing of Near-fault Ground Motions Preserving Forward Directivity and Fling Effects: An Application to the 2022 Chishang, Taiwan, and 2023 Pazarcik, Türkiye Earthquake Sequences. **Lavrentiadis, G.**	STUDENT: Determining Small Earthquake Focal Mechanisms Using 360° S-wave Polarization. **Han, S.**, Kim, Y.
11:30 AM	Shear Wave Velocity Measurements in Fine Grained Soils With Muted Surface Fault Displacement Following the February 2023 Kahramanmaraş, Türkiye Earthquake. **Mason, H. B.**, Wood, C. M., Ayhan, B. U., Clahan, K. B., Coin, B. A., Seçen, B., Uray, E., Asimaki, D., Lavrentiadis, G., Simpson, A. B.	Application and Adaptation of Global Ground Motion Models to the Eastern Caribbean Lesser Antilles. **Hudson, K. S.**, Lockhart, J. M., Hudson, M. B., Stewart, J. P.	INVITED: How S/P Amplitude Ratio Data Can Bias Focal Mechanism Estimates. **Trugman, D. T.**
Noon–2:00 PM	Annual Business and Awards Luncheon		

Time	*Holiday Ballroom 1*	*Holiday Ballroom 4–6*	*Key Ballroom 9*
	Data-driven and Computational Characterization of Non-earthquake Seismoacoustic Sources (see page 1354).		**Earth's Structure from the Crust to the Core** (see page 1359).
2:00 PM	STUDENT: Catching the Sonic Boom From the NASA's OSIRIS-REx Capsule Re-entry. **Bazargan, S.**, Horton, S., Mitra, I., Islam, S., Langston, C. A.		Full-waveform Modeling Explains Surface-wave Diffraction Patterns Observed on Large Dense Seismic Networks. **Kolínský, P.**, Loeberich, E., Long, M. D.
2:15 PM	STUDENT: Coupled Seismic and Acoustic Waves Generated by Satellite Starlink-2382's Reentry. **Eickhoff, D.**, Ritter, J.		Ambient Noise Tomography Along the Mexican Volcanic Belt. **Dominguez, L. A.**, Perton, M., De la Cruz-López, C. A., Real, J. A.
2:30 PM	Seismoacoustic Source Characterization and Uncertainty Quantification. **Berg, E. M.**, Koch, C., Wynn, N. R.		Upper Mantle Anisotropy in North America and the Pacific From Global Adjoint Tomography. **Bozdag, E.**, Orsvuran, R., Peter, D., Lebedev, S.
2:45 PM	Inversion of Helicopter Characteristics Using Infrasound Data. **Marcillo, O.**, Lees, J. M.		AK112: Full Waveform Inversion Tomography of Alaska Improves Waveform Fits While Imaging Crustal, Mantle and Slab Structure. **Rodgers, A. J.**
3:00 PM	STUDENT: Estimating an Airborne Dipole Source Using 3D Wavefield Simulations and Seismic Stations on the Ground. **McPherson, A.**, Tape, C., Bishop, J. W., Fee, D.		INVITED: Constraints on Mantle Dynamics From a Massive Seismic Dataset. **Wolf, J.**
3:15– 4:30 PM	Poster Break		

Time	*Key Ballroom 10*	*Key Ballroom 11*	*Key Ballroom 12*
	Unusual Earthquakes and Their Implications (see page 1475).	**Station Installations and Site Conditions, a Quest for Improved Strong Motion Database** (see page 1466).	**Advances in Reliable Earthquake Source Parameter Estimation** (see page 1324).
2:00 PM	Challenges Created by Unusual Earthquakes for Operational Tsunami Assessment and Response. **Ohlendorf, S. J.**	The Origin of Unusually High Earthquake Strong Motion Recordings at Three California Stations. **Graizer, V.**	A Deep Learning Approach for Non-binarizing the Impulsive/Emergent Phase Labels. **Park, Y.**, Alfaro-Diaz, R. A., Carmichael, J. D., Delbridge, B. G.
2:15 PM	Characteristics of Intermediate and Deep-focus Earthquakes Along the Tonga Subduction Zone Revealed by Cross-correlation Earthquake Relocation. **Aziz Zanjani, F.**, Wiens, D. A., Wysession, M. E., Wei, S. S.	STUDENT: Site-specific Ground Motion Response Analysis for Bridges in Western Tennessee. **Alidadi, N.**, Pezeshk, S.	Coda Calibration Technique for Reliable Moment Magnitudes and Source Characterization in SW USA and NNSS. **Barama, L.**, Chiang, A., Gok, R.
2:30 PM	Low Aftershock Productivity of the 2017 Delaware Earthquake. **Pearson, K. M.**, Lekic, V., Wagner, L.	Combining Empirical Approaches to Address the Site-specific Seismic Hazard Estimation: Application to Three Populated Cities and an Area of Two Nuclear Facilities in France. Perron, V., Buscetti, M., Grendas, I., Hollender, F., Douste-Bacque, I., Burlot, R., Regnier, J., **Traversa, P.**	Using 3D Crustal Velocity Models and Multiazimuth Back Projection to Image Rupture Processes of Intermediate-sized Earthqukes. **Zhu, H.**, Yang, J.
2:45 PM	Satellite Optical Image Correlation Measurements for a Moderate Magnitude Thrust Earthquake: The January 2024 Wushi (Aykol), China Mw 5.7 Aftershock. **Hanagan, C. E.**, Jobe, J. A. T., Reitman, N., Hatem, A. E.	Importance of Using 3-component F-K Methods for Processing Ambient Vibration Array (AVA) Measurements for Improved Site Characterization. **Hollender, F.**, Cox, B. R., Ohrnberger, M., Wathelet, M., Rischette, P., Cornou, C.	Broadband Spectral Characteristics of Moderate-sized Earthquakes Using Nearby Recordings. Ji, C., **Archuleta, R. J.**
3:00 PM	Revisiting an Enigma on California's North Coast: The Seismotectonics of the M6.5 Fickle Hill Earthquake of December 1954. **Hellweg, M.**, Lee, T. A., Dreger, D. S., Lomax, A., Hagos, L., Haddadi, H., McPherson, R., Dengler, L., Hough, S. E.	INVITED: 20 Years After the Sesame Guidelines: Should Anything Be Changed? **Castellaro, S.**	INVITED: Random and Systematic Uncertainties in EGF Spectral Ratio Analysis and Their Implications for Source Scaling. **Abercrombie, R. E.**, Chen, X., Huang, Y.
3:15– 4:30 PM	Poster Break		

Time	*Holiday Ballroom 1*	*Holiday Ballroom 4–6*	*Key Ballroom 9*
	Fifty Years and Beyond of Broadband Seismic Instrumentation: Performance, Precision and Uncertainties (see page 1393).		**Earth’s Structure from the Crust to the Core** (see page 1359).
4:30 PM	Low-uncertainty SI-traceable Seismic Measurements. **Chijioke, A.**, Allen, R., Pratt, J., Reschovsky, B.		Global Mantle Imaging With the Multi-mode Body Wavefield. **Olugboji, T.**, Zhang, Z., Carr, S., Legre, J.
4:45 PM	Methods for Laboratory Seismometer Calibration Traceable to the Si – a Current Overview of Challenges and Solutions. **Bruns, T.**, Klaus, L., Yan, N.		Sequencing Postcursors of P and S Core-diffracted Waves: Implications for the Hawaiian Mega-ULVZ Properties. **Kim, D.**, Song, J., Dobrosavljevic, V., Lekic, V.
5:00 PM	Challenges in Seismometer Electrical Calibration. **Merchant, B. J.**		Global Observations of Melt-induced Low Velocity Zones Surrounding the Mantle Transition Zone. **Frazer, W.**
5:15 PM	Advancements in Quality Assurance for the Comprehensive Nuclear-test-ban Treaty International Monitoring System and Calibration Challenges for Seismic and Infrasound Technologies. **Doury, B.**, Campus, P., Kramer, A., Le Blanc, J.		A New Constraint on Vp and Vs in the Uppermost Mantle From Late Coda. Ritsema, J., **Liu, M.**
5:30 PM	Calibration Techniques in the Manufacture and Field Use of Seismic Instruments. **Bainbridge, G.**, Townsend, B., Laporte, M.		Student: Investigating the Intrinsic Attenuation of Large Low Velocity Provinces. **Cunion, D. M.**, Lekic, V.
6:00–8:00 PM	Joyner Lecture and Reception		

Time	*Key Ballroom 10*	*Key Ballroom 11*	*Key Ballroom 12*
	Predictability of Seismic and Aseismic Slip: From Basic Science to Operational Forecasts (see page 1452).	**Station Installations and Site Conditions, a Quest for Improved Strong Motion Database** (see page 1466).	**Seismology for the Energy Transition** (see page 1462).
4:30 PM	The Time-saturation of Tectonic Tremor With Low-frequency Earthquakes. **Song, C.**, Rubin, A. M.	Invited: Student: Geologically Informed Non-ergodic Site Effects Model for California Enhanced With Geotechnical Measurements. **Roberts, M. E.**, Baise, L. G., Nie, S., Kaklamanos, J., Meyer, E. H., Zhan, W.	De-risking Deep Geothermal Energy Projects: The Deep and GeoTwins Approach. **Wiemer, S.**, Lanza, F.
4:45 PM	Invited: A Unified Fracture Mechanics Model for Fault Slip Throughout the Seismic Cycle: Interseismic Decoupling, Precursory Transients and Earthquake Nucleation. **Cattania, C.**, Verwijs, R., Cui, X.	Temporal and Directional Variations in Shallow Seismic Velocities and Vp/Vs Ratio: Insights From a Borehole Array. **Roumelioti, Z.**, Hollender, F., Grendas, I., Theodoulidis, N.	Fiber Optic Seismic Vector, Acoustic, Pressure, Strain and Temperature Sensor Combinations Are Setting New Standards for Geothermal, CCUS, and UGS Reservoir Characterization and Monitoring. **Paulsson, B. N. P.**, Wylie, M. T. V., He, R.
5:00 PM	Student: The Search for Time-dependent Coupling Changes in Southern Cascadia. **Roy, A.**, Jackson, N. M.	Are Seismological Signals Recorded at Free-field? Recommendations for Taking Better Account of Installation Conditions When Using Existing Databases and for Installing New Stations. Rischette, P., **Hollender, F.**, Theodoulidis, N., Roumelioti, Z., Perron, V., Traversa, P., Buscetti, M., Douste-Bacque, I., Konidaris, A.	Towards Thermo-hydro-mechanical Constitutive Models for Deep Geothermal Reservoirs: Experiments on Thermal Cracking Under Stress With Near-field Acoustic Sensing. **Holtzman, B. K.**, O’Ghaffari, H., Beaucé, E., Mittal, T., Barth, A., Mok, U., Peč, M.
5:15 PM	Invited: Earthquake Predictability, Insight From Dynamical Models of Earthquake Sequences. **Avouac, J.**, Kaveh, H., Shrestha, R., Stuart, A.	Ground Motion Models Uncertainties and Variability: The Impact of Seismic Station Installation Conditions. **Traversa, P.**, Hollender, F., Rischette, P., Buscetti, M., Perron, V.	Detectability of a CO2 Well Leakage using Amplitudes of Ambient Seismic Signals on DAS. **Glubokovskikh, S.**, Lyu, B., Collet, O., Shashkin, P., Gurevich, B., Pevzner, R.
5:30 PM	Automatic Speech Recognition Predicts Contemporaneous Earthquake Fault Displacement. **Johnson, C.**, Johnson, P.	Site Amplification and Crustal Attenuation in the CEUS: Joint Tomographic Models for Ground Motion Analysis. **Mahanama, A.**, Cramer, C., Levandowski, W.	Learning Permeability from Acoustic Emission with Distributed Acoustic Sensing. **Donahue, C. M.**, Johnson, C. W.
6:00–8:00 PM	Joyner Lecture and Reception		

Poster Sessions

The Landscape Record of Earthquakes and Faulting (see page 1411).

1. Student: Landscape Response to Deformation in the Northern Ecuadorian Forearc. **Andramuno, M.**, Meltzer, A., Alvarado, A., Wickham, A., Ponce, G., Garcia, A., Ruiz, M.
2. A Multi-scale Look Utilizing Seismic Reflection Profiles and Paleoseismic Trenching Across Quaternary Active Faults in the Kittitas Valley, Washington, USA. **Angster, S. J.**, Stephenson, W. J., Sherrod, B. L., Huddleston, G., Lahser, J.
3. Near-fault-observation in a Seismic Gap Area: The Case of Mt. Morrone-Maiella Fault System (Central Italy). **Anselmi, M.**, De Gori, P., Bagh, S., Menichelli, I., Fonzetti, R., Chiarabba, C.
4. Lidar Analysis of an Elevated Marine Terrace Along the Olympic Peninsula, Washington State, USA. **Briggs, R.**, Sherrod, B. L., Kelsey, H., Angster, S. J., Grant, A.
5. Geophysical Investigation of a Quaternary Fault Beneath the National Mall and Memorial Parks in Washington DC. **Counts, R.**
6. Left-lateral Faulting Beneath the Monte Cristo Range, West-central Nevada. **Hatem, A. E.**, Briggs, R., Hanagan, C. E., Reitman, N., Elliott, A., Collett, C., Acree, A.
7. Paleoseismic Trenching Reveals Multiple Recent Earthquakes on the Great Southern Puerto Rico Fault Zone. **Lynch, E. M.**, Jobe, J. A. T., Briggs, R., DuRoss, C. B., Nicovich, S., Hanagan, C. E., Tan, M., Ortega Díaz, V., Gray, H., Strickland, L. E., Hughes, K., López Venegas, A. M.
8. Student: Geomorphic Characterization of Fault Creep in the San Francisco Bay Area, California. **Martin, H.**, Rowe, C. D., Koehler, R. D.
9. Student: Preliminary Insight Into Volcanic and Tectonic Controls on Crustal Deformation Near Ljósufjöll, Snæfellsnes Peninsula, West Iceland. **Owens, E. R.**, De Pascale, G. P.
10. Expression of the Creeping San Andreas Fault at the Topo Creek Site. **Philibosian, B.**, Vermeer, J., Trexler, C., Elliott, A., Alongi, T., Hammer, M., DeLong, S. B., Hanagan, C. E.
11. 30 Years of Landscape Response Following the 1992 Landers, CA, Earthquake. **Reitman, N.**, Arrowsmith, R., Rhodes, D., Hatem, A. E., Schwarz, M., Zuckerman, M., Powell, J. H.
13. Evidence for Dextral-transpressional Quaternary-active Faults in the Northern Central Valley, California. **Jobe, J. A. T.**, Besana-Ostman, G., Klinger, R., Crowell, B. W., Cataldo, K.

Unusual Earthquakes and Their Implications (see page 1476).

14. Surface Rupture From an Aftershock: Remote Observations From the January 2024 Wushi (Aykol) Earthquakes, China. **Jobe, J. A. T.**, Hanagan, C. E., Hatem, A. E., Barnhart, W., Goldberg, D., Yeck, W. L.
15. Student: Deciphering the Multi-fault System of the 2024 Mw 7.4 Hualien, Taiwan Earthquake Using Combined Seismic, Geodetic and Insar Datasets. **Fagan, C.**, Huang, M.
16. Deep Lithospheric Rupture and Dual-mechanism Transition During the 2024 Mw 7.4 Calama Earthquake, Chile. **Jia, Z.**, Mao, W., Flores, M., Ruiz, S., Potin, B., Becker, T. W., Moreno, M., Barra, S., Báez, J., Ceroni, D., Cabrera, L.
17. A New Perspective on the Origin of Seismic and Tectonic Activity of the Sichuan Basin, Central China. **Su, Z.**, Wang, E., Zhang, B.
18. Student: Tidally Modulated Icequakes Along a Ross Ice Shelf Rift in Antarctica. **Udell-Lopez, K.**, Huang, M., Schlossnagle, Z., Schmerr, N., Harkleroad, E., Eisl, S., Hurford, T.
19. Student: 3D Dynamic Rupture Modeling of the 2021 Haiti Earthquake Used to Constrain Stress Conditions and Fault System Complexity. **Yin, H. Z.**, Marchandon, M., Haase, J. S., Gabriel, A., Douilly, R.
20. Implications of a Reverse Polarity Earthquake Pair on Fault Friction and Stress Heterogeneity Near Ridgecrest, California. **Shearer, P.**, Senobari, N. S., Fialko, Y.

Advances in Reliable Earthquake Source Parameter Estimation (see page 1328).

21. Earthquake Source Spectra Estimates Vary Widely for Two Ridgecrest, California, Aftershocks Because of Differences in Attenuation Corrections. **Shearer, P.**, Vandevert, I., Fan, W., Abercrombie, R. E., Bindi, D., Calderoni, G., Chen, X., Ellsworth, W. L., Harrington, R., Huang, Y., Knudson, T., Rossbach, M., Satriano, C., Supino, M., Trugman, D. T., Yang, H., Zhang, J.
22. Update and Future Plans for the International SCEC/USGS Community Stress Drop Validation Study. **Abercrombie, R. E.**, Baltay, A.
23. Student: Focal Mechanism and Uncertainty Estimation in Data-sparse Settings. **Agaba, V.**, van der Lee, S., Babirye, P.
24. Student: Source and Along-path Seismic Parameters of S-waves From Earthquakes in the Central-northern Gulf of California, Mexico. **Azua Flores, J. M.**
25. The International Seismological Centre (ISC) Earthquake Toolbox for MATLAB: Interactive Access to Earthquake Observations and Parameters. **Garth, T.**, Gallacher, R., Leptokaropoulos, K., Poiata, N.
26. Student: Upper Plate Control on Earthquake Stress Drop: Comparison Between High and Low Ground Velocity Zones in Costa Rica. **Hajaji, S.**, Chaves, E. J.
27. Student: Micro-EQpolarity: Transfer Learning for Microseismic P-wave First-motion Polarity Determination and Its Application in the Western Canada Sedimentary Basin (WCSB). **Hu, J.**, Chen, Y., Chen, Y., Yu, H., Zhang, F., Li, X.
28. Student: Refining Stress Drop Measurements Using Spectral Asymptotes: Insights From the Ridgecrest Sequence. **Knudson, T.**, Ellsworth, W. L., Beroza, G. C., Shaw, B. E.
29. Student: Earthquake Energy Calculations From Seismogeodetic Data. **Kunwer, H. M.**, Newman, A., Hirshorn, B., Bock, Y.
30. Mb Magnitude Station-station Spatial Correlations and Station Mb Biases. **McLaughlin, K. L.**
31. Student: The Influence of 3D Velocity Models on Seismic Moment Tensor Estimation in Alaska. **McPherson, A.**, Tape, C., Onyango, E., Chow, B., Peter, D.
32. Student: Joined Double Difference Earthquake Location and Estimation of Vp/Vs-Ratio from Earthquake Clusters. **Ostermeier, R.**, Rietbrock, A.
33. Kinematic Slip Model of the Mw7.0 December 5, 2024 Offshore Cape Mendocino Earthquake. **Pollitz, F. F.**, Guns, K.
34. Student: Evaluating Scaling Relationships From Reliable, Insar-derived Earthquake Source Parameters. **Rivera, K. M.**, Funning, G.
35. Regionalized Earthquake Source Models of Subduction Interface Earthquakes. **Skarlatoudis, A.**, Thio, H., Somerville, P.
36. Quantitatively Assessing the Importance of Three-dimensional Structure for Finite Fault Inversions. **Small, D. T.**, Fadugba, O., Sahakian, V. J., Melgar, D.
37. Student: Using a High- to Low-frequency Spectral Ratio to Distinguish Variations in Earthquake Source Properties. **Vandevert, I.**, Shearer, P., Fan, W.
38. Source Characterization of Complex Earthquakes via Subevent Decomposition: Application to Apparent-repeating Earthquakes. **Yoshida, K.**
39. Robust Earthquake Location Using Random Sample Consensus (RANSAC). **Zhu, W.**, Rong, B., Jie, Y., Wei, S.

Predictability of Seismic and Aseismic Slip: From Basic Science to Operational Forecasts (see page 1453).

40. Student: Use of Repeating Earthquakes to Discriminate Slow Earthquakes in the Central Pacific Subduction Zone of Costa Rica. **Campos, N. A.**, Chaves, E. J.
41. Synchronization Among Characteristic Earthquakes. **Dascher-Cousineau, K. D.**, Bürgmann, R.
42. Rupture Propagation Dynamics in Branch Fault Systems: A Case Study of the San Andreas–Garlock Fault Junction Applying a Machine Learning Approach. Niyogi, S., **Ghosh, A.**, Marschall, E., Douilly, R., Oglesby, D.
43. Bayesian Inference of Stress Evolution in Rate-and-state Governed Faults Constrained by Seismicity Rate Observations. **Jiang, Y.**, Trugman, D. T., González, P. J.
44. Synergizing Seismo-geodetic Coupling and Slip Models with Optimal Transport and Machine Learning to Determine if Megathrust Earthquake Ruptures are Slip-deficit Controlled. **Oryan, B.**, Gabriel, A.
45. Student: Role of Foreshock Sequences in Triggering the 2016 Mw 6.9 Fukushima Mainshock. **Pun, H.**, Lui, S. K. Y., Kato, A.
46. Sliding and Healing of Frictional Interfaces That Appear Stationary. **Sirorattanakul, K.**, Larochelle, S., Rubino, V., Lapusta, N., Rosakis, A. J.
47. Student: Towards an InSAR Catalog of Creep Events on the Imperial Fault. **Tan, M.**, Materna, K., Bilham, R., Gittins, D.
48. Student: Ultrasonic Probing of Slow Slip Fronts in a M-scale Laboratory Fault. **Van Linn, J.**, McLaskey, G. C.
49. Student: How Did the 2016 Mw 7.8 Kaikōura Earthquake Affect the Megathrust Earthquake Potential in the Hikurangi Subduction Zone? **Yun, J.**, Wong, J., Gabriel, A., Fialko, Y., Wallace, L. M., Williams, C. A.

Recent Advances in Modeling Near-source Ground Motions for Seismic Hazard Applications (see page 1457).

50. Rupture Process and Ground Motion Complexity of the February 6, 2023, Mw 7.8 Kahramanmaraş Earthquake in Türkiye: Insights from Analysis of Deterministic Broad-band Simulations using a Regional 1D Velocity Model. **Akinci, A.**, Pitarka, A., Artale Harris, P., Tsuda, K., Graves, R.
51. Student: Kinematic Source Variability in Ground-motion Simulations and Implications for Seismic Hazard Analysis. **Aquib, T.**, Cruz, D., Mai, P.
52. Student: Nonergodic Seismic Hazard Assessment Based on Multi-cycle Earthquake Simulations. **Aspiotis, T.**, Zielke, O., Mai, P.
53. Linear and Nonlinear Site Effects at Several Sites in the Noto-hanto Area in Japan and Its Possible Cause as 2D/3D Deep Basin Resonance. **Kawase, H.**, Nakano, K., Ito, E., Wang, Z.
54. Modeling Path Effects From 3D Velocity Structure in the San Francisco Bay Area. **Nye, T.**, Parker, G. A., Hirakawa, E., Baltay, A., Withers, K. B., Moschetti, M. P.

55. A Near-source Saturation Model for EAS Based on the NGA-west3 Database. **Parker, G. A.**, Baltay, A., Atkinson, G. M., Boore, D. M., Buckreis, T. E., Stewart, J. P.
56. Regional Variations in the Site-amplification Variability. **Pretell, R.**, Katuwal, S., Kuo, C.
57. STUDENT: Quantifying Uncertainties in Earthquake Source Models: Implications of Slip Distribution Variations and Fault Parameters on Ground Motion Studies. **Sunday, E. U.**
58. Methods for Evaluating and Improving Rupture Directivity Modeling in Seismic Hazard Assessment. **Withers, K. B.**, Kelly, B., Bayless, J., Moschetti, M. P.
59. STUDENT: Assessment of Site-specific Features in and Around Varanasi City, Uttar Pradesh, India, Using Microtremor Measurements. **Yadav, A. K.**, Sengupta, P.

Station Installations and Site Conditions, a Quest for Improved Strong Motion Database (see page 1469).

60. Identifying Site Resonance in the Central and Eastern U.S. Using HVSR: Insights From Ambient-noise and Earthquake S-wave Energy Sources and Implications for Site Characterizations. **Carpenter, S.**, Wang, Z.
61. Vertical Arrays Drilled Passing Through an Active Fault With Very Short Recurrence Interval – Investigations and Preliminary Observations. **Kuo, C.**, Chang, Y.
62. Estimation of Vs Profiles from Strongmotion Records. **Leyton Flórez, F.**
63. STUDENT: Development of a Linear Site Amplification Model for the CEUS based on Physiographic Province and Sediment Thickness: Incorporating Lessons from Station Placement Biases. **Meyer, E. H.**, Baise, L. G., Nie, S., Zhan, W., Kaklamanos, J., Roberts, M. E.
64. STUDENT: Geologically Informed Non-ergodic Site Effects Model for the Western US Outside of California. **Roberts, M. E.**, Baise, L. G., Nie, S., Kaklamanos, J., Meyer, E. H., Zhan, W.
65. 100m-Resolution Site Condition Map of China. **Xie, J.**

Data-driven and Computational Characterization of Non-earthquake Seismoacoustic Sources (see page 1355).

66. Probabilistic Tsunami Hazard Assessment in the Southern Atlantic. **Arcos, M. E. M.**, Youngs, R. R., Neveling, J., Roberds, W., Dunga, N.
67. STUDENT: Evaluating Synthetic Acoustic Waveforms From Fire Sources Using 3D Finite Difference Method. **Bauer, I. A.**, Lees, J. M., Marcillo, O., Yedinak, K. M.
68. STUDENT: A Novel Physics-guided Contrastive Learning Strategy for Seismic Signal Analysis. **Kara, D.**, Bhattacharyya, J., Goldman, G. H., Kaplan, L., Abdelzaher, T.
69. Advancing Geophysical Data Training With MsPASS and GeoLab. **Bravo, T.**, Pavlis, G., Wang, I., Weekly, R., Wilson, S., Hamilton, A., Haberli, G., Johnson, S., Trabant, C., Hubenthal, M.
70. Deep Clustering of Ambient Volcanic Seismicity: An Example at Erebus Volcano, Antarctica. **Chaput, J.**, Rick, A., Emerson, T.
71. STUDENT: Seismic Reflection Imaging of Fluid-filled Sills in the West Eifel Volcanic Field, Germany. **Eickhoff, D.**, Ritter, J., Hloušek, F., Buske, S.
72. STUDENT: Dense Seismic Noise Measurements for the Assessment of Site Response Variabilities: Application to a Liquefiable Site in the Po Plain. **El Hitti, J.**, Régnier, J., Cultrera, G., Di Giulio, G., Minarelli, L., Gélis, C., Lenti, L., Langlaude, P., Pernoud, M., Ignacio Bustos, J., Schibuola, A., Riccio, G.
73. Scaling Implications of Terrestrial Impact of Meteors: Cratering, Ejecta and Cloud Formation, Induced Ground Motions. **Ezzedine, S. M.**
74. Seismoacoustic Tracking and Characterisation of Space Debris Re-entries. **Fernando, B.**
75. STUDENT: Fast Probabilistic Seismic Hazard Analysis Through Adaptive Importance Sampling. **Houng, S.**, Ceferino, L.
76. Data-informed Polarization Analysis to Improve Seismic Discrimination and Source Characterization. **Kintner, J. A.**, Alfaro-Diaz, R. A., Carmichael, J. D.
77. A Moment-based Correction for Non-stationarity in Random Vibration Theory. Seifried, A., Bahrampouri, M., **Kottke, A. R.**, Toro, G. R.
78. Waveform Modeling of Acoustic-seismic Interactions Using a Hybrid Wavenumber Integration Method. **Langston, C. A.**
79. Thermo-mechanical Modeling of Deformation Sources Driving Seismicity at Campi Flegrei Caldera. **Nardoni, C.**, De Siena, L.
81. STUDENT: Urban Acoustics and Infrasonic Detection of Crowd Noise. **Saunders, J.**, Lees, J. M.
82. Exploring Sensitivity of Infrasound Signal Predictions to Atmospheric Inputs. **Schaible, L. P.**, Silber, E. A.
83. STUDENT: Classification of Aircraft Type Using Seismic Data in Alaska. **Seppi, I.**, Tape, C., Fee, D.
84. Tsunami Warning Cancellation Using Data Assimilation Approach. **Wang, Y.**
85. Making the Cloud Accessible for Geophysical Research: EarthScope's Path for Cloud Adoption and Workflow Migration. **Wilson, S.**, Weekly, R., Bravo, T., Hamilton, A., Trabant, C.

Earth's Structure from the Crust to the Core (see page 1364).

86. Toward an Accessible Framework for Synthesizing Solid Earth Models Across Multiple Scales. **Ajala, R.**, Kolawole, F., Share, P., Sahakian, V. J., Delph, J., Hooft, E., He, B.
87. STUDENT: Exploring the Mackenzie Mountains Lithosphere: 3D P Wave Velocity Tomography and Thermal Structure. **Bankher, A.**, Schutt, D. L., Rawlinson, N.
89. STUDENT: Imaging Lateral Boundaries in the San Bernardino and San Gabriel Basins With Scattered Phases in Ambient Noise Data. **Bird, E.**, Biondi, E., Clayton, R.
90. Toward a Radially and Azimuthally Anisotropic Adjoint Model for the Middle East. Orsvuran, R., **Bozdag, E.**, Gok, R., Chiang, A., Tarabulsi, Y., Hosny, A., Yousef, K., Mousa, A.
91. STUDENT: Seismic Imaging of Kilauea East Rift Zone Magma Reservoirs Using Receiver Functions. **DaSilva, S.**, Shen, Y., Farrell, J., Lin, F., Wei, X., DaSilva, S.
93. STUDENT: High-resolution 3D Seismic Imaging and Aftershock Catalog for the 2021 Mw 7.2, Nippes, Haiti Earthquake. **Doreme, G.**, Douilly, R., Monfret, T., Symithe, S. J.
94. STUDENT: Enhancing the Observability of Precritical PKiKP Phases with Polarization Filters and Incoherent Array Processing. **Geng, J.**, Koper, K. D.
95. STUDENT: Full Waveform Inversion for Homogeneous 21-parameter Anisotropic Materials. **Gupta, A.**, Chow, B., Tape, C.
96. STUDENT: Validation of a Tilted Transversely Isotropic Model of Alaska Using 3D Seismic Wavefield Simulations. **Gupta, A.**, Tape, C., Liu, C.
97. Preliminary Results from the Active/Passive San Francisco Volcanic Field Nodal Seismic Experiment in Northern Arizona. **Kiser, E.**, Mahanti, S., Bradford, J. M., Porter, R., Chindandali, P., Li, C., Phillips, J., Richardson, C., Santra, P., Tauber, S., Ward, G., Juarez-Zuniga, A., Flanigan, J., Moitra, P.
98. Seismic Structure of the Lithosphere in SW Australtila Based on New Data From the Western Australia Array. **Levin, V.**, Yuan, H., Murdie, R., Miller, M. S., Gessner, K.
99. Effects of Olivine Fabric Type on Seismic Anisotropy in the Mantle Wedge: A Wavefield Modeling Case Study. **Loeberich, E.**, Wolf, J., Long, M. D.
100. STUDENT: Crustal Imaging of the Southern Central Andes by Seismic Autocorrelation of Nodal Seismic Data. **Mahanti, S.**, Kiser, E., Bradford, J. M., Beck, S. L., Leon-Rios, S., Roecker, S., Tauber, S., Porter, R., Fernandez, M., Comte, D., Trad, S., Saez, M.
101. STUDENT: Imaging the Moho Topography Beneath the Northern Canadian Cordillera from Virtual Deep Seismic Sounding. **Sanusi, S. O.**, Pilia, S., Schutt, D. L., Rawlinson, N.
102. STUDENT: Full-waveform Tomography of Europe and Western Asia and Full-waveform Moment Tensor Inversions. **Schiller, C. J.**, Noe, S., van Herwaarden, D. P., Boehm, C., Thrastarson, S., Rodgers, A. J., Barrera-Lopéz, P., Marty, P., Fichtner, A.
103. Large Lithospheric Seismic Velocity Variations Across the Northern Canadian Cordillera. **Schutt, D. L.**, Porritt, R., Estève, C., Audet, P., Gosselin, J. M., Scheffer, A., Aster, R. C., Freymueller, J. T., Cubley, J. F.
106. Tectonic Imprints of Multiscale Craton Margin Deformation on the Continental Lithosphere of the Korean Peninsula From Regional Seismicity, Seismic Traveltime and Waveform Tomography. **Song, J.**, Rhie, J., Kim, S.
107. STUDENT: Making Love Visible in Noise: Enhanced Surface Wave Detection Using Slepian Tapers. **Swar, S. K.**, Olugboji, T.
108. Seismic Computational Platform for Empowering Discovery (Scoped): Software, Containers, Workshops, Science. **Tape, C.**, Bozdag, E., Denolle, M. A., Waldhauser, F., Wang, Y.
109. Crustal Structure Beneath Carpathian-panonian Region by Ambient Noise Tomography and Teleseismic P Wave Coda Autocorrelation. **Thapa, H.**, Vlahovic, G.
110. Constraining Slab Geometry and Seismic Velocity Structure From Tillamook to Portland, Oregon. **Wirth, E. A.**, Trehu, A. M., Stone, I., Hooft, E., Ward, K.
111. Hessian Vector Product in Transversely Isotropic Media. **Xie, Y.**, Sen, M.
112. Anisotropic Kilometer-scale Structures With a Near-zero Poisson's Ratio on the Japan Subduction Zone Plate Interface. Huang, Y., Ide, S., Kato, A., Yoshida, K., Jiang, C., **Zhai, P.**

Performance and Progress of Earthquake Early Warning Systems Around the World (see page 1449).

114. Installation and Optimization Advances in Earthquake Early Warning System (Rast-Vs) for Business Continuity and Public Safety in Mexico. **Avila, J. M.**, Yegres, L. A., Vargas, Z. J.
115. Enhancing Earthquake Early Warning with FinDer: Advances in Rapid Finite-source Modeling, Performance Evaluation, and New Features. **Böse, M.**, Saunders, J., Thompson, M., Andrews, J., Hartog, J., Felizardo, C., Ceylan, S.
116. STUDENT: Testing DAS-integrated Earthquake Early Warning in Northern California: Design and Implementation. **Gou, Y.**, Allen, R. M., Nof, R. N., Henson, I., Lux, A. I., Pardini, B., Zhu, W., Taira, T.

117. Real-time Correction of Ground Motion Amplification for a Rapid Seismic Intensity Reporting System. Jeong, S., Oh, J., **Kwak, D.**
118. An End-to-end Approach for Earthquake Early Warning Using IoT and Deep Learning. **Kwon, Y.**, Lee, J., Park, E., Lee, H., Ahn, J.
120. Mitigating Noise in Real-time GPS Positions to Improve Reliability of Geodetic Magnitude Estimates in the ShakeAlert Earthquake Early Warning System. **Manaster, A. E.**, Murray, J. R., Murray, M. H., Ulberg, C., Santillan, M., Scrivner, C., Melbourne, T., Szeliga, W., Crowell, B. W.
121. Real-time GNSS Data in ShakeAlert: Potential Improvements for Subduction Megathrust Earthquakes Through Network Design and Distributed Slip Models. **Murray, J. R.**
122. Student: Evaluating the Impact of Earthquake Early Warning Systems on Casualty Reduction: A Global Framework With a Focus on Central America. **Orihuela, B.**, Clinton, J. F., Papadopoulos, A., Danciu, L., Boese, M.
123. The Value of Distributed Acoustic Sensing for Earthquake Early Warning in Southern California. Biondi, E., **Saunders, J. K.**, Tepp, G., Yu, E., Banda, E., Zhan, Z., Husker, A. L.
124. Student: Evaluating the Effectiveness of Past and Present Seismic Arrays in Detecting Off-shore Earthquakes in Cascadia. **Sparks, A.**, Hartog, J., Hutko, A.
125. Testing Cascadia and San Andreas Fault-specific Finder Templates with the 5 December 2024 M7 Offshore Cape Mendocino Earthquake and Scenario Earthquakes. **Thompson, M.**, Hartog, J., Böse, M., Saunders, J. K., Felizardo, C., Andrews, J.

Seismology for the Energy Transition (see page 1463).

127. Student: Ambient Noise Tomography for Natural Hydrogen Exploration: A Case Study From the Gawler Craton, South Australia. **Dong, S.**, Jiang, C., Eakin, C. M., Wallenius, S., Miller, M. S., Moresi, L., Heinson, G., H2EX Ltd.
128. Improving Event Depth Constraint of a Local-scale Surface Seismic Network With Downhole DAS. **Dzubay, A. J.**, Friberg, P., Stachnik, J.
129. Student: DAS-recorded Microseismic Monitoring in Geothermal Field Stimulation With Waveform Imaging and Deep Learning. **Frigerio, J. O.**
130. The Problem of Uncontrolled Impacts on Natural Spheres. **Kerimov, I.**, Kerimov, S.
131. Find the Fluid: Using Cutting Edge-sensing to Track Geothermal Fluid and Gas Migration Underneath Sulfur Springs in the Valles Caldera. **Maier, N.**, Donahue, C. M.
132. Student: Denoising Seismic Migration Images Using ConvNeXt-style Neural Networks. **McNease, J. D.**, Huang, L., Zheng, Y.
133. Utah FORGE 2024 Stimulations: Improvement of Surface-based Microseismic Mapping of Fracture Zones via Nodal Geophone Patches. Niemz, P., **Pankow, K. L.**, Isken, M. P., Whidden, K., McLennan, J., Moore, J.
134. Shear Wave Velocity Structure and Moho Depth Beneath the Virginia Coastal Plain (VCP) From Fundamental-mode Rayleigh-wave Group-velocity Measurements. **Parija, M. P.**, Chapman, M. C., Biswal, S., Conley, E., Ogunleye, J., Pollyea, R. M.
135. A Novel Passive Source Basin Scale Seismic Monitoring Approach of Carbon Storage Sites. **Tian, Y.**, Yang, X.
136. Using Machine Learning to Enhance Microseismicity Monitoring and Support Carbon Storage Initiatives in Oklahoma. **Xiao, H.**, Walter, J., Ogwari, P. O., Thiel, A., Gregg, N., Mace, B.
137. Seismic Monitoring Analogs for Hydrothermal Processes in Controlled Fracture Networks. **Yuan, C.**, Saltiel, S., Mittal, T., Barth, A., Beaucé, E., Holtzman, B. K.

Fifty Years and Beyond of Broadband Seismic Instrumentation: Performance, Precision and Uncertainties (see page 1394).

138. Comparison of the Performance of a Wide Range of Sensors in Various Applications in the Field of Earthquake Engineering, From Low-noise to 2 G. **Hollender, F.**, Perron, V., Rischette, P., Langlais, M., Douste-Bacque, I.
139. Guralp Stratis - a Commercial 6 Degree of Freedom Seismometer for Academic and Research Applications. **Lindsey, J. C.**, Watkiss, N. R., Hill, P., Restelli, F.

Thursday, 17 April 2025—Oral Sessions

Presenting author is indicated in bold.

Time	*Holiday Ballroom 1*	*Holiday Ballroom 4–6*	*Key Ballroom 9*
	Exploring Planetary Interiors and Seismology: Observations, Models, Experiments and Future Missions (see page 1383).	**Advancements in Forensic Seismology and Explosion Monitoring** (see page 1316).	**Numerical Modeling in Seismology: Theory, Algorithms and Applications** (see page 1441).
8:00 AM	Reading a Marsquake Seismogram: A Case Study of S1222a. **Lekic, V.**, Kim, D., Maguire, R. R., Irving, J. C. E., Schmerr, N.	A New Paradigm for Nuclear Explosion Monitoring of Test Sites and Broad Areas: Full Waveform Inversion Tomography and Moment Tensor Inversion With 3D Greens Functions. **Rodgers, A. J.**, Gebraad, L.	Physics Informed Meshing for Accelerating the 3D Indirect Boundary Element Method Computation of Imaginary Part of Green's Function at the Source. **Sanchez-Sesma, F. J.**, Spurlin, J. H., Baena-Rivera, M., Valverde-Guerrero, I. R., López Sugahara, O., González, J. G.
8:15 AM	INVITED: Quantitative Assessment of Atmospheric and Teleseismic Excitation of a 2.4 Hz Resonance in Insight Data From Mars. **Panning, M. P.**, Pou, L., Kedar, S., Asimaki, D.	Bayesian Optimal Experimental Design With Constraints for Seismo-acoustic Sensor Networks. **Catanach, T. A.**, Callahan, J. P.	Dynamic Earthquake Rupture and Tsunami Modeling for the Gulf of Aqaba. **Li, B.**, Mai, P.
8:30 AM	Lems-A3: The Lunar Environmental Monitoring Station—a Seismometer Station for the Moon Deployed by Artemis III Astronauts. **Schmerr, N.**, Benna, M., McCall, N., DellaGiustina, D., Marusiak, A., Bray, V., Bailey, H., Byrne, P., Avenson, B., Kim, D., Artemis III Science Team.	Bayesian Inference for the Seismic Moment Tensor Using Regional Waveforms and Teleseismic-P Polarities with a Data-derived Distribution of Velocity Models and Source Locations. **Chiang, A.**, Ford, S., Pasyanos, M., Simmons, N.	Implications of the Recent Findings for Practical Calculations and Designing the Time-domain Finite-difference Schemes. Kristek, J., Valovcan, J., **Moczo, P.**, Galis, M., Kristekova, M.
8:45 AM	INVITED: Along-trajectory Infrasound Signals Generated by the OSIRIS-REx Sample Return Capsule Re-entry. Silber, E. A., **Bowman, D. C.**	From Source to Receiver: Numerical Simulations of Underground Explosions, Cavity and Chimney Formations, Subsurface Gas Transport and Prompt Atmospheric Releases. **Ezzedine, S. M.**, Velsko, C., Vorobiev, O., Sun, Y., Hao, Y., Herbold, E., Balco, G., Myers, S. C.	Bento: Benchmark for Assessing Topographic Site Effects Through 3D Numerical Simulations. Bou Nassif, A., Maufroy, E., Chaljub, E., Rischette, P., Cornou, C., Bard, P., El Haber, E., **Hollender, F.**
9:00 AM	Examining Acoustic Arrivals From the OSIRIS-REx Capsule Reentry Recorded on a Large-N Infrasound Array. **Wynn, N. R.**, Silber, E. A., Bowman, D. C.	Variable Global Grid Refinement and Prediction Using RSTT Model. **Ranasinghe, N. R.**, Begnaud, M. L., Rowe, C. A., Myers, S. C., Young, B.	STUDENT: Modeling of HVSR for an Inhomogeneous Medium Over a Varying Lateral Interface Using 3D IBEM and the Diffuse Field Concept. **López Sugahara, O.**, Santoyo, M., Sánchez-Sesma, F.
9:15–10:30 AM	Poster Break		

Time	*Key Ballroom 10*	*Key Ballroom 11*	*Key Ballroom 12*
	Earthquakes, Lithospheric Structure, and Dynamics in Stable Continental Region (see page 1375).	**Challenges and Opportunities in Constraining Ground-motion Models from Physics-based Ground-motion Simulations** (see page 1346).	**Earthquake-triggered Ground Failure: Data, Hazards, Impacts and Models** (see page 1372).
8:00 AM	Imaging Intraplate Faults in Puerto Rico With New Aeromagnetic Data: The Roles of Fault Reactivation and Tectonic Inheritance. **Shah, A. K.**, Jobe, J. A. T., Briggs, R., Lynch, E. M., Pratt, T., Ten Brink, U., Wilson, F.	INVITED: Incorporating Results From Numerical Simulations Into Ground-motion Models. **Abrahamson, N.**	STUDENT: Earthquake-induced Landslides Susceptibility and Controlling Factors in Vancouver Island, British Columbia, Canada. **Pino-Rivas, C. A.**, Sepulveda, S. A., LeSueur, P.
8:15 AM	A Railway-spotters Guide to Earthquakes: Coseismic Slip, Dynamic Strain and Ground Motion Intensity. **Bilham, R.**, Hough, S. E., Bulut, F.	Toward Utilization of Physics-based Simulations in Seismic Hazard Assessment: Insights From Japan Experiences. **Iwaki, A.**, Morikawa, N., Maeda, T., Fujiwara, H.	STUDENT: Sea Level Rise Effects on Earthquake-induced Soil Liquefaction. **Kota, M. L.**, Brandenberg, S. J., Maple, M., Gallien, T.
8:30 AM	Velocity and Fault Structure of the New Madrid Seismic Zone. **Powell, C.**, Langston, C. A.	INVITED: Epistemic Uncertainties in Seismic Source Modeling for Finite-fault Ground-motion Simulations. **Mai, P.**	Duration Matters: Impacts of Ground Motion Selection on Seismic Slope Displacement Analyses. **Cabas, A.**, Chowdhury, I., Kaklamanos, J., Kottke, A. R.
8:45 AM	INVITED: High-resolution Seismic Imaging of Crustal and Upper Mantle Structures Across the Southern Eastern North American Passive Margin. **Li, C.**, Yu, C., Gao, H.	Implications of the SCEC/USGS Community Stress Drop Validation Study for Physics-based and Empirical Ground Motion Modelling. **Baltay, A.**, Abercrombie, R. E., Parker, G. A.	Liquefaction and Ground Failure Considerations During Long-duration, Subduction Zone Earthquakes. **Carey, T. J.**, Fayaz, Z.
9:00 AM	Indications of Earthquake Activity in Northeastern North American from Native Americans. **Ebel, J. E.**	Ground Motion Simulations Based on Source Slip Distribution, Fourier Amplitude and Phase Models for the Chilean Subduction Zone. **Montalva, G. A.**, Osses, M., Leyton Flórez, F., Ojeda, J.	STUDENT: Synergic Use of Radar and Optical Sensor Data for Mapping Earthquake Triggered Landform Changes. Azeem, A., Atif, S., **Ahmad, A.**
9:15–10:30 AM	Poster Break		

Time	*Holiday Ballroom 1*	*Holiday Ballroom 4–6*	*Key Ballroom 9*
	Visualization and Sonification in Solid Earth Geosciences, What's Next? (see page 1478).	**Advancements in Forensic Seismology and Explosion Monitoring** (see page 1316).	**Numerical Modeling in Seismology: Theory, Algorithms and Applications** (see page 1441).
10:30 AM	Shakemovie: Rapid Post-earthquake Animation of Near-fault Ground Shaking. **Graves, R.**	STUDENT: Integrating Machine Learning for Near-real-time Earthquake Monitoring and Public Notification. **Rakotoarisoa, A.**, Razafindrakoto, H.	Implications of Recent Advances in Anelastic Seismic Ray-tracing Algorithms for Alluvium-basin Response and Seismic-tomography Models of the Crust and Mantle. **Borcherdt, R. D.**
10:45 AM	Optimizing Earthquake Ground Motion Visualizations to Enhance Public Understanding and Preparedness. Kuratle, L., **Kilb, D.**, Gabriel, A., Rekoske, J. M.	An Efficient Subspace Detector for Rayleigh Waves, Demonstrated Against Explosions. **Carmichael, J. D.**, Kintner, J. A., Alfaro-Diaz, R. A.	Finite-domain Full-waveform Ambient Noise Inversion for Structure and Source Parameters. **Keating, S.**, Fichtner, A., Zunino, A.
11:00 AM	Sonic and Visual Representations of Seismic Data, Coupled to Machine Listening and Pattern Discovery. **Holtzman, B. K.**, Barth, A., Beaucé, E.	Differential Seismic Phase Detection Probability as a Potential Attribute for Discrimination of Explosions and Earthquakes. **Schmandt, B.**, Duan, C., Maguire, R. R.	Leveraging Boundary Integral Equations for Efficient, Fully-dynamic Simulation of Earthquakes and Aseismic Slip on Fault Networks. **Ciardo, F.**, Romanet, P.
11:15 AM	Sonifying Seismic Data on the Go, for Research and STEM Engagement. **van der Lee, S.**, Tejedor, H., Marzen, M., Ranadive, O., Anderson, J., Schirbel, L.	Probabilistic Source Type Analysis with Applications to Seismic Source Classification. **Alvizuri, C. R.**	A Velocity Structure Model for Ground Motion Simulation in Japan. **Koketsu, K.**, Miyake, H., Suzuki, H.
11:30 AM	Sonification and Visualization of High-resolution Earthquake and Tremor Catalogs. **Peng, Z.**, Hyde, R., Kato, A.	Seismic Source Characterization: Context to Confidence. **Alfaro-Diaz, R. A.**, Kintner, J. A., Carmichael, J. D.	Earthquake Rupture Propagation and Arrest in a Highly Variable Stochastic Stress Field. **McLaskey, G. C.**, Kammer, D. S., Ke, C. Y.
11:45 AM–2:00 PM	Lunch Break		

Time	*Key Ballroom 10*	*Key Ballroom 11*	*Key Ballroom 12*
	Earthquakes, Lithospheric Structure, and Dynamics in Stable Continental Region (see page 1375).	**Challenges and Opportunities in Constraining Ground-motion Models from Physics-based Ground-motion Simulations** (see page 1346).	**Why Ignore the Structure? Soil-structure Interaction and Site Response at Local and Regional Scales** (see page 1479).
10:30 AM	Deep Quakes Beneath the Moho: Insights From the Wind River Basin, Wyoming. **Woo, J.**, Chen, T.	Characterizing Ground Motion Through Multi-fault Dynamic Rupture Simulations in Central New Zealand. **Li, D.**, Bora, S., Benites, R., Thingbaijam, K., Howell, A., Williams, C. A., Yuan, S., Kaiser, A., Manea, E., Hill, M., Gerstenberger, M. C.	Vs30-Fd Relationship for Measured-Vs30 Stations in the Western United States. Yong, A., Kottke, A. R., **Hudson, K.**, Matsushima, S., Stephenson, W. J., Bonilla, F., Martin, A., Hassani, B.
10:45 AM	INVITED: The Seismic Sources of Northeastern US: New Insights Into Their Detailed Geological Structure and Reactivation Mechanics. **Kolawole, F.**, Ajala, R., Foster-Baril, Z., Beaucé, E., Kim, W., Waldhauser, F., Seeber, L.	Evaluation of Uncertainties Using Simulations of Small Earthquakes for the Northern California Velocity Model Adopted for the Cybershake Study 24.8. **Pinilla Ramos, C.**, Ben-Zion, Y., Abrahamson, N., Su, M., Maechling, P. J., Callaghan, S., Tang, H., Meng, X.	Probabilistic Seismic Assessment of Nuclear Power Plants. **Wang, L.**, Gutierrez, S.
11:00 AM	Long-term Erosion as a Catalyst of Shallow Seismicity in Stable Continental Regions – a Global View. **Mazzotti, S.**, Malcles, O., Vernant, P., Grosset, J., Damon, A., Vergeron, X.	Aleatory Variability and Epistemic Uncertainty from Physics-based Ground-motion Simulations as part of Probabilistic Seismic Hazard Analysis. **Liou, I. Y.**, Abrahamson, N., Cotton, F.	STUDENT: Sub-regional Site Response for the San Francisco Bay Area. **Mohammed, S. A.**, Shams, R., Buckreis, T. E., Nweke, C. C., Brandenberg, S. J., Stewart, J. P.
11:15 AM	Old News Papers, New Felt Reports, New Earthquakes, New Ways to Look for Old Earthquakes. **Moran, N. K.**	Site Response High-frequency Frontiers and the Added-value of Site-Specific Earthquake Record-based Measurements of Velocity and Attenuation. **Pilz, M.**, Zhu, C., Cotton, F.	City-scale Assessment of Site and Basin Effects in Selected CEUS Sedimentary Basins: Memphis and New York City. **Kaklamanos, J.**, Guzman, I. M., Sachs-Walor, G. A., Meyer, E. H., Baise, L. G.
11:30 AM	Well Logs from the South Florida Basin. **McNutt, S. R.**, Herbert, T. A.	Assessing the Applicability of the Use of Simulation Results in Non- Ergodic GMMs for Areas Without Empirical Data. **Sung, C.**, Abrahamson, N.	Investigation of Basin Effects in Po Plain in Italy: A Case Study From 2012 Emilia Earthquake Sequence. **Paramasivam, B.**, Seyhan, E.
11:45 AM–2:00 PM	Lunch Break		

Time	Holiday Ballroom 1	Holiday Ballroom 4–6	Key Ballroom 9
	Earthquake Shaking and the Geologic Record: Triggered Phenomena and Preserved Fragile Geologic Features (see page 1370).	**Advancements in Forensic Seismology and Explosion Monitoring** (see page 1316).	**New Directions in Environmental, Seismic Hazard and Mineral Resource Exploration Studies** (see page 1436).
2:00 PM	Evaluating the New Zealand National Seismic Hazard Model 2022 with Fragile Geologic Features. **Stirling, M. W.**, Pratt, T.	New Constraints on Seismic Source Type Evident in 3D Waveform Inversions, Application to Remote Historical Nuclear Explosions in Western China. **Kintner, J. A.**, Modrak, R., Nelson, P. L.	STUDENT: Construction of 3D Finite Element Meshes from Drone Images: A Step Towards a Non-destructive Testing Framework for Engineering Structures and Their Response to Earthquakes. **Delaney, E. T.**, Marty, P., Gebraad, L., Zunino, A., Fichtner, A.
2:15 PM	Paleoseismic Records of the Dead Sea Reveals Climatic Modulation of Seismicity Along the Continental Transform Faults. Marco, S., Wdowinski, S., Lu, Y., Le Blanc, A., **Higgins, M.**	Characterization of Road Construction Explosions Recorded Along an Ocean-bottom Fiber With Distributed Acoustic Sensing. **Viens, L.**, Delbridge, B. G., Beckett, J.	INVITED: Ambient Noise Tomography (ANT) as a Scalable Data Platform for Machine-learning Driven Mineral Discovery. **Muir, J.**, Olivier, G., Reid, A.
2:30 PM	Directivity Effect of the 1976 Guatemala Earthquake Observed in Lacustrine Turbidites. **Maurer, J.**, Obrist-Farner, J., Gibson, D., McEnaney, T., Eckert, A., Kenney, W.	The Source Physics Experiment and Distributed Acoustic Sensing. **Porritt, R.**, Stanciu, C., Luckie, T., Abbott, R. E.	INVITED: STUDENT: Producing a State-wide Ground Deformation Map of Alaska With Satellite Remote Sensing. **Atkins, C. M.**, Lucy, J. T., Werth, S., Shirzaei, M.
2:45 PM	3D Mapping and Dynamic Analysis of Precariously Balanced Rocks for Fragility Modeling. Chen, Z., Rodge, D., Mahalle, A., **Arrowsmith, R.**, Das, J., Wittich, C., Madugo, C., Kottke, A. R.	Reviewing Seismoacoustic Coupling Mechanisms for Infrasound From Underground Explosions. **Kim, K.**, Green, D. N., Bowman, D. C., Blom, P. S., Bishop, J. W.	Subsurface Geologic Controls on Seismic Site Response Across the Continental United States. **Kehoe, H. L.**, Boyd, O. S., Moschetti, M. P., Bozdağ, E., Caylor, E. A.
3:00 PM	Rapid Assessment of Precariously Balanced Rocks Using UAVs and 3D Semantic Structure from Motion. **Chen, Z.**, McPhillips, D., Scharer, K., Ross, Z.	Assessment of Seismoacoustic Signals From Wavefield Experiments at a Nuclear Facility in Texas. **Park, J.**, Arrowsmith, S., Clarke, J., Hayward, C., Chai, C., Marcillo, O., Maceira, M., Thomas, J. O., Cunningham, J.	Probabilistic Seismic Hazard Assessment in Namibia. **Kadiri, U. A.**, Sitali, M., Midzi, V.
3:15– 4:30 PM	Poster Break		

Time	Key Ballroom 10	Key Ballroom 11	Key Ballroom 12
	Exploring the Complexity of Fault Discontinuities (see page 1386).	**Challenges and Opportunities in Constraining Ground-motion Models from Physics-based Ground-motion Simulations** (see page 1346).	**Macroseismic Intensity: Past, Present and Future** (see page 1417).
2:00 PM	How Wide Are Faults? **Rowe, C. D.**, Hatem, A. E.	Development of a Non-ergodic Ground Motion Model for the Groningen, Netherlands Region Based on a Hybrid Empirical and Simulation Dataset. **Lavrentiadis, G.**, Oral, E., Asimaki, D.	Making the Case for Implementing the International Macroseismic Scale (IMS) in the United States. **Wald, D. J.**, Hortacsu, A., Quitoriano, V., Ortiz-Millan, M., Tremayne, H., Porter, K. A., Silva, V.
2:15 PM	Building Non-planar 3D Fault Models From Earthquake Hypocenters. **Alongi, T.**, Elliott, A., Skoumal, R., Hatem, A. E., Shelly, D. R.	STUDENT: Estimating Systematic Source, Site, and Path Effects in Non-ergodic Ground Motion Models: Insights From the Turkish Ground Motion Database. **Liu, C.**, Macedo, J.	The U.S. Contribution to the International Macroseismic Scale. **Porter, K. A.**, Hortacsu, A., Wald, D. J.
2:30 PM	Sentinel-1 InSAR Analysis Reveals Longer Periods of Creep and the Segmentation of Enriquillo Plantain Garden Fault Following the 2021 M7 Nippes, Haiti. **Higgins, M.**, Wdowinski, S.	Non-ergodic Site Model for Ground Motion Analysis: Incorporating Regionalization, Kappa and Basin Effects. **Nie, S.**, Baise, L. G.	Towards the Integration of Field and Web-based Macroseismic Surveys in Italy. **Rovida, A.**, Antonucci, A., Bernardini, F., De Rubeis, V., Ercolani, E., Graziani, L., Locati, M., Rossi, A., Sbarra, P., Sorrentino, D., Tertulliani, A., Tosi, P.
2:45 PM	Fault Geometric Complexity and Displacements of 2016 Kaikōura Earthquake Surface-ruptures, New Zealand. **Nicol, A.**, Howell, A., Walsh, J., Mouslopoulou, V., Boulton, C., Parker, M.	Research, Development and Implementation Priorities for Ground-motion Characterization in USGS Earthquake Hazards Program Hazard, Risk Assessment and Forecast Products. **Aagaard, B. T.**, Baltay, A., Moschetti, M. P., Thompson, E. M., Luco, N., Boyd, O. S., Grant, A., Graves, R., Hirakawa, E., Hough, S. E., Kehoe, H. L., Makdisi, A. J., Parker, G. A., Petersen, M. D., Powers, P. M., Rezaeian, S., Stephenson, W. J., Stone, I., Wald, D. J., Wirth, E. A., Withers, K. B., Yong, A.	Exploring the Capabilities of Llms for Earthquake Science: A Case Study on Macroseismic Intensity Measurement. **Mousavi, S.**
3:00 PM	The Impact of Pre-existing Weaknesses on Early Strike-slip Fault Evolution. **Cooke, M. L.**, Ramos Sánchez, C.	Uncertainty in Ground-motion Forecast: A Perspective From New Zealand National Seismic Hazard Model Revision. **Bora, S.**, Bradley, B., Gerstenberger, M. C., Kaiser, A.	INVITED: STUDENT: A New Intensity Data Set and Intensity Prediction Equation for Crustal Earthquakes in the Western United States. **Fathian Sabet, A.**, Sung, C., Abrahamson, N.
3:15– 4:30 PM	Poster Break		

Time	*Holiday Ballroom 1*	*Holiday Ballroom 4–6*	*Key Ballroom 9*
		Advancements in Forensic Seismology and Explosion Monitoring (see page 1316).	**New Directions in Environmental, Seismic Hazard and Mineral Resource Exploration Studies** (see page 1436).
4:30 PM		Seismoacoustic Yields of Local to Near-regional Distance Explosions Using Distributed Acoustic Sensing (DAS). **Delbridge, B. G.**, Viens, L., McLaughlin, J. M., Luong, L., Ta, T., Cadol, D., Bilek, S.	Ten Days of Continuous Aftershock Hum Following the 2019 Ridgecrest, California, Mainshocks Observed With Borehole Seismometers. **Shearer, P.**, Senobari, N. S.
4:45 PM		Possible Double Bolide Measured Across the Idaho National Laboratory Broadband Seismic Network. **Bockholt, B.**, Langston, C. A.	Seismic Hazard from the Aftershocks of Subduction Interface Earthquakes. **Onur, T.**, Herrera, C., Cassidy, J., Seemann, M.
5:00 PM		STUDENT: Cardinal: Seismic and Geoacoustic Array Processing. **Ronac Giannone, M.**, Arrowsmith, S., Silber, E. A.	STUDENT: Does the Mississippi Embayment Edge Have Any Effect on Site Amplification? **Abbasi Hafshejani, Z.**, Cramer, C., Pezeshk, S.
5:15 PM		STUDENT: Leveraging Seismic Particle Motion of Air-to-ground Coupled Waves to Investigate the Structure of the Shallow Subsurface. **Scamfer, L. T.**, Fee, D., Bishop, J. W., Haney, M., Macpherson, K. A.	Analytical Approximations for Propagating Epistemic Uncertainty and Modeling Virtual Faults for Areal Sources in Seismic Hazard Analysis. **Lacour, M.**, Abrahamson, N.
5:30 PM		Diurnal and Weekly Acoustic Background Noise Fluctuations in the Vicinity of the P-tunnel Complex at the Nevada National Security Site. **Bowman, D. C.**, Malach, A. K., Wharton, S., Turley, R. S., Schalk, W. W., White, R. L., PE1 Experiment Team.	Does Detailed Site Characterization and Ground Response Analysis Change Projected Building Damage Estimates? Sanon, C., **Baise, L. G.**, Kaklamanos, J.

Time	*Key Ballroom 10*	*Key Ballroom 11*	*Key Ballroom 12*
	Compiling Active Faults for Improved Hazard Modeling from Cascadia to Alaska (see page 1352).	**Modern Waveform Processing and Engineering Datasets - Accessibility, Quality Control, and Metadata** (see page 1426).	
4:30 PM	Crustal Stress in Alaska and NW Canada: New Insights Into Intraplate Deformation and Fault Slip Potential. **Levandowski, W.**, Ruppert, N.	INVITED: Recent Improvements and Lessons Learned From Processing Ground Motions at the U.S. Geological Survey. **Thompson, E. M.**, Aagaard, B. T., Hearne, M., Smith, J. A., Worden, C. B., Smith, K., Schleicher, L. S., Steidl, J. H., Kottke, A. R.	
4:45 PM	Current State of Paleoearthquake Data for the Alaska Range. **Bemis, S. P.**, Koehler, R. D.	STUDENT: Exploring the Utility of Earthquake Spectra Collected From Smartphones for Ground-motion Modeling. **Marcou, S.**, Allen, R. M.	
5:00 PM	Active Faulting in Western Canada: Definition and Review of Current Knowledge. **Hobbs, T. E.**, Clague, J. J., Harrichhausen, N., Finley, T., Douglas, K., Schaeffer, A., Barrie, J. V., Mendoza, R. B., Leonard, L. J., Zaleski, M., Journeay, J. M., Kolaj, M., Podhorodeski, A., Styron, R.	The Next-generation ESM: Generating Reference Earthquake Data Sets from High-quality Semi-automated Waveform Processing. **Luzi, L.**, Mascandola, C., Felicetta, C., Lanzano, G., Russo, E., Clinton, J. F., Cauzzi, C., Bienkowski, J., Sleeman, R., Marmureanu, A., Predoiu, A., Ktenidou, O. J., Melis, N., Theodoulidis, N., Konstantinidou, K., Hollender, F., Perron, V., Riga, E., Manakou, M., Cambaz, D., Hancilar, H., Roumelioti, Z., Sokos, E., Jerše Sharma, A., Zupancic, P., Vanneste, K., Mihaljevic, J., Weatherill, G., Rupakhety, R., Tepeuğur, E.	
5:15 PM	CRESCENT CFM: Building a Community Fault Model for the Cascadia Subduction Zone. **Fildes, R. A.**, Streig, A. R., Amos, C., Bennett, S. E. K., Hatem, A. E., Meigs, A., Roland, E., Styron, R., Tobin, H., Ledeczi, A., Lucas, M.	Australian Ground-motion Records Portal. **Ghasemi, H.**, Allen, T.	
5:30 PM	Seismicity Relocations Between 2016 and 2019 Near the 1872 Entiat Earthquake in Central Washington. **Wu, Q.**, Wong, I. G., Cakir, R., Gray, B., Bubeck, A.	Deep Learning-based Approaches to Assess Waveform Quality for Engineering Applications. **Zaker Esteghamati, M.**, Namin, A., Kottke, A. R.	

Poster Sessions

Earthquake-triggered Ground Failure: Data, Hazards, Impacts and Models (see page 1373).

1. Regionalized Geospatial Liquefaction Model for California Using Bayesian Logistic Regression. Shirzadi, H., **Baise, L. G.**, Moaveni, B.
2. Student: Site-characterization Vis-À-vis Surface-consistent Probabilistic Seismic Hazard From Kashmir Himalaya to Northwest Himalaya. **Bind, A.**, Nath, S., Sengupta, P.
4. Earthquake Damage Assessment Empowered by AI Remote Sensing: Case Studies in 2023 M7.8 Kahramanmaraş Earthquake, 2023 M6.0 Jishishan Earthquake and 2025 M7.1 Southern Tibetan Plateau Earthquake. **Hu, X.**, Yu, X., Xu, Y., Song, Y., Lin, F.
5. Nonergodic-based Risk Assessment of Liquefaction-induced Ground Damage. **Macedo, J.**, Liu, C.
6. Mathematical Support for Slope Processes Risk Zoning Using Data About Possible Earthquakes. **Zimin, M.**, Kondratyeva, N., Zimin, M.

Why Ignore the Structure? Soil-structure Interaction and Site Response at Local and Regional Scales (see page 1481).

7. Student: Evaluating Soil-structure Interaction and Site Response in Urban Excavation: Insights From the I-495 Project Next. **Faizan, A.**, Halata, M.
8. Student: Nonlinear Dynamic Analysis of RC Structures and Soil Structure Interaction Effects. **Haghani, M.**
9. Student: Application of Bayesian SPAC to Estimate Vs30 and Classify Soils in Ponce, Puerto Rico. **Herazo, M.**, Vanacore, E., Pachhai, S., Martínez-Cruzado, J. A.
10. Toward Neural Network Based Automated Structural Health Monitoring With MyShake Smartphones. **Kumar, U.**, Marcou, S., Allen, R. M.
11. Student: Incorporating Uncertainties Into Vs-delta Kappa_0 Corrections. **Lee, J.**, Barba, D., Cabas, A.
12. Nonlinear Site Response Observed by the NDHU Downhole Array During the April 2, 2024 Taiwan M7.4 Earthquake. **Lin, C.**, Kuo, C., Hsieh, H., Wang, Y., Huang, J.
13. Student: Willamette Valley Site Characterization With HVSR. **Mann, C. A.**, Sahakian, V. J.
14. Cosmos Site Characterization Working Group: Achievements and Perspectives, From the Determination of Soil Properties to the Consideration of Topography and Installation Effects. **Pilz, M.**, Askan, A., Hollender, F.
15. Shear-wave Velocities in the Bellingham and Everett Basins, Washington State: Insights From Multimethod Characterization With krSPAC and Active-source Linear Arrays. **Stephenson, W. J.**, Lindberg, N. S., Leeds, A., Holland-Goon, K., Odum, J. K.

Macroseismic Intensity: Past, Present and Future (see page 1419).

17. The Scientific Value of Internet Macroseismic Data in Operational Seismology. **Bossu, R.**, Cheny, J., Issartel, S., Landès, M., Roch, J., Roussel, F., Steed, R., Ucciani, G.
18. A Proposed Canadian National Annex to the International Macroseismic Scale. **Hobbs, T. E.**, Porter, K. A., Wald, D. J., Onur, T., Crane, S.
19. To Intensity and Beyond: On the Limits of the Conventional Macroseismic Intensity Scale. **Hough, S. E.**
20. Invited: Student: Using “Did You Feel It?” Data to Map Spatially Variable Site Amplification in the Central and Eastern United States: Lessons From the 2024 M 4.8 Tewksbury, New Jersey, Earthquake. **Meyer, E. H.**, Baise, L. G., Kaklamanos, J., Nie, S., Roberts, M. E., Zhan, W.
21. Guidelines on Using (Uncertain) Macroseismic Data in ShakeMap. **Quitoriano, V.**, Worden, C. B., Thompson, E. M., Wald, D. J.
22. The Effect of Structural Damage on Shakemap. Vitale, A., **Rosti, A.**, Giorgio, M., Iervolino, I.
23. Twenty Years of EMS-98 Practice in Italy: A Successful Experience. **Rovida, A.**, Tertulliani, A., Antonucci, A., Arcoraci, L., Azzaro, R., Berardi, M., Bernardini, F., Camassi, R., Castellano, C., D’Amico, S., Del Mese, S., Ercolani, E., Fodarella, A., Graziani, L., Locati, M., Maramai, A., Pessina, V., Rossi, A., Tuvè, T.
24. Constraints of the Non-ergodic Path Effects for Short Distances in GMMs using the Modified Mercalli Intensity Data. **Sung, C.**, Abrahamson, N.

Earthquake Shaking and the Geologic Record: Triggered Phenomena and Preserved Fragile Geologic Features (see page 1371).

25. A New Type of Paleoseismic Evidence From Lake Sediments. **Morey, A. E.**
26. New Methods for Analyzing Precariously Balanced Rocks in the Eastern U.S. **Pratt, T.**, Stirling, M. W., McPhillips, D., Figueiredo, P.
28. Developing a New Intensity Measure for USGS’s ShakeMap: Cumulative Absolute Velocity (CAV). **Smith, K. K.**, Thompson, E. M., Worden, C. B., Wald, D. J.
29. Precariously Balanced Rocks in Northern New York and Vermont, U.S.A.: Ground-motion Constraints and Implications for Fault Sources. **McPhillips, D.**, Pratt, T.

Temporally Variable Records of Earthquake Behavior and Considerations for Seismic Hazard Analyses (see page 1470).

30. Invited: Disentangling Slip-rate Variability in Time and Space at the Cucamonga Fault, Southern California, USA. **McPhillips, D.**, Scharer, K., Mere, A. M.
31. Wasatch Fault Zone Paleoseismic Rupture Models. **DuRoss, C. B.**, Hatem, A. E., Wong, I. G., Schwartz, D., McDonald, G., Hiscock, A., Kleber, E., Lund, W.
32. Earthquake and Slip-rate History of the Middle Branch of the Northern Anatolian Fault, Türkiye. **Harrichhausen, N.**, Aykut, T., de Sigoyer, J., Klinger, Y., Yıldırım, C., Baka, Ç., Allemand, A., Wenqian, Y., Karakaş, M.
33. Assessment of Legacy Fault Studies and New Geological Mapping: Towards Improving Seismic Hazard Models at Yucca Mountain, Nevada. **Koehler, R. D.**, Faulds, J. E., Vlcan, J.
34. Student: Reconstructing Vertical Deformation Using Stratigraphy and Microfossils to Infer Megathrust Rupture History on Sitkinak Island, Alaska. **Nowak, T.**, Dura, T., Engelhart, S., Koehler, R. D.
35. Invited: Short-term Variations in Earthquake Production in the Southern San Andreas Fault System Due to Lake Level Variations in Lake Cahuilla, Salton Trough, California: Implications for Short-term Slip Rate Variability. **Rockwell, T. K.**
36. The Secondary Zone of Subsidence (SZS) During Subduction Zone Interseismic Deformation and Its Implications for Megathrust Earthquake Potential. **Wang, K.**, Luo, H., Feng, L., Hill, E.
37. Non-ergodic Probabilistic Fault-displacement Hazard Analysis. **Liou, I. Y.**, Abrahamson, N.

Challenges and Opportunities in Constraining Ground-motion Models from Physics-based Ground-motion Simulations (see page 1350).

39. Simulation of Physics-based 0-10 Hz Ground Motion Using High-performance Computing Supporting Refinements to Regional Ground Motion Models for the Central Eastern U.S. Pitarka, A., **Graizer, V.**, Aguiar, A., Rodgers, A. J.
40. Estimation of the Horizontal Site Amplification Factors at Sites in the Noto-hanto Area in Japan based on the Microtremor Horizontal-to-vertical Spectral Ratios: A Special Case for the Vertical Amplification Correction Function. **Ito, E.**, Nakano, K., Kawase, H., Matsushima, S., Bao, Y.
41. Student: Advancing Seismic Site Response Predictions: Integrating Vs Gradients and Vs Contrasts. **Katuwal, S.**, Pretell, R.
42. Student: Tamp1.5: Estimating the Effect of Site-specific Kappa on High-frequency Ground Motion Utilizing Elastic Response Spectral Shapes. **Largent, M.**, Abrahamson, N.
44. Validation of Two New CyberShake Studies in California. **Meng, X.**, Graves, R., Callaghan, S., Milner, K. R.
45. Incorporating Stress Drop into Non-ergodic Ground Motion Models. **Nie, S.**, Wang, Y.
46. Basin Identification Using the Continuous Wavelet Transform on Digital Elevation Models for Seismic Hazard Analysis. **Nie, S.**, Baise, L. G.
47. Evaluating the Relationship Between Slip and Slip-velocity on Large-magnitude Ruptures Based on Surface Displacement. **Pinilla Ramos, C.**, Abrahamson, N.

Modern Waveform Processing and Engineering Datasets - Accessibility, Quality Control, and Metadata (see page 1427).

48. Student: A Curated Database of High Quality Microtremor HVSR From U.S. Permanent Seismic Stations. **Anbazhagan, B.**, Vantassel, J. P., Rodriguez-Marek, A.
49. Student: An Updated Review of Ground Motion Flatfiles in the Chilean Subduction Zone. **Bastias, N.**, Montalva, G. A., Leyton Flórez, F., Heresi, P., Dominguez, H.
50. Marsquakes Then and Now: Revisiting Viking With Insight. **Charalambous, C.**, Fernando, B., Lazarewicz, A., Nakamura, Y., Pike, T.
52. Operational Response Insights from the December 2024 Cape Mendocino, California Earthquake Waveform Data Processing and Quality Review. **Schleicher, L. S.**, Steidl, J. H., Blair, L., Terra, F., Hagos, L., Brody, J., Shao, H., McClain, A., Bradshaw, R., Dhar, M., Amador, V., Marcus, J., Luna, E., Carrasco Rodriguez, V., Childs, D., Kinkaid, K., Smith, J., Haddadi, H., Croker, D.
53. Ground Motion Dataset Verification and Validation, Insights Into Unexpected Sources of Uncertainties Associated to Ground Motion Modeling. **Traversa, P.**, Buscetti, M., Perron, V., Rischette, P., Hollender, F., Arroucau, P.
54. Usability of Records by China Earthquake Early Warning Network for Ground Motion Model Development. **Xie, J.**, Wang, W., Li, X.

Advancing Seismic Hazard Models (see page 1332).

55. Subduction Zones in USGS National Seismic Hazard Models. **Altekruse, J. M.**, Powers, P. M.
56. Geologic and Seismotectonic Data for the 2026 American Samoa and Mariana Islands National Seismic Hazard Model Update. **Herrick, J. A.**, Briggs, R., Hatem, A. E.,

Jobe, J. A. T., Ten Brink, U., Stephenson, W. J., Lindberg, N. S., Leeds, A. L., Lynch, E. M., Powell, J. H., Miller, N. C.

57. Sensitivity of Seismic Hazard Models to Catalog Magnitude Conversion Relations. **Llenos, A. L.**, Shelly, D. R., Shumway, A. M.
58. The USGS 2025 Puerto Rico and U.S. Virgin Islands Earthquake Rupture Forecast. **Milner, K. R.**, Hatem, A. E., Briggs, R., Jobe, J. A. T., Llenos, A. L., Michael, A. J., Shumway, A. M., Field, E. H., Haynie, K. L.
60. Comparing Site-specific Seismic Hazard Analyses with the National Seismic Hazard Model for the Central and Eastern U.S. **Wong, I. G.**, Zandieh, A., Darragh, B., Kayastha, M., Chowdhury, I., Lewandowski, N., Thomas, P., Wu, Q., Yenihayat, N.
61. Update of the Lower Seismogenic Depth Model for Western U.S. Earthquakes. **Zeng, Y.**, Petersen, M. D., Boyd, O. S.

Earthquakes, Lithospheric Structure, and Dynamics in Stable Continental Region (see page 1377).

62. The February 2024 M4.1 Earthquake Offshore Cape Canaveral, Florida. **Braunmiller, J.**, Rodriguez Cardozo, F. R., Thompson, G., McNutt, S. R.
63. Student: A New Fault Characterization in Lajas Valley, Southwestern Puerto Rico. **Justiniano, C.**, Vanacore, E., Pratt, T., López Venegas, A. M.
64. Stress and Slip Potential of Quaternary Faults and Possible Tectonic Features in the Central and Eastern U.S. **Levandowski, W.**
65. New Seismotectonic Models of Metropolitan France and Neighboring Intraplate Regions for Seismic Hazard Assessment. Jeandet, L., Jomard, H., **Mazzotti, S.**
66. Long-term Erosion as a Catalyst of Shallow Seismicity in Stable Continental Regions – Examples of Metropolitan France. **Mazzotti, S.**, Malcles, O., Vernant, P., Grosset, J., Damon, A., Le Bec, R.
67. Three Earthquakes in the Baltimore Gneiss. **McLaughlin, K. L.**
68. Spatial Distribution of the Mohorövicic Discontinuity Beneath Northeastern Mexico Based on Receiver Functions From Acceleration and Velocity Records. Montalvo-Lara, C. E., **Pérez-Campos, X.**, Montalvo-Arrieta, J. C.
69. Student: Maryland Seismicity: Insights From Moment Tensor Inversion With a Sparse Seismic Network. **Ravinsky-Gray, Y. A.**, Lekic, V.
70. Student: Magnetotelluric (MT) Upper Mantle Resistivity Structure of the Mississippi Embayment and Alabama-Oklahoma Lineament. **Sarker, K.**, Cramer, C.
71. Event Detection and Hypocenter Uncertainty Analysis of Induced Earthquakes the Rome Trough, West Virginia. **Schmidt, J. P.**, Carpenter, S., Wang, Z.
72. Student: Reassessing Tectono-structural Units and Crustal Thickness Variations in Southwest Cameroon Using Gravity and Seismic Data. **Stephane Landry, K.**, Franck Eitel, K.
73. Source Characteristics of the 2020 Mw 5.1 Sparta, North Carolina, Earthquake Sequence. **Wu, Q.**, Chapman, M. C.
74. 3D Shear-wave Velocity Structure of the North American Midcontinental Lithosphere. **Yang, X.**, Stevens Goddard, A., Liu, L., Li, H., Ridgway, K., Marshak, S.

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Abstracts of the Annual Meeting

Accuracy and Variability of Physics-based Ground Motion Modeling

Oral Session • Tuesday 15 April • 2:00 PM Local

Conveners: Evan Hirakawa, U.S. Geological Survey (ehirakawa@usgs.gov); Kim B. Olsen, San Diego State University (kbolsen@mail.sdsu.edu); William Stephenson, U.S. Geological Survey (wstephens@usgs.gov)

Toward a Multi-scale Community Velocity Model for California

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The Statewide California Earthquake Center (SCEC) Community Velocity models (CVMs) provide a great resource for ground motion modeling, but the accuracy of the resulting ground motions is limited by their generally coarse resolution. However, recent studies have shown that multi-scale models (e.g., models with varying resolution due to inversion strategies, ray path coverage, and data integrity) generated by combining locally imaged models into coarser reference models can significantly improve the fit between simulations and data (e.g., Yeh and Olsen, 2023; Zhang and Ben-Zion, 2023). Here, we assemble and test the ground motion prediction efficacy for a multi-scale CVM generated by embedding a series of high-resolution models from central and southern California into the SCEC CVM-S4.26M01 as the reference model. The high-resolution velocity models are generated from travel time tomography, joint inversion of short-period Rayleigh wave ellipticity, phase velocity, teleseismic receiver functions, and ambient noise cross-correlation from land and ocean-bottom recordings. We validate the assembled multi-scale CVM by comparison of seismic recordings from a series of local M4-5 earthquakes to physics-based simulations using the scalable 4th-order finite-difference method AWP-ODC (Cui et al., 2013) including surface topography (O'Reilly et al., 2022), anelastic attenuation (Withers et al., 2015), and a discontinuous mesh (Nie et al., 2017).

Development of a Data-driven Near-surface Velocity Models for the San Francisco Bay Area: Stationary and Spatially Varying Approaches

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In this presentation, we introduce two new sedimentary velocity models for the San Francisco Bay Area (SFBA) to improve near-surface shear-wave velocity (V_S) representation in large-scale broadband numerical simulations. The goal is to enhance the accuracy of sedimentary layer characterization in the Bay Area community velocity model. The first model uses only the time-averaged shear-wave velocity of the top 30 m (V_{S30}), while the second model applies location-specific adjustments to account for spatial variability. A dataset of 200 measured V_S profiles supports the development of both models, which are formulated within a hierarchical Bayesian framework to ensure robust scaling.

The spatially varying model incorporates a slope adjustment term, modeled as a Gaussian process, to capture site-specific effects. Residual analysis shows that both models remain unbiased for V_S values up to 1000 m/s. Along-depth variability models, derived from within-profile residuals, further refine the V_S predictions. Compared to the USGS Bay Area community velocity model, the proposed models predict up to twice as high V_S values in areas such as San Jose and the Livermore Valley.

Goodness-of-fit (GOF) comparisons, based on one-dimensional linear site-response analyses at selected sites, reveal that the proposed models outperform the USGS model by better capturing near-surface amplification across a broad frequency range. Incorporating along-depth variability further improves GOF scores by reducing over-amplification at high frequencies.

These results emphasize the importance of integrating data-driven shallow crust models, like those presented here, into regional community velocity models to enhance seismic hazard assessments in the SFBA.

Velocity and Attenuation Models of a 18km Section of Mississippi Embayment Sediments

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The lack of detailed knowledge about the velocity and attenuation models of the Mississippi Embayment sedimentary column increases uncertainty in determining whether the sediments amplify or de-amplify strong ground motion. This study focuses on developing quantitative velocity and attenuation models for a ~1 km thick sedimentary column of the Mississippi Embayment. It utilizes an east-west oriented ~18 km long profile consisting of 60 5-Hz nodal seismometers from a USGS piggy-back experiment associated with the Embayment Seismic Excitation Experiment 2022 (ESEE2022) which employed two 200-lb explosions as sources detonated 3 km apart. The profile captured high signal-to-noise ratio, accurately timed body wave and surface wave data. A 22-layer S-wave velocity model is derived from the fundamental mode Rayleigh wave dispersion. Travel time and slowness estimates from P and converted P-S wave body waves constrain the P wave structure. The first arrival, a P head wave from the basement, has a velocity of 6.28 km/s, while the velocities of Psed and Ssed are 1.96 km/s and 1 km/s, respectively. The body wave data constrain the deeper parts of the structure with an estimated basement depth of 1 km. Synthetic seismograms are computed from a wavenumber integration technique in an effort to match phase arrivals and amplitude-distance behavior to constrain both velocity and anelastic attenuation.

Distance-amplitude decay of the data indicates that shallow and deeper structures exhibit different anelasticity for P-waves with Qs being larger than Qp. Down to 160 m, Qp is 95; beyond that, it increases to 185. In contrast, Qs for S-waves is 190 across all depths. An interesting byproduct of the distance decay analysis that is matched with the synthetic seismograms is that the apparent attenuation modeled by a simple distance decay parameter is complexly related to the anelastic attenuation in the model.

SPE Rock-valley-direct-comparison Chemical Explosions Near-field 3D Ground Motion Simulations and Predictions

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Rock Valley Direct Comparison (RV/DC) is Phase III of the Source Physics Experiment (SPE). RV/DC includes two chemical explosion experiments. The first, RVDC-1, is a 1-ton equivalent TNT located at 1.8km depth, while the second, RVDC-2, is a 10-ton equivalent TNT located at 1.7km depth. The local geology of the site is complex and encompasses a deep hard-rock, dolomite starting at 1km depth, and the shallow 1km is a mixture of tuff and sedimentary layers, deposited under a rugged topography. The water table is located 500m deep. The layered beds are crosscut by a series of faults. The source package is sized to be 3.5 to 4.5 feet diameter emplaced in a 4 to 5 feet diameter ground-zero (GZ) borehole. The characterization of the geology is limited and includes one straight continuous core-hole (CH), and two directional observation boreholes (OB) cored as needed sporadically. Based on this complex geological conceptual setting, we have conducted 3-dimensional non-linear numerical simulations of the ground motions generated from both explosions. First, we used deterministic geophysical properties of the layered model and assessed the response of the system with and without the faults to assess their effect on the anisotropic radiation of the ground motions. Second, we have included stochastic variations in the geological layers. We adopted a scheme of including stochastic discrete fractures in the deep dolomite layer, while a continuous stochastic variation of lenses in the shallow geological layers. Assessing the effect of those stochastic parametrizations on the overall response of the system were obtained using a sophisticated interval Monte Carlo method. Material models have been calibrated to laboratory experiments and assessed under variably saturation conditions. Differentials of ground motion under different conditions of physical and structural uncertainties are then derived for both RVDC-1, RVDC-2, and a hypothetical earthquake.

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Are Empirical Models Adequate for Risk Estimation?

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Seismic hazard poses a significant risk in California, particularly in regions with complex fault systems and dense populations. Physics-based simulations developed by the Statewide California Earthquake Center (SCEC), such as the CyberShake project, enhance our understanding of ground motion impact by capturing critical phenomena like rupture directivity, waveguide effects, and 3D basin amplification—factors usually not included in empirical models. In addition, data at distances of less than 10-20 km from the faults, as well as for large magnitude events, are sparse, severely limiting the accuracy of Ground Motion Models (GMMs), usually used to obtain ground motion estimates for risk estimation. Preliminary results from CyberShake Study 22.12 in Southern California demonstrate the unique insights provided by physics-based models, highlighting key differences in ground motions compared to empirical models. For example, comparisons for a M6.85 Puente Hills rupture scenario suggest that leading NGA-W2 GMMs on average may overpredict the spectral accelerations at a period of 0.3 s and peak ground accelerations by up to 30% and thus lead to overestimates of building damage within a distance of 20 km from the fault. In addition, the physics-based simulations have the potential to reduce the uncertainty associated with the model space, in particular at longer periods considering source- and site-specific effects, as compared to ergodic GMMs at critical near-fault sites, allowing for more targeted policy making. Our analysis will be extended to additional scenarios and rupture variations for earthquake sources affecting downtown Los Angeles.

Evaluating Bias in Simulated Ground Motions for Moderate Magnitude Earthquakes in Southern California: A Study Using the Graves-Pitarka Method

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This study utilizes the Graves-Pitarka broadband ground motion simulation method, integrated within the SCEC Broadband Platform (BBP), to conduct finite fault simulations for 51 well-recorded moderate magnitude earthquakes in Southern California, with magnitudes ranging from M 3.95 to 5.55. The primary aim is to assess whether simulated ground motions exhibit bias when compared to observed data, focusing on Effective Amplitude Spectra (EAS) and Pseudo Spectral Acceleration (PSA). Building on previous findings by Nweke et al. (2022), which indicated systematic underprediction of low-frequency spectral accelerations, this study expands the scope by including additional events and broadband records (BBR) recordings from the Community Seismic Network and incorporating EAS in the analysis. Our results confirm the persistence of bias at frequencies below 1 Hz. Further examination of residuals indicated that while site and path-related biases do exist, they are relatively minor, leaving substantial bias unaccounted for even after these factors are considered. Therefore, we posit that the remaining bias is likely linked to earthquake source characteristics, particularly the empirical magnitude-rupture area scaling relationship used in the simulations, as proposed by Leonard (2010), which appears to falter for lower magnitude events. This hypothesis holds for the 2008 M 5.39 Chino Hills earthquake, though further validation is constrained by the lack of finite fault models to accurately establish rupture areas for other events in our dataset. Ongoing research is focused on understanding the effects of fault rupture area, stress drop, and average slip on the overall bias, and includes a sensitivity study of other earthquake source attributes, such as average rupture speed, on a case-by-case basis to explore potential solutions for the observed bias.

3D Broadband (0-25 Hz) Ground Motion Simulations for Statewide California

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The Statewide California Earthquake Center (SCEC) Broadband Platform (BBP) is an important tool for structural and geotechnical earthquake engineering applications, as well as for probabilistic seismic hazard analysis, with the capability to simulate ground motions up to 25 Hz. The BBP models scenario earthquakes by a combination of physics-based ground motion simulations at low frequencies (typically up to 1 Hz) and stochastic signals for higher frequencies. However, a notable limitation of this approach is the use of 1D velocity models for the low-frequency component, which do not capture the complexities introduced by 3D sedimentary basins and complex topography. These factors may significantly influence local peak ground motions and durations, potentially leading to inaccuracies in seismic hazard assessments.

To overcome these limitations, we have integrated into the BBP the 3D physics-based ground motion simulation code AWP-ODC with support for topography (O'Reilly et al., 2022), frequency-dependent anelastic attenuation (Withers et al., 2015), statistical distributions of small-scale heterogeneities (Savran and Olsen, 2016) and extended the physics-based simulations' maximum frequency to 2 Hz. We extract 3D velocity models for California using the SCEC Unified Community Velocity Model (UCVM) and compare ground motion predictions from 1D and 3D simulations to Ground Motion Models and recordings of the 1989 Loma Prieta, 2019 Ridgecrest and 1994 Northridge earthquakes in northern, central and southern California, respectively. Then, we simulate a series of M7-7.7 scenario earthquakes in California, combining the 3D deterministic simulations with stochastic signals up to 25 Hz. The results will identify and quantify deficiencies in existing hazard models and are expected to contribute to more accurate and comprehensive seismic hazard assessment across California.

Simulation of Ground Motions for the November 11, 2019, Mw 4.9, Le Teil, France Earthquake Using a Hybrid Approach

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The November 11, 2019, M_W 4.9 Le Teil earthquake occurred in the lower Rohn Valley of Southeastern France, a region characterized by moderate seismic activity. The earthquake resulted in surface ruptures (up to 15 cm uplift) despite its moderate magnitude. This event was located approximately 15 km from the Cruas nuclear power plant (NPP) and led to shutdown of the plant's operating reactors. At the initiative of the Institute for Radiation Protection and Nuclear Safety (IRSN) and the Électricité de France (EDF), and under the sponsorship of the Organization for Economic Co-operation and Development (OECD), an international benchmark program named SMATCH was launched in 2022. The aim of this benchmark is to assess, in the case of the Le Teil seismic event, the best practices for predicting seismic ground motions at the Cruas site and their propagation in the reactor building.

In this study, a hybrid approach is used to simulate ground motions of the Le Teil earthquake at five stations, including Cruas NPP, where earthquake recording from the event are available. These five stations are located within 25 km of the earthquake epicenter. The simulation combines a kinematic source modeling along with a discrete wavenumber/finite element wave propagation model (Spudich and Xu, 2002) for the low frequency part with a stochastic finite-fault simulation model (Tang et al., 2021) for the high frequency part of the ground-motion. The low and high frequency portions are combined to develop a simulated broad-band ground-motion using a matched filter centered at 3.0 Hz. The simulations aim to investigate the suitability of the approaches used in modeling the ground motions. Results of simulations at the five stations are compared with the ground motion recordings in terms of time histories, Fourier spectra, and response spectra. Potential improvements on the simulation are discussed based on the comparison.

How Many Earthquake-rupture Simulations Are Required to Quantify Epistemic Ground-Motion Variability?

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Modern probabilistic seismic hazard assessment increasingly relies on ground-motion simulations to quantify epistemic uncertainties. Seismic source characteristics — such as rupture length and slip distribution — strongly influence ground motion intensity, highlighting the need for comprehensive analyses of how rupture process variations affect the resulting shaking levels and their spatial distribution. Physics-based simulations (PBS) have become an essential tool for rupture scenario computations by solving the seismic wave equation, thereby also bypassing the ergodic assumption. However, PBS's high computational cost, especially for 3D Earth structure and frequency bands of engineering interest (up to 20 Hz), leads to a critical question: How many simulations are needed to accurately characterize the epistemic ground-motion uncertainties?

This study addresses the challenge of determining the optimal number of simulations for seismic hazard assessment across various locations and scenarios. Using a kinematic rupture generator, we simulate strike-slip and dip-slip earthquakes at magnitude 6.5. The radiated seismic wave fields are computed via a wave-number integration method in a 1D layered Earth model. We then use the resulting database of ~1600 simulations to quantify the standard deviations of seismic ground motion intensities. Based on these calculations, we estimate the number of simulations required to capture ground-motion intensity distributions within a specified confidence interval. Results reveal significant variability in the required simulations, ranging from a few dozen to thousands, depending on earthquake characteristics, the relative location of the station to the fault, and the adopted error margin for intensity estimation. For example, strike-slip earthquakes for stations aligned with the fault show high variability in peak ground velocity (PGV), requiring over 600 simulations to estimate the PGV distribution accurately. These findings provide a framework for optimized resource allocation and improved seismic hazard assessment using PBS-based approaches.

Repeatable Source, Path and Site Effects on Ground Motion Variability Based on Dataset From the Central and Eastern United States

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This study analyzes the repeatable source, path, and site effects on ground-motion variability using a dataset from the Central and Eastern United States (CEUS). We used the ground motion models (GMMs) developed by Pezeshk et al. (2018) for outside the Coastal Plain and Akhani et al. (2024) for inside the Coastal Plain to compute empirical residuals of the response spectral values. Our analyses used a combination of datasets from Goulet et al. (2014), Chapman and Guo (2021), and Thompson et al. (2023), which comprise horizontal peak ground acceleration (PGA) and spectral acceleration (SA) at periods ranging from 0.01 to 10 seconds. Total residuals were calculated as the difference between the natural logarithm of the observed ground motion and the natural logarithm of the ground motion predicted by the GMMs. The total residuals are used to identify the repeatable source, path, and site effects by removing the ergodic assumption. We used a mixed-effects regression algorithm to decompose the total residuals into between-event (δB_e) and within-event (δW_{es}) components. The study area (CEUS) was divided into a grid of 2 by 2 degrees, with each cell considered an individual region. We further partitioned δB_e into repeatable ($\delta L2L_r$) and purely random (δB_0) parts. Then, δW_{es} was split into between-station ($\delta S2S_s$) and event-site corrected residuals (δWS_{es}). δWS_{es} was divided into a systematic path term ($\delta P2P_{sr}$), and the remaining within-event residual δW^0_{es}. We also presented the epistemic uncertainties associated with each component and the pure aleatory variability (single-path standard deviation). The results show that single-path standard deviations are lower than those derived under the ergodic assumption. These findings can be applied to nonergodic probabilistic seismic hazard analysis (PSHA).

Accuracy and Variability of Physics-based Ground Motion Modeling [Poster]

Poster Session • Tuesday 15 April

Conveners: Evan Hirakawa, U.S. Geological Survey (ehirakawa@usgs.gov); Kim B. Olsen, San Diego State University (kbolsen@mail.sdsu.edu); William Stephenson, U.S. Geological Survey (wstephens@usgs.gov)

POSTER 79

Developing International Standards and Guidelines for Curating, Validating and Disseminating Simulated Ground-motion Data

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We are leading a working group within the Consortium of Organizations for Strong Motion Observation Systems (COSMOS) to develop international standards and guidelines for curating, validating, and disseminating simulated ground motion data for engineering applications. The scope encompasses all methods for generating simulated ground motions, including stochastic, three-dimensional wave propagation, and machine learning methods. We envision connecting geographically distributed data archives with a unified catalog to provide users with improved access to the simulated data through a standard interface.

Over the past three years, we have been building a worldwide community interested in producing or using simulated ground motion for engineering applications through special sessions, workshops, and presentations at various scientific and engineering meetings. Our current focus centers on forming three technical activity groups: (1) archiving and disseminating simulated ground motions, (2) validating simulated ground motions, and (3) utilizing simulated ground motions for engineering applications. The three groups will collaborate over the next one to two years to develop the international guidelines and standards. We expect the initial work will target a small set of representative vetted datasets to define standard metadata, validation metrics, and interfaces for searching and accessing the data. We want to link the application-specific validation metrics based on engineering design parameters, such as interstory drift, to features of the ground motions to make it easier for producers of simulated ground motions to improve their methodologies. Subsequent work will likely incorporate additional datasets and expand the metrics to accommodate additional engineering use cases.

POSTER 80

Sensitivity of Focal Mechanism and Depth of the 2024 M4.8 Tewksbury Earthquake to Seismic Velocity Model and the Impacts on Earthquake Ground Motions

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On April 5th, 2024, a magnitude 4.8 earthquake occurred in Tewksbury Township, New Jersey. The earthquake was felt by millions of people from Virginia to Maine and beyond and generated more than 180,000 U.S. Geological Survey (USGS) "Did You Feel It?" felt reports, the largest number of any earthquake. Ten percent of the reports came from New York City, 65 km east of the epicenter, and modified Mercalli intensities exceeded V within 10 km of the earthquake. There is significant uncertainty about how shallow the earthquake ruptured and modest uncertainty regarding the earthquake's focal mechanism. This combination of uncertainty impacts expectations for the frequency-dependent spatial variability of ground motions, hazard, and risk.

Ground-motion simulations of notable earthquakes in the central and eastern United States are limited and typically assume one-dimensional Earth structure. In this study, we use a three-dimensional seismic velocity model to investigate the spatial variability of earthquake ground motions and the effects of nearby sedimentary basins and the soft post-glacial sediments overlying hard basement rocks beneath New York City and elsewhere. We perform earthquake ground-motion simulations up to 0.5 Hz using the Cartesian version of the three-dimensional spectral-element wave-propagation solver SPECFEM3D over a region 280-km wide by 260-km long by 77-km deep.

Topography and subsurface geophysical structure are assigned using the USGS National Crustal Model and imposing a minimum shear-wave velocity of 200 m/s. Moving to a higher frequency and lower minimum shear-wave velocity is possible but would require greater computational resources and, at some point, a better-resolved velocity model. We use earthquake time-series from 13 broadband seismic stations in the region that have a relatively uniform azimuthal distribution and epicentral distances ranging from 76 to 131 km to compare with synthetics and explore the effects of topography and three- versus one-dimensional seismic structure on focal mechanism and depth solutions and discuss the impact on earthquake ground motions in the region.

POSTER 81

A New Ground Motion Model for Coastal Plain Region of the U.S Considering Sediment Thickness

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This study aims to derive adjustment factors for the median of the NGA-East ground-motion models (GMMs) targeting the Gulf Coast and the Coastal Plain of the United States. Within the region collectively referred to as the Coastal Plain, we formulate a set of adjustment factors based on sediment thickness and rupture distance. This study uses sediment thickness contour maps from Boyd et al. (2024) and a comprehensive dataset to compute residuals by subtracting the natural logarithms of observed data from those predicted by the median of the NGA-East GMMs. This dataset merges the NGA-East dataset (Goulet et al., 2014), the Chapman and Guo (2021) dataset, and the newly compiled and verified USGS dataset (Thompson et al., 2023). A mixed-effects regression separates total residuals into between-event and within-event components. Adjustment factors for stations within the Coastal Plain are derived by regressing within-event residuals using a functional form incorporating sediment thickness and rupture distance. The results indicate that the proposed adjustment factors effectively mitigate residual trends related to site and path terms across most periods for stations within the Coastal Plain. These findings apply to seismic hazard and risk assessments for sites within the Coastal Plain.

POSTER 82

Nonergodic Ground Motion Model for the Central and Eastern United States

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In this study, using the varying-coefficient model (VCM) and based on Gaussian processes (GPs) regression, we develop a nonergodic ground motion model (GMM) for the Central and Eastern United States (CEUS) based on backbone models. In the VCM method, the coefficients (nonergodic adjustment terms) vary spatially (based on earthquake and station location) and are estimated by Gaussian process regression. We use the GMM developed by Pezeshk et al. (2018) as a backbone model for areas outside the Coastal Plain and the GMM developed by Akhani et al. (2024) as a backbone model for areas inside the Coastal Plain. A benefit of developing nonergodic GMMs based on VCM is that the model can be smoothly extrapolated to large magnitudes and short distances, making the developed nonergodic GMM applicable for any event-station combination. The developed model contains a spatially varying nonergodic source term, a spatially varying nonergodic site term, and a spatially independent nonergodic site term. Individual coefficients are developed for each earthquake and station location, containing the median and the associated epistemic uncertainty of the coefficient. The aleatory variability of nonergodic GMMs is significantly reduced compared to ergodic GMMs. Additionally, in nonergodic PSHA, the median ground motion calculated by ergodic GMMs is affected by nonergodic terms. These changes in median GMMs and aleatory variability significantly impact the results of probabilistic seismic hazard analysis (PSHA) in CEUS, and the calculated hazard might increase or decrease compared to ergodic PSHA.

POSTER 83

Linked Earthquake and Tsunami Hazard Modeling on Puget Sound's Crustal Faults

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Shallow tectonics in the U.S. Pacific Northwest result in north-south compression in the Puget Sound region of Washington State. Much of this shortening is accommodated by deformation along shallow (depths ≤ 35 km), generally east-west striking crustal faults. Many of these crustal faults, including the Seattle Fault (SF) and Saddle Mountain Fault (SMF), underlie the Puget Sound and have produced earthquakes of ~M6.5–7.8 with subsequent tsunamis throughout the Holocene. Recent paleoseismic investigations found that the SF and SMF either ruptured separately within a span of six months or ruptured together as a combined, multifault rupture with an estimated magnitude of M7.8. An M7.8 multifault rupture is significantly larger than the previously-estimated upper bound for an SF earthquake (M7.5) and is not currently included in seismic hazard estimates for the region.

Here, we develop 3-D linked earthquake/tsunami simulations of potential multifault and single fault earthquake scenarios along the SF and SMF to quantify the range of expected shaking and tsunamigenesis, as well as the time-dependent impacts of these cascading hazards. We run 3-D physics-based kinematic ground motion simulations using the code SPECFEM3D Cartesian to generate synthetic seismograms resulting from these potential crustal fault earthquake scenarios. The results demonstrate that an M7.8 earthquake in the Puget Sound region would result in more ground shaking over a wider area and would put a much larger region at risk. Next, we simulate and propagate the tsunami waves that result from our synthetic earthquakes and seafloor displacements. To model these tsunamis, we use the GeoClaw and Method of Splitting Tsunamis (MOST) modeling softwares. Our "linked" earthquake and tsunami simulations allow for a time-dependent analysis of earthquake ground shaking and tsunami inundation from Puget Sound area crustal faults. This study aims to advance critical knowledge of seismic processes and hazards that may inform engineering standards and emergency response efforts, so as to better protect human life and infrastructure.

POSTER 84

Strong Ground Motions From Large Earthquakes on the Creeping Hayward, Rodgers Creek and Calaveras Faults, California

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Large earthquakes have a high likelihood of occurring in California in the next 30 years. Most of the faults these earthquakes may rupture are locked during the times between large events, but some creep, slowly slipping much of the time. In the San Francisco Bay area, significant creeping faults include the Hayward fault and its connected companions to the north and the south, the Rodgers Creek and Calaveras faults, respectively. These three faults have the highest probabilities of producing a large earthquake in this region, and because these faults occur in a densely populated area, they also pose significant seismic risk. We used the dynamic rupture method, as implemented in the finite-element software FaultMod (https://code.usgs.gov/esc/faultmod), and assumed the 3D San Francisco Bay area velocity model with elastic rock properties, slip-weakening friction, and initial stress conditions based on where the faults are creeping versus locked, to simulate 3 seconds and longer-period strong ground motions from large (M7) scenario earthquakes on these faults. The lowest shear-wave velocity we assigned to the rock properties in our models is 1950 m/s, so we used the Boore et al. (Earthquake Spectra, 2014) ground motion model with Vs30 set equal to 1950 m/s as a comparison. We show that our dynamic rupture simulation results produce reasonable agreement with the Boore et al. (2014) empirical relations.

POSTER 85

Development of a Peak Spectral Displacement Ground-motion Model Using Global HR-GNSS Observations

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Ground motion models (GMMs) are a key tool in the estimation of seismic hazard for engineering, describing the relationship between ground-motion intensity and predictive parameters such as magnitude and distance. GMMs most often utilize higher-frequency based intensity metrics such as Peak Spectral Acceleration (PSA). Peak displacement-based metrics are less common, as most intensity measures are derived from acceleration or velocity measurements from seismometers, which, as inertial sensors, pose uncertainties in lower-frequency measurements. However, these metrics are still important to assessing seismic hazard across the full frequency range generated from earthquake rupture. Advancements in high-rate global navigation satellite systems (HR-GNSS) have allowed for accurate measurements of dynamic seismic displacement directly up to 20Hz, and are now the basis of some peak ground displacement (PGD) GMMs. We present work towards developing a ground motion model for peak spectral displacement (PSD), using HR-GNSS observed waveforms. We develop GMMs for PGD as well as PSD, of interest for structures sensitive to low frequency energy, such as base isolators and long span bridges (among others).

We produce an expanded catalog of HR-GNSS waveform data, combining data from "DeGrande, J., & Crowell, B. (2023). Improvement in GNSS Magnitude Estimation Performance with a Combined PGD-PGV Scaling Law for Earthquake Early Warning. AGU23." with the Ruhl et al. (2018) dataset. The resulting catalog contains global observations from 75 M5+ earthquakes (2003 –2021). We compute the peak spectral displacements using a multi-taper method and perform a mixed effects regression on the resulting values to create our model. With this model we present, we will also examine the relative sensitivities of lower-frequency displacement-based metrics to source and site properties, to establish the most robust final functional form for these intensity measures.

POSTER 86

Preliminary Results of 3D Site Response Analysis in the Norcia (Italy) Sedimentary Basin

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As part of the INGV project PD-GEMME, 3D physics-based numerical simulations are carried through the spectral element code SPEED (http://speed.mox.polimi.it/), with the aim of investigating seismic wave propagation features within the Norcia sedimentary basin (central Apennines, Italy). In particular, the historic town of Norcia (Nursia), which has been settled within the basin since the fifth century A.D., was recently hit by the M6.5 earthquakes that occurred on October 30th, 2016. This extensional intermountain basin, measuring about 8x4 km, is filled with Quaternary fluvio-lacustrine sediments.

In this study we focus on i) a sensitivity numerical analysis based on a preliminary simplified geological-geophysical model of the area; ii) the definition of a numerical model suitable to reproduce the basin seismic response, including non-linear effects, in the high frequency range. The first goal is achieved using a homogeneous description of the sedimentary basin, whose 3D geometry is derived from Di Giulio *et al.* (2020). Seismic input is given by vertical-incident Ricker-wavelets with different dominant frequencies (0.5, 1 and 2 Hz), in order to assess the accuracy of the numerical simulation in different frequency ranges and for different boundary conditions. To fulfill the second goal, and therefore to improve the knowledge on the lateral and vertical variation of velocities within the basin, a series of new site investigations have been carried out including: 5 passive seismic arrays, 4 MASW investigations and a stratigraphic borehole with undisturbed sampling, where a downhole test is performed. The results of these investigations are combined with the available literature information, to develop a numerical model suitable to simulate ground motion with a frequency content reliable at least up to 5 Hz at each of the stations of the 3H-2009 network (Bindi *et al.*, 2011) as well as of the other permanent and temporary networks installed in the study area.

References
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Bindi *et al.* (2011) https://doi.org/10.1007/s10518-011-9273-3

POSTER 87

Ground Motion Characterization in Regions of "Intermediate" Attenuation

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For shallow crustal earthquakes, global ground motion models (GMMs) are generally grouped in two categories, those for "Active Tectonic Regions" (low Q, fast attenuation) and those for "Stable Continental Regions" (high Q, slow attenuation). The recent empirical GMMs developed for active tectonic regions take advantage of large strong motion datasets (e.g. NGA West2 and NGA East). While these datasets make use of strong motion data from around the world, they are mostly dominated by recordings from North America. These GMMs are often used to represent ground shaking in parts of the world where locally recorded data is sparse. However, in many cases, the attenuation in the source region (where strong motion was recorded) does not match the target region (too low or too high for the target region). This can be due to various reasons, including small- or large-scale geological differences. Where strong motion recordings are sparse, this poses a challenge in characterizing the ground motions for the purposes of seismic hazard assessments. We present how attenuation tomography studies and ground motion simulations can be useful in these cases, using case studies from regions where attenuation is neither as high as California or as low as eastern North America. We also highlight a case study from the Caucasus, which shows that the deviation of attenuation from global GMMs can be period/frequency-dependent.

POSTER 88

Region-specific Spatial Correlation Models for Ground Motion Intensity Measures in South Korea

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Seismic intensity maps, which depict the spatial distribution of intensity measures (IMs), are crucial for evaluating seismic disaster impacts after earthquake events. The ShakeMap system, developed by the USGS, is widely used to generate the intensity maps by interpolating the IMs spatially using a semi-variogram model. However, the default semi-variogram model pre-set in the ShakeMap, developed based on data from high seismic regions, may not be appropriate for the Korean Peninsula, which is classified as a low-to-moderate seismic region. The ground property of the Korean Peninsula is also characterized by shallow soil layers that amplify site effects in high-frequency ranges. This study aims to develop spatial correlation models tailored to South Korea using local seismic records and the region-specific ground motion model (GMM). We conducted the following steps to achieve this: 1) collect seismic data from 33 local earthquake events with $M_L \geq 3.5$, 2) calculate residuals between observed IMs and predictions from the region-specific GMM, and 3) construct semi-variogram models using weighted least-squares regression to improve the fit for short separation distances across IMs, including PGA, PGV, $SA_{0.2}$, and $SA_{1.0}$. Validation tests conducted on the 2017 M_L 5.4 Pohang earthquake scenario showed that the developed region-specific semi-variogram model reduced the mean squared error (MSE) of intensity predictions by approximately 3.5% compared to the default ShakeMap model. This result highlights that the developed models generate intensity maps more accurately reflecting the spatial variability of ground motion in South Korea.

POSTER 89

Analysis of Seismic Waves Amplification in Sedimentary Basins Using 3D Wavefield Simulation

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The geometry and low wave speeds of sedimentary basins trap seismic waves, leading to amplification and long-duration shaking. This seismic response of a sedimentary basin can be relevant both for understanding active tectonics and for assessing seismic hazards relevant to society. Using 3D seismic wavefield simulations on different models, we can explore how the basin depth and its boundary geometry affect the seismic waves amplitude, radiation patterns. Nenana basin in central Alaska is a promising region for studying basin wave propagation because its basement surface has been estimated from detailed active-source imaging and because there are about 15 broadband seismic stations in the region, enabling comparisons between simulations results (synthetics) and observations (data). We have created four Nenana basin region model: 1) the Berg et al. (2020) 3D tomographic model, 2) the Berg model with an embedded basin model, 3) a simplified model of an elliptical basin embedded in the Berg model. 4) a model with upper 8km from 1d velocity profile from Brocher2008 and bottom from the Berg model. By comparing and analyzing the seismic simulation results in both time and frequency domain from these models, together with the real data collected in this region, we can investigate the detailed mechanism of basin amplification for a variety of different seismic sources, 3-D basin geometry and frequencies.

POSTER 90

Near-fault Strong-motion of the 2023 Mw7.8 Kahramanmaraş Earthquake: Insights Into High-frequency Radiation Mechanisms

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Classic earthquake models can accurately explain the seismic wavefield below an earthquake's corner frequency. However, at higher frequencies, seismic radiation exhibits significantly more complex and stochastic characteristics. While various types of on-fault and off-fault complexity have been proposed to generate high-frequency radiation, their respective contributions and trade-offs remain the subject of ongoing debate.

The 2023 Mw 7.8 Kahramanmaraş earthquake provides a unique dataset to explore high-frequency radiation mechanisms. It was well recorded by a regional strong-motion network operated by the Turkey Disaster and Emergency Management Authority (AFAD), including 20 strong-motion stations within 10 km of the East Anatolian Fault. These near-fault stations, evenly distributed along the fault strike, captured seismic radiation emanating from the rupture front as it propagated southward.

In this study, we investigate the high-frequency characteristics of the Mw 7.8 southern rupture using these 20 near-fault strong motion stations. We find that most high-frequency signal energy arrives at these stations alongside the low-frequency signals, suggesting that the high-frequency radiation is generated near the fault rather than by medium scattering. Compared to their lower-frequency counterparts, seismic radiations above ~0.4 Hz display distinct characteristics: high-frequency signals do not maintain discernible radiation patterns, and the two horizontal components lose correlation, suggesting there may be multiple phases with different origins arriving simultaneously. Comparison with regional stations and back-projection analysis suggests that high-frequency generation information may be preserved even at distant stations.

Our findings imply a need to update our current earthquake source representations for modeling high-frequency radiations. The results of this study may provide valuable constraints for future theoretical work aimed at distinguishing different high-frequency radiation mechanisms.

POSTER 91

Validation of Shallow Crustal Structure in Northern California and Community Velocity Model Validation Using Ambient-noise-derived Rayleigh Wave Ellipticity and Receiver Functions

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Northern California has numerous active faults, including the Hayward Fault near the San Francisco Bay Area, which is prone to generating a devastating large-magnitude earthquake. An accurate three-dimensional (3D) seismic velocity model is an important component for accurately predicting ground motions upon realistic earthquake scenarios. In Northern California, the regional Northern California USGS seismic velocity model (USGS_SVM) was constructed for this purpose, and it has been iteratively refined using 3D ground-motion simulations, body wave travel times, and surface wave dispersion measurements to minimize discrepancies between model predictions and observations. Recent studies indicate that Rayleigh wave ellipticities (H/Vs) from ambient noise cross-correlations and a time delay of the first peak of receiver functions (RFs) could provide additional constraints on the shallow crustal structure that can further improve the existing velocity models.

We compute nine-component ambient noise cross-correlations using data from a combination of permanent and temporary stations in Northern California. This includes 200 broadband stations from permanent networks during January to March 2024 and temporary broadband and dense geophone arrays deployed during various time periods. Rayleigh wave H/V values are measured at periods of 6–26 s, producing period-dependent H/V maps. The maps highlight higher H/Vs in the Central Valley and Coastal Ranges and lower values in the Sierra Nevada and northern regions like Clear Lake. RFs, derived from teleseismic earthquake data collected by broadband and short-period stations available during 2014–2024 reveal significantly large first-peak delay times in the Central Valley and correlate well with H/V observations. Our comparisons of H/V and RF results with USGS_SVM predictions identify key discrepancies and areas for refinement, specifically in areas of the San Francisco bay and Mendocino Junction where observations suggest higher values to be considered. We will also present preliminary seismic velocity models by joint inversion of H/V and RF measurements.

Advanced Geophysical Observations, Analytical Methods, and New Insights for Earthquake Swarms

Oral Session • Tuesday 15 April • 2:00 PM Local

Conveners: Kyren R. Bogolub, Nevada Seismological Laboratory, University of Nevada, Reno (kbogolub@unr.edu); Xiaowei Chen, Texas A&M University (xiaowei.chen@tamu.edu); Jeffrey L. Fox, Ohio Geological Survey (jeffrey.fox@dnr.ohio.gov); Yu Jiang, Nevada Seismological Laboratory, University of Nevada, Reno (yujiang@unr.edu); Andrea L. Llenos, U.S. Geological Survey (allenos@usgs.gov); Krittanon Sirorattanakul, Chevron (krittanon.pond@gmail.com); Elizabeth A. Vanacore, University of Puerto Rico Mayagüez, Puerto Rico Seismic Network (elizabeth.vanacore@upr.edu)

The 2024 Mw7.5 Noto Peninsula Earthquake and Recent Earthquake Swarms in Japan Triggered by the Upward Migration of Deep Crustal Fluids

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Crustal fluids are considered a significant factor in upper plate earthquakes in subduction zones such as Japan. This hypothesis is supported by geophysical imaging techniques, including seismic velocity and electrical conductivity, revealing fluid-indicative anomalous regions beneath many intraplate earthquakes in Japan. These regions often extend from the subducting slab and are interpreted as concentrated regions of slab-derived fluids. Volcanic activity patterns and isotope ratios further support this interpretation. However, direct evidence linking deep crustal fluids to earthquake generation has remained indirect.

Following the 2011 M9 Tohoku earthquake, evidence of crustal fluid influence on earthquake generation increased significantly. The event reduced accumulated strain, yet earthquake swarms activated after a delay of several weeks, particularly near volcanic regions. These swarms migrated from deep to shallow depths along multiple fault planes. Beneath the source regions, low-velocity zones continuous with the slab and prominent reflectors were observed. These findings suggest that fluid migration within the upper plate was triggered, with ascending fluids subsequently activating earthquake swarms.

The foreshock activity before the 2024 Mw7.5 Noto Peninsula Earthquake showed striking similarities to these swarms, with seismic migration along multiple fault planes suggesting fluid-driven triggering from deeper to shallower depths. In the Noto Peninsula, active faults responsible for past tectonic uplift are widely distributed. The preceding swarm occurred on smaller-scale faults, distinct from the recognized active faults. Upward fluid migration, along with fluid-induced seismic and aseismic slip, likely triggered large fault slip, ultimately causing the 2024 event. Such processes may have contributed to the progressive maturation of active faults and the uplift of the peninsula over time. This case clearly demonstrates that when fluids intrude into a fault nearing failure, large slip events like the Mw7.5 Noto Peninsula Earthquake can be triggered.

Intermediate-depth Earthquakes Driven by Migrating Strain Localization in the Bucaramanga Earthquake Nest

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Intermediate-depth earthquakes occur in subduction slabs where extremely high pressures and temperatures make frictional slip unlikely. Understanding the mechanism potentially reveals a mechanical state of the fault zone and the origin of magma in subduction zones. Using a systematic methodology established for shallow earthquakes, we explore for the first time the fine-scale spatiotemporal evolution of intermediate-depth earthquakes within the Bucaramanga earthquake nest to obtain new insight into the physical mechanism from their recurrence intervals and locations. We first construct a high-resolution earthquake catalog through matched-filter detection using the largest 100 earthquakes as template waveforms and continuous waveform data in six years (2016-2021) from 13 stations operated by the Servicio Geológico Colombiano (SGC). Our catalog detects 71,621 events classified into smaller clusters based on the cross-correlation coefficients between the template and continuous waveform. Subsequently, we apply the second round of matched-filter detection for one cluster that records the largest number of detections in the first round. We observe a multi-year evolution of different earthquakes characterized by the number of events in one template family. Relocation of these hypocenters highlights a spatial migration over several kilometers toward the plate interface over several years, highlighting a continuously evolving forcing that drives earthquake activity within the Bucaramanga nest.

Benchmarking Remote Seismic Monitoring Against Local Seismic Monitoring of Hazardous Volcanoes: Application to the May 2021 Nyiragongo Eruption

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When seismic monitoring systems are available near regions of volcanic eruptions, relative locations of recorded earthquakes may provide important insights into the volcanic plumbing system and eruption dynamics. In May 2021, Nyiragongo volcano in the Democratic Republic of the Congo experienced a six-hour-long flank eruption recorded by Nyiragongo's local seismic network (KivuSNet, Smittarello et al., 2022). The seismic recordings from stations within KivuSNet facilitated a retrospective analysis (Smittarello et al., 2022) of seismic signals using a catalog of roughly 6,800 earthquakes with magnitudes (M) between M 0.3 and M 4.7. The catalog was used to investigate the progression of eruptive activity and document the timeline of magma withdrawal and dike propagation. However, unlike Nyiragongo, many volcanoes are located in regions where seismic instrumentation is limited or nonexistent. Seismic methods that facilitate distant detection, location, and characterization of volcano-related earthquakes must be tested and evaluated to improve the monitoring of hazardous volcanoes from afar. We present results documenting the contribution of surface-wave relative relocation and back projection to remote seismic monitoring of Nyiragongo's May 2021 eruption. We use the seismic catalog published by Smittarello et al. (2022) as a reference data set and surface-wave observations of earthquakes (> M 3) between May 22 and June 1 from several seismographic networks with stations located more than 190 km away. We validate the ability to precisely relocate more than 90% of the local catalog with epicentroid latitude and longitude uncertainties less than 1.5 km from the initial catalog locations. We continue to further our investigation by exploring the use of long-period signals in remote seismic detection and investigate how well we can capture the validated earthquakes using surface-wave back projection. If the locations and detections from both surface-wave analyses agree with local catalog locations, future research will explore method transportability to other volcanic regions with no local seismic monitoring.

Spatio-temporal Evolution of Seismicity Controlled by Damage Zone Architecture

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Seismic swarms and foreshocks occur both in laboratory experiments and on tectonic faults. However, their statistical properties and relation to the mainshock differ between the two: natural fault systems are dominated by Poissonian background seismicity, aftershocks and swarms, with rare foreshock activity; in contrast, laboratory experiments often produce a relatively quiescent interseismic phase and abundant foreshocks. To investigate these differences, here we use numerical earthquake cycle simulations to study seismicity patterns in a fault zone comprised of a main fault surrounded by damage, represented by an ensemble of discrete faults with a power-law decay with distance from the main fault. We find that during the interseismic period, seismicity takes place predominantly in the damage zone, and it consists of Poisson background events, episodic swarms, and foreshock sequences. The statistical behavior of seismicity varies systematically as a function of fault zone architecture: for broadly distributed damage, seismicity is dominated by background events and earthquake rates are constant in time, while more localized damage leads to an increase in temporal clustering. Clusters include aftershock sequences triggered by mainshocks on the main fault, isolated interseismic swarms, and accelerating foreshock sequences. Foreshock characteristics are also controlled by fault zone architecture: localized damage favors accelerating foreshock sequences and a progressive coalescence towards the main fault. Narrow damage zones produce a surplus of foreshocks relative to standard triggering models, as part of a cascade process and without requiring an aseismic precursor. These findings suggest that the abundance of foreshocks in laboratory experiments on smooth faults may due to the presence of narrow, rapidly decaying damage zones. On the other hand, broader and more slowly decaying damage produces episodic swarms and fewer foreshocks, consistent with seismicity in complex fault systems in nature.

Characterization of Seismicity Rates on the Megathrust and Sliver Fault in Southern Mexico With Potential Relationships to Aseismic Slip

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The Mexican subduction zone is considered a natural laboratory for studying slip processes due to the relatively short (~50 km) trench-to-coast distance which brings broad portions of the seismogenic and transition zones ~250 km inland. Slow slip events (SSEs) have been identified to occur downdip of the megathrust seismogenic zone where the friction style changes from stick-slip to stable sliding. A recent study by Fasola et al. (2019) found that correlated SSEs and seismicity in the Oaxaca Region also occurred on a crustal sliver fault that accommodates the partitioning of oblique convergence in Mexico. Thus this region provides an opportunity to pursue a detailed characterization of potential relationships between the seismicity and aseismic slip on a complex fault plate boundary system. In this study, we investigate temporal variations in seismicity rates using template-matching strategies to enhance seismic sequences cataloged over the years 2006-2022. Specifically, we use waveform correlation primarily focused on earthquake swarms to enhance the detection of smaller magnitude sequences not identified by the original catalog. This allows us to improve the detection of fluctuations in seismicity rates and their potential relationships to processes identified in geodetic data such as SSE or variations in interseismic coupling. Overall, this study aims to estimate variations in fault behavior during the earthquake cycle, characterize the seismic hazards presented by SSEs, and quantify how these hazards have varied over time in the Mexican subduction zone.

Advanced Geophysical Observations, Analytical Methods, and New Insights for Earthquake Swarms [Poster]

Poster Session • Tuesday 15 April

Conveners: Kyren R. Bogolub, Nevada Seismological Laboratory, University of Nevada, Reno (kbogolub@unr.edu); Xiaowei Chen, Texas A&M University (xiaowei.chen@tamu.edu); Jeffrey L. Fox, Ohio Geological Survey (jeffrey.fox@

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POSTER 109

Reexamining Historical Yellowstone Swarms Using a Relocated Earthquake Catalog From 1995-2023

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The Yellowstone region is the most seismically active area in the U.S. Intermountain West with an average of ~1,500 – 2,500 earthquakes per year. About half of Yellowstone seismicity occurs as part of earthquake swarms which have been attributed to processes such as hydrothermal fluid migration, magma injection or creep along faults. Swarms have been examined and relocated using a multitude of methods. We have generated a high-precision relocated earthquake catalog of over 50,000 events between 1995 and 2023 for the Yellowstone region. These relocations were done using NonLinLoc – Source Specific Station Terms with Coherence (NLL-SSST-Coherence), a nonlinear high-precision earthquake location method that builds on the conventional NLL method. The NLL source specific station terms are created iteratively using a 3D velocity model and waveform coherence is used to reduce arrival time errors. We compare swarm absolute locations from NLL-SSST-coherence with 1D routine locations produced by the University of Utah Seismograph Stations and with 3D relocations using standard NLL. Using a precise catalog allows us to examine in more detail the background seismicity and reactivations of swarms in highly active areas such as Yellowstone Lake and the Madison Plateau. Initial results show an improvement in location quality in almost all events and swarms converging on previously unobserved linear features. These findings suggest that using a more advanced location method for swarm events could reveal previously unobserved structures and dynamics of historical and modern swarms.

POSTER 111

Investigating an Earthquake Swarm in Ohio: Reactivation of a Large Precambrian Fault With a Destructive Past?

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On August 28, 2023, a ML 4.0 (Mw 3.6) earthquake occurred in northeast Ohio near a feature known as the Akron Magnetic Lineament (AML). This feature is thought to be a large throughgoing Precambrian fault identified on aeromagnetic anomaly maps, within the most seismically active region of the state. Since the main shock in 2023, more than 70 earthquakes of magnitude ML 1.0—2.8 have been recorded in the epicentral area. Through waveform cross-correlation (template) matching, more than 500 additional earthquakes have been observed. The sequence does not follow typical mainshock–aftershock magnitude rate decay (Omori's Law) but does demonstrate correlation with Båth's Law. Earthquakes are still occurring regularly at the time of this writing. In July 2024, the Ohio Seismic Network set up a temporary seismic station directly over the epicentral region of the swarm, and it has recorded dozens more earthquakes. The AML was the site of a destructive ML 5.0 earthquake in 1986, only 7 km south along strike from the current activity. This recent seismic activity has gained much attention from the local citizens after the mainshock (ML 4.0) in 2023 caused minor damage to local wineries. Over 1,600 Did-You-Feel-It (DYFI) reports have been generated from the ongoing seismic activity in this swarm, as the local population has become very sensitive to the shaking. The Ohio Seismic Network continues to monitor and analyze this surge in seismic activity to assess its causes and determine whether this is a swarm or a typical mainshock–aftershock sequence.

POSTER 112

Seismic Swarm Dynamics in the Atacames Region, Ecuador

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The April 2016 Mw 7.8 Pedernales megathrust earthquake offshore central Ecuador triggered a seismic swarm 8 months later, approximately 70 km northwest of the epicenter, in the Atacames region. The northern part of the megathrust ruptured in 1906 (M 8.8) and 1958 (M 7.6). The Atacames swarm includes 278 events (Ml <1 to 5.8; depths ~2 to 18 km) between December 2 and 28, 2016. Four events ≥Ml 5 contributed to ground shaking that damaged buildings in the region. The swarm was recorded by a dense network of temporary stations deployed as a rapid response effort to the Pedernales mainshock. Using PhaseNet and GaMMA, we built a catalog of 8 P and 6 S phases and located the 278 events using NonLinLoc and HypoDD. The shallow seismicity aligns along a south-dipping structure above a high-velocity basement uplift, imaged in a 3D tomographic inversion, suggesting activation of a previously unrecognized crustal fault. The swarm evolved through three distinct bursts of seismicity separated by quiescent phases. The first burst (December 2–3) included 9 events in a localized central area. The second burst (December 10–14) included 45 events and expanded westward and eastward. The third and most significant burst (December 19–28) contributed over 75% of the total events, migrating northeast and deeper. The spatiotemporal evolution of epicenters suggests dynamic processes, including stress redistribution, localized fault slip, and potential fluid migration. Waveform cross-correlation identified 26 event families and three repeaters, signifying repetitive rupture processes likely driven by localized stress reloading or pore pressure changes. While these observations are consistent with fluid-related mechanisms, ongoing investigations aim to refine our understanding of their specific role in driving seismicity. The Atacames swarm highlights the need to include moderate-magnitude earthquakes along crustal faults, in addition to the rupture of the megathrust, in hazard assessments in general, and as part of earthquake sequences following large ruptures like those in the last two centuries.

POSTER 113

Improved Characterization of Earthquake Sequence Patterns in the Mexican Subduction Zone Using Seismogram Correlation to Enhance Detection of Smaller Seismicity

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In the past decade, there has been a staggering ten magnitude 7 or larger earthquakes in Mexico, while detailed studies have identified earthquake swarms are also prominent in this region. Ventura-Valentin et al. (2024) generated a catalog of 667 sequences with at least 10 clustered earthquakes in the 2012-2022 Mexico SSN catalog using the approach of Zaliapin & Ben-Zion (2013). They developed an automated characterization of these sequences to help distinguish which are mainshock-aftershocks and which are swarms. However, nearly half of the sequences have less than 15 events, making it difficult to understand their behavior. To investigate whether undetected smaller events could enhance our understanding of these sequences, we sought to apply the template-matching form of seismogram correlation to improve the detection of events in each sequence. We developed an efficient strategy for determining the cross-correlation threshold for positive detections at a single station based on statistical deviation from the background rate of detection for spurious noise.

Of the 100 sequences we focused on, template matching produced a change in characterization type for approximately half of the sequences (change greater than 0.3 units on the automated rating scale). We then explored template matching of the sequences over the full 10 years which revealed 3 general temporal patterns of seismic activity associated with the patches of fault the sequence represents. Approximately two-thirds of the sequences showed evidence for episodic activity over the longer time frame, with other sequences showing activity that was either isolated to the time frame of the original sequence or ongoing activity every month of the 10 years. However, we also identified that some sequences match with each other, indicating spatial proximity and potential relationships that make sequence characterization more complicated. To address this, we explored the relative influence of swarm-like behavior, similarity with nearby sequences, and distance from the station on the overall productivity of the template matching.

POSTER 114

Microseismicity and Fault Structure in the Daliangshan Subblock within the Southeastern Tibetan Plateau

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The Eastern Himalayan Syntaxis (EHS) is a critical region for understanding the interactions between tectonic stress, geothermal activity, and seismic behavior. Despite its significance, previous studies have been hindered by harsh environmental conditions and limited seismic station coverage, resulting in incomplete earthquake catalogs and insufficient analysis of fluid-induced seismic activity. This study addresses these gaps by constructing a high-resolution earthquake catalog for the EHS over 20 months (2023–2024) using deep learning and template matching techniques. Key findings include the identification of three major earthquake swarms (Bianba, Bomi, and Luolong), each exhibiting distinct spatiotemporal evolution patterns and fault geometries. The study reveals that fluid diffusion and aseismic slip are primary drivers of swarm activity, with complex fault geometries and permeability structures playing a critical role. The Bianba swarm showed multiple migration fronts with varying fluid diffusion rates, while the Bomi swarm demonstrated characteristics of aseismic slip-driven activity. Stress perturbations and Coulomb stress interactions were found to significantly influence seismicity patterns, especially in the Luolong swarm. This manuscript provides a unique contribution by integrating advanced seismic analysis methods to elucidate the mechanisms driving swarm evolution in a tectonically and geothermally complex region. The findings have implications for understanding the interplay between fluids, faults, and seismic activity in geologically dynamic settings.

POSTER 115

Automated Detection and Characterization of Swarms and Mainshock-aftershock Sequences in Nicaragua and Costa Rica

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A new methodology for the automated identification and characterization of swarms and Mainshock-Aftershock (MsAs) sequences was recently developed and applied to seismicity in the Mexico subduction zone (*Ventura-Valentin et al.*, in review). This method uses a nearest neighbor approach to identify clusters (*Zaliapin & Ben-Zion*, 2013) and then integrates five quantitative characteristics derived from Omori, Båth, and Gutenberg-Richter laws to differentiate swarms from MsAs. Specifically, the algorithm calculates these attributes: magnitude difference, mainshock order, rate decay, magnitude decay, ratio of magnitude range to number of events. Intriguingly, the analysis in Mexico found twice as many swarms as MsAs. Our project is investigating whether this method produces a similar result in the nearby portion of the Central American subduction zone in Nicaragua and Costa Rica.

Using publicly available catalogs for this region, our preliminary results indicate the opposite: there were about twice as many MsAs as swarm sequences in Nicaragua and Costa Rica. Individual sequences were manually reviewed to confirm that automated ratings of sequence types was appropriate. MsAs were more common offshore and associated with the subducting plate interface, although some were also common near inland volcanoes. Alternatively, swarms were more common along the inland sliver fault and also near some volcanoes such as Poas in Costa Rica. Swarms were also more common along sliver faults in Mexico, indicating some similarity in origin but there is notable a difference in swarm productivity between the two regions.

POSTER 116

Seismicity Characterisation in the Mount Cameroon Region

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Mount Cameroon is an active volcano rising to almost 4100 m above sea level on Cameroon's south-western coast on the Gulf of Guinea. Over the past century, it has experienced 7 major volcanic eruptions, the most recent of which occurred in 1999 and 2000. Its volcanic eruptions are usually preceded by a major seismic crisis, with seismicity rising from an average of 30 events in the quiescent period to over 100 events per month as an eruption approaches. At the end of the year 2010, over a period of almost 3 months, we witnessed an increase in seismicity, with a peak of just under 200 events reached in September, yet no eruption followed. In order to better understand the physical phenomena behind this crisis, we therefore proposed to use a seismological statistical approach, in this case the non-stationary ETAS model and the analysis of the magnitude distribution, to characterize this seismicity. The b value, considered as one of the important parameters representing the nature of earthquake occurrence and characterizing the state of stress in the crust was found to be high. The background rate, obtained from the inversion of the non-stationary ETAS parameters, reveals a slow transient deformation with gradual onset. The computation of the forcing rate show so far that almost 55% of the seismicity is due to an external process like fluid intrusion.

POSTER 117

Rapid Migration of Seismic Swarms in the Central-north Ecuadorian Subduction Zone Revealed by Deep Learning and Dense Seismic Arrays

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The Ecuadorian subduction zone has hosted multiple Mw 7.7–8.8 megathrust earthquakes (1906, 1942, 1958, 1979, 2016), with the 2016 event re-rupturing the 1942 patch. Many seismic swarms and slow-slip events related to structures in the subducting and the overriding plates have occurred along this margin. During 2016-2017, swarm-like aftershocks were recorded by temporary and permanent stations up to ~90 km inland. Nodal arrays were deployed in 2020 and 2022, and 59 broadband stations operated in 2021-2022 from the coast to the Andes foothills. Between 15 March and 9 April 2022, we detected and located more than 200 earthquakes (excluding the 2022 Atacames mainshock–aftershock sequence) using deep-learning-based methods. These events were further refined in a high-resolution 3D velocity model derived from the nodal arrays and relocated with the HypoDD algorithm, producing an unprecedentedly detailed image of local seismicity.

Offshore seismicity occurred in both the southern and northern 2016 slip patches. On 16 March, a two-hour swarm (M < 2) began at shallow depths (< 5 km) in the overriding plate, then extended to 10–25 km in the subducting plate, migrating northward over time. On 17 March, a 2.5-hour swarm (M < 4) occurred in the northern slip patch of the 2016 rupture area, with events deepening with time from ~10 to 30 km across the plate interface and migrating north. The northern swarm follows a U-shaped pattern similar to the near-trench re-entrant scarp of the Atacames seamounts, above and on the eastern front of a high-velocity zone (Vp 7.6–8.0 km/s), likely reflecting the roots of the seamounts. Migration velocities of the events (~9 km/hr southern swarm and ~6 km/hr northern swarm) over short durations indicate slow-slip-driven behavior near the threshold for fluid-driven mechanisms. Neither sequence fits a hydraulic diffusion model; instead, they appear self-driven, with each new rupture nucleating near the high-stress tip of the previous one. Rapid swarm migration likely reflects stress transfer between adjacent ruptures, likely aided by aseismic slip.

POSTER 118

Geophysical Case Studies of Buildings in Tehran Against Earthquakes

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Earthquakes are natural phenomena that occur annually in various parts of the world, leading to significant human and financial losses. Since earthquake engineering cannot precisely predict the time, location, or intensity of earthquakes, one of the primary strategies to mitigate earthquake damages is proactive preparation and the identification of vulnerable structures. Structural retrofitting efforts, based on scientific and technical solutions, are essential for urban development, though the approaches vary across regions. Iran, situated within the seismically active Alpine-Himalayan belt at the collision boundary of the Eurasian and Arabian plates, is highly prone to earthquakes.This research investigates the seismic vulnerability of government buildings in

Tehran using geophysical assessments. For each seismic vulnerability evaluation method, specific criteria were selected based on their importance and drawn from previous validated studies. The data collected were analyzed using analytical and descriptive methods, with tools such as MATLAB, GMT, Saizen, statistical programs, and Excel.The findings confirm that probabilistic seismic risk assessment maps are highly effective as predictive tools. The satisfactory alignment of conventional results with those obtained through the newly processed method indicates the reliability of this approach. The research demonstrates that real-time probabilistic seismic hazard assessments can be achieved, with updates incorporating the probability of seismic sources within shorter temporal and spatial intervals. These updated assessments are highly valuable for risk analysis processes. Future research can enhance these models by incorporating smaller time frames for seismic source probabilities, improving both the robustness and accuracy of earthquake,occurrence predictions.

POSTER 119

Investigating Potential Relationships Between Rates of Seismicity, Strain Accumulation, and Slow Slip in the Oaxaca Region of Mexico

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Recent research has suggested that seismicity may be more likely during slow slip episodes (SSEs). The Mexico subduction zone is an ideal location for studying the interaction between slow slip events and earthquakes due to the region's frequent seismic activity. In fact, there have been notably ten magnitude 7 or larger earthquakes from 2012 to 2022. GNSS time series data from seismic stations near Oaxaca, Mexico has revealed a variety of SSEs and that the rate of strain accumulation associated with subduction has varied in between SSEs. Analyzing GNSS data from an inland and a coastal station from the years 2004-2021, we compared the geodetic rates of motion with estimates of the seismicity rate in neighboring regions over the same time frames. Our preliminary results indicate that there are no strong relationships between either the rate of slow slip or the rate of strain accumulation with the concurrent seismicity rate. However, we do observe a weak correlation between the seismicity rate and the geodetic velocities during both SSEs and strain accumulation at the coastal station. Additionally, both stations showed a strong negative relationship between the duration of an SSE and the concurrent geodetic velocity, suggesting there are SSEs with slower slip rates that last longer.

Advancements in Forensic Seismology and Explosion Monitoring

Oral Session • Thursday 17 April • 8:00 AM Local

Conveners: Richard Alfaro-Diaz, Los Alamos National Laboratory (rad@lanl.gov); Louisa Barama, Lawrence Livermore National Lab (barama1@llnl.gov); Miles Bodmer, Sandia National Laboratories (mabodme@sandia.gov); Brandon Schmandt, University of New Mexico (bschmandt@unm.edu); Julien Thurin, University of Alaska Fairbanks (jthurin@alaska.edu); Cleat Zeiler, Nevada National Security Site (zeilercp@nv.doe.gov)

A New Paradigm for Nuclear Explosion Monitoring of Test Sites and Broad Areas: Full Waveform Inversion Tomography and Moment Tensor Inversion With 3D Greens Functions

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Advances in the workflow for full waveform inversion (FWI) tomography, improved open broadband waveform data sets and more powerful high-performance computing (including GPU accelerated platforms) now make it possible to easily develop three-dimensional (3D) seismic Earth models for improved simulations of complete waveforms. Regional- and continental-scale FWI models enable physics-based simulations of observed complete waveforms including path-specific propagation effects of wavespeed heterogeneity. Forward waveform simulations in 3D models can provide Greens functions (GFs) for source inversions to estimate the moment tensor, seismic moment (and magnitude) as well as depth and location. This presentation will demonstrate how FWI tomography models can be obtained with modern workflow tools and openly available broadband waveform data. The resulting models improve waveform simulations for earthquakes and nuclear explosions. We show how reciprocity can be used to precompute databases of Strain Greens Tensors for use as receiver-side GFs. Precomputation of databases liberates operational pipelines from dependence on "on demand" HPC for event-specific analysis. Such databases can provide GFs via HDF5 file or web-services queries (e.g. InstaSeis). Rapid access of GFs enables stochastic inversions (e.g. Random Walk Hastings-Metropolis, Hamiltonian Monte Carlo) for source parameters with their improved representation of posterior probabilities (parameter variance and covariance). We propose that FWI models can be developed for nuclear test sites and broad areas enabling moment tensor inversion with improved accuracy provided by better representation of path-specific propagation effects. Stochastic inversions of source parameters with improved parameter uncertainties and covariances support quantitative source-type characterization that compliments traditional identification and magnitude/yield estimation.

Bayesian Optimal Experimental Design With Constraints for Seismo-acoustic Sensor Networks

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Bayesian optimal experimental design (OED) offers a principled framework for designing sensor networks that maximize the information gain about critical monitoring objectives, such as event location and magnitude. Our presentation will address two significant challenges in Bayesian OED that arise in realistic monitoring scenarios: the impact of emplacement constraints and sensor budgets on network performance, and the integration of heterogeneous sensors differing in fidelity and sensing modality (e.g. seismic vs. infrasound). These complexities require the development of advanced optimization methods to enhance our OED workflow, ensuring robust and efficient sensor network design. We demonstrate our approach using a local seismic monitoring case study in Nevada, leveraging existing sensor networks and well characterized earth models to explore the proposed methods.

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Bayesian Inference for the Seismic Moment Tensor Using Regional Waveforms and Teleseismic-P Polarities with a Data-derived Distribution of Velocity Models and Source Locations

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The largest source of uncertainty in any source inversion is the velocity model used in the transfer function that relates observed ground motion to the seismic moment tensor. However, standard inverse procedure often does not quantify uncertainty in the seismic moment tensor due to error in the Green's functions from uncertain event location and Earth structure. We incorporate this uncertainty into an estimation of the seismic moment tensor using a data-derived distribution of velocity models based on complementary geophysical data sets, including thickness constraints, velocity profiles, gravity data, surface wave group velocities, and regional body wave travel-times. The data-derived distribution of velocity models is then used as a prior distribution of Green's functions for use in Bayesian inference of an unknown seismic moment tensor using regional and teleseismic-P waveforms. The use of multiple data sets is important for gaining resolution to different components of the moment tensor. The combined likelihood is estimated using data-specific error models and the posterior of the seismic moment tensor is estimated and interpreted in terms of most-probable source-type.

From Source to Receiver: Numerical Simulations of Underground Explosions, Cavity and Chimney Formations, Subsurface Gas Transport and Prompt Atmospheric Releases

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Radionuclide monitoring is complementary to seismic, hydroacoustic, and infrasound monitoring techniques used in verification, and it is the only one that can discriminate and confirm whether an explosion is indicative of a nuclear explosion. To understand radioactive noble gas prompt releases from underground nuclear explosions, their atmospheric transport to monitoring stations, and to discriminate nuclear explosion generated radioisotopes from those, generated and released by nuclear reactors, or radionuclide generators, one must accurately and numerically simulate the explosion phase, the interaction of the explosive energy released with the fractured hosting rock, and cavity formation, the radionuclide generation and their circulation within the cavity, and the eventual prompt release or seepage of the radionuclide gases to the atmosphere. LLNL has, therefore, developed an HPC-based numerical framework to simulate, from source-to-atmosphere, the gas releases by coupling a non-linear explosion hydrocode to a geomechanical code that converts explosion-induced damage to rock permeability, key parameter to subsurface and surface coupled gas transport codes. The resulting releases source to the atmosphere is then used as an input to a global atmospheric circulation code to reach the monitoring stations. We numerically illustrate the onset of the different regimes and their combined effect of flow, heat and mass transport of different gas species, the fraction of molten rock and their impact on the noble gas fractionation. We also present a sensitivity analysis of the effect of heat loss and cooling to the adjacent rock formation. We demonstrate several scenarios of prompt releases to the atmosphere using a first-ever fully coupled prompt subsurface-to-atmospheric transport without ad-hoc boundary conditions between different numerical codes. We illustrate, using hypothetical explosion scenarios, the benefits of the proposed approach versus the conventional ones.

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Variable Global Grid Refinement and Prediction Using RSTT Model

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Regional seismic travel time (RSTT) is a global model (Myers *et al.* 2010, Begnaud *et al.* 2021) that rapidly predicts travel times of regional seismic phases (Pn, Sn, Pg and Lg), while accounting for key effects of the 3-dimentional crustal and upper mantle structures on the regional travel times. Previous versions of RSTT model utilizes, a model grid of constant one-degree cells and in a recent study Babikoff *et al.* (2022) focused on Israel and the Middle East, showed that iterative data driven grid refinement improves the resolution of P wave (Pn and Pg) tomography in the tectonically complex region. We are further refining the methods outlined by Babikoff *et al.* (2022) to improve the travel time tomography of regional seismic phases globally to explore the effects of model parameterization with the iteratively decreasing grid sizes as well as trade-offs relating to the retrieved crustal and upper mantle velocity structures.

We conducted tomography for upper mantle Pn velocity and Pn gradient iteratively on a global scale at grid resolutions of 1.0°, 0.5°, 0.25°, and 0.125°, systematically varying the damping and smoothing parameters to determine their optimal values using the L-curve method. We also solved for the event term at each grid level after identifying the most appropriate tomography parameters from the above step. At each grid level, we removed phase arrivals whose travel-time residuals exceeded 3 standard deviations from the mean. We observed 7.6% reduction in root mean square from the 1° grid to the 0.125° grid and as the grid spacings decreases, robustness of smaller tectonic features in data-rich regions such as western US, Alaska, western Europe, Middle East, and Japan vastly improves, increasing the confidence of the model for accurate event location. We are conducting Pn travel time prediction using the global RSTT models developed using the variable grid refinement method.

Integrating Machine Learning for Near-real-time Earthquake Monitoring and Public Notification

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An earthquake early warning system is essential for providing timely information to the public during an earthquake. This information is valuable to various organizations, including stakeholders and research teams, where accuracy and speed are crucial. Because machine learning has emerged as a powerful tool for phase picking, event locating, and event discrimination, we developed a near-real-time earthquake monitoring system that uses machine learning for phase picking (PhaseNet) and event discrimination through audio parameter extraction from waveforms using Random Forest (RF) and Support Vector Machine (SVM) models. This study focuses on the evaluation of the method used in the event discrimination (SVM and RF) and discusses the application named SeismicBox2, a mobile application for notifications, as part of the monitoring system.

The system was tested with three months of continuous data (November 2023 to January 2024) from the Madagascar local seismic network. The created models (RF and SVM) were trained, validated, and tested using waveforms from 153 mining/quarry blasts and 2339 earthquake events. Both RF and SVM models achieved an average accuracy of 0.99, with precision, recall, and F1 scores of 0.99 for both quarries and earthquakes. The developed model successfully predicted event nature from the three-month data, leading to the discovery of new mining sites. Meanwhile, the SeismicBox2 application provided comprehensive information to the public, including the earthquake information, waveforms with the arrival times, USGS ShakeMap, exposed population numbers, and optional comments with GPS coordinates. While the system has shown promising results, its performance is limited by the number of monitoring stations. Expanding the network of stations is anticipated to enhance the overall effectiveness of the system.

An Efficient Subspace Detector for Rayleigh Waves, Demonstrated Against Explosions

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We develop and validate a Rayleigh waveform detector that we derive from a hypothesis test between two competing, approximate models for elliptically polarized, three channel seismic data. Our algorithm processes these data with sliding windows to output continuous estimates of source back azimuths and ~45 data products that it fuses from multiple frequency bands, at computational speeds comparable to energy detector algorithms. The sliding windows adapt to consume a fixed number of waveform cycles per frequency band and automatically adjust trigger thresholds to maintain fixed false alarm rates against noise. We summarize five tests that demonstrate these capabilities against both synthetic Airy phase seismograms and real, explosion-triggered waveforms sourced in Ukraine. These experiments demonstrate reliable detections against explosions and accurate estimates of source back-azimuths that we cross-validate with the Stockwell transform and an event catalog. Performance curves that measure the true positive rate of the detector against real sources indicate that our algorithm provides very reliable detection rates for cataloged explosions, beyond 50 km. Median errors and uncertainties in our back-azimuthal angles indicate a good localization capability. We provide physical, statistical, and computation justifications for our algorithms.

Differential Seismic Phase Detection Probability as a Potential Attribute for Discrimination of Explosions and Earthquakes

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Deep learning models trained to estimate the probability of seismic P and S phases are rapidly expanding the scale of event detections. Here, we evaluate the potential for phase detection probabilities to contribute to event type classification, particularly discrimination of single-fired borehole explosions and earthquakes at local distances of <300 km. Motivated by the empirical success of P/S amplitude ratios for explosion discrimination, we consider the difference between P and S pick probability, P_{prob} - S_{prob}, as a discriminant. Test data include M_L~1-4 earthquakes and explosions observed by common seismographs in ten geologically diverse localities. PhaseNet (Zhu and Beroza, 2019) trained with STEAD (Mousavi et al., 2019) shows higher P_{prob} - S_{prob} for explosions than for earthquakes. Binary classification with PhaseNet P_{prob} - S_{prob} with at least 3 stations yields a Receiver Operating Characteristic area under the curve of 0.85, compared to 0.88 for P/S amplitude ratios. Although the performance is slightly lower, P_{prob} - S_{prob} is efficient as an automated byproduct of event detection and use of phase probability avoids the binary choice of picking or not picking weakly visible S waves that are common to explosions. The results generally suggest that phase pick probabilities may be useful event classification attributes.

Probabilistic Source Type Analysis with Applications to Seismic Source Classification

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Moment tensor estimation provides critical information on seismic mechanisms and magnitudes, enabling classification of seismic events. The moment tensor, a 3x3 symmetric matrix, represents three orthogonal dipoles whose magnitudes and orientations define the source mechanism. It can be decomposed into an eigenvalue and a rotation matrix, with eigenvalues analyzed on the lune source-type diagram. The lune provides a natural setting for source classificaton. On this diagram, explosions, earthquakes, and collapses map to distinct regions: positive isotropic sources (+ISO or explosions) at the top, negative isotropic sources (-ISO or collapses) at the bottom, and double-couple (DC or earthquakes) at the center. Traditional classifications relying on single-point solutions are limited, as uncertainties often span boundaries and source types. We present a probabilistic framework that incorporates these uncertainties, represented as probability density functions (PDFs) on the lune. Two methods are explored: (1) sampling posterior PDFs to compute conditional probabilities for source types (e.g., P(+ISO), P(-ISO), P(DC)), and (2) modeling the PDF as a mixture of elementary probabilistic source models. These approaches enable robust classification and uncertainty quantification, supporting automated moment tensor analysis and event screening. We validate the methodology using seismic events, including earthquakes, collapses, and the North Korean nuclear tests.

Seismic Source Characterization: Context to Confidence

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We develop a probabilistic framework that advances the characterization seismic events through robust uncertainty quantification and fusion of multiple data streams. We present two complementary methods: (1) source identification through contextual data fusion, and (2) probabilistic estimation of explosive yield and depth of burial. We employ probabilistic programming to structure and exchange information across diverse data categories via hierarchal modeling. These methods are transportable across geologically diverse region overcoming limitations of conventional techniques. Unlike traditional techniques our framework provides quantitative measures of uncertainty enabling more informed decision-making for seismic monitoring applications.

New Constraints on Seismic Source Type Evident in 3D Waveform Inversions, Application to Remote Historical Nuclear Explosions in Western China

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Using historical nuclear tests from Western China, we compare the performance of legacy 1D and new 3D Earth models in scenarios involving sparse station coverage, low signal-to-noise ratio, and complex local geology. In such challenging circumstances, conventional best-fitting inversions fail to reliably constrain moment tensor source type. Detailed uncertainty analysis using the Moment Tensor Uncertainty Quantification (MTUQ) software package highlights the pronounced nonuniqueness of conventional 1D inversions, with error bars spanning nearly the entire space of source types. By using 3D Earth models and jointly inverting multiple data types, however, we show that well-constrained solutions are possible. This enhanced resolution allows for additional experimentation with source wavelet selection and moment magnitude analysis. These results highlight the complimentary character of body waves, Rayleigh waves, Love waves, and first motions for constraining source type, and point to the emergence of entirely new constraints in 3D inversions. Particularly striking are new Rayleigh wave constraints, which persist even with highly lopsided stations distributions and thus appear distinct from radiation pattern constraints that tend to dominate 1D inversions, and new Love wave constraints on moment tensor trace, which are completely absent from 1D inversions.

Characterization of Road Construction Explosions Recorded Along an Ocean-bottom Fiber With Distributed Acoustic Sensing

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Ocean-bottom Distributed Acoustic Sensing (DAS) arrays offer a novel approach to densely sample offshore regions that typically lack seismic instrumentation. This study focuses on characterizing road construction explosions recorded along a telecommunication fiber-optic cable offshore Cordova, AK. Continuous data have been recorded along 50 km of fiber since April 2024 using an AP Sensing DAS interrogator unit. These recordings include seismic waves from over 10 explosions associated with the construction of a new road near Cordova. Clear seismic signals from these explosions, which occurred as close as 10 km from the fiber, are detectable over 30 km along the fiber-optic cable, enabling detailed analysis of the explosion sources. We use a combination of beamforming and coda spectral ratio techniques to characterize the explosion sources, validating our findings with ground truth information provided by the blasting company. Our results demonstrate that DAS data recorded along offshore telecommunication fibers can be used to detect and characterize onshore explosion sources, further supporting the potential of DAS for explosion monitoring in regions with limited seismic instrumentation.

The Source Physics Experiment and Distributed Acoustic Sensing

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The Source Physics Experiment (SPE) is a multi-decadal program to study explosion-source phenomenology using a combination of modeling and extensive field experiments. In SPE Phase II, Dry Alluvium Geology (DAG), fiber optic cables for Distributed Acoustic Sensing (DAS) were deployed and interrogated with a Silixa iDAS interrogator. The surface and subsurface in a monitoring well recordings with both DAS and co-located traditional geophones provide an unprecedented view of the seismic wavefields generated by the series of chemical explosions. Utilizing these wavefield observations, synthetic wavefield calculations, and machine learning methods, we explore how best to deploy and analyze DAS data for SPE Phase III, Rock Valley Direct Comparison (RV/DC). Key findings include (1) optimal results are derived from treating the dataset as an array, (2) polygonal arrays with odd numbers of sides reduce artifacts, and (3) channel-to-channel similarity can be leveraged for new methods of denoising and arrival picking. The first two of these findings will inform array designs of new integrated large scale multidisciplinary geophysical field experiments and campaigns, such as future phases of the SPE. The first and third findings will be more generally useful to any DAS data analysis, including cases where pre-existing fiber networks are utilized. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

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Reviewing Seismoacoustic Coupling Mechanisms for Infrasound From Underground Explosions

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Infrasound from underground explosions is a key component of explosion monitoring, and is useful for constraining the explosion depth-of-burial. Many chemical explosion experiments have been conducted to understand the seismoacoustic coupling mechanisms for infrasound. Previous experiments showed that gas release and spall generation at the epicenter can govern infrasound characteristics. However, those detonation depths were generally shallow and may not represent deeper events such as overburied explosions or earthquakes. Here, we report a rare infrasound observation from a large, overburied chemical explosion and describe possible seismoacoustic coupling mechanisms. A multi-physics experiment (PE1-A) for low-yield nuclear explosion monitoring was conducted at the Nevada National Security Site in 2023. The PE1-A experiment was a fully coupled, chemical detonation with a TNT-equivalent yield of 16.3 tons at a 254-m depth. This overburied explosion produced unusually long duration infrasound signatures recorded at a range of several kilometers. These signals may indicate complex seismoacoustic coupling mechanisms for overburied explosions, which differ from gas release or spall mechanisms invoked to explain signals from shallower explosions. Preliminary numerical modelings and analysis indicate the extent of seismoacoustic coupling area and local topography affect the duration and amplitudes of generated infrasonic waveforms. Seismoacoustic coupling at this depth may be fully governed by linear elastic-to-acoustic conversion along the surface without the gas venting and spall generation observed in shallow explosions. In this case, local topography and subsurface seismic structures are likely to play a critical role in infrasound generation. In this study, we review seismoacoustic coupling mechanisms for underground explosions depending on the depths of burial and local topography.

Assessment of Seismoacoustic Signals From Wavefield Experiments at a Nuclear Facility in Texas

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Seismoacoustic measurements play a critical role in detecting, locating, and characterizing explosions. Between 2021 and 2024, we carried out four experiments at a facility in the Texas Panhandle to investigate the spatial and temporal evolution of seismoacoustic signatures from explosions at local distances. Southern Methodist University and Oak Ridge National Laboratory jointly deployed a dense array of seismic and acoustic sensors to capture ground motions and acoustic pressure perturbations from 32 targeted shots. We quantified the spatial signal evolution by estimating the decrease in signal correlation as sensor separation increased. Within ~2.5 km of the source, signals were dominated by source characteristics, while path effects, primarily influenced by atmospheric conditions, prevailed at greater distances due to the region's flat terrain. By comparing the spatial evolution in infrasound and air-to-ground-coupled signals across different seasons (summer, fall, and winter), we assessed the variation due to different atmospheric conditions. We found that signal amplitudes were similar within a near-source distance (<0.3 km), while those beyond 0.5 km exhibited significant scatter because of varying weather conditions, particularly wind-induced turbulence from boundary layer heating (smaller amplitude during the summer). We documented that regional infrasound detectability and celerity varied with each experiment and event time, suggesting a seasonal influence of atmospheric winds (less detectability at the western station during the summer). The experiments provided a unique dataset capturing signals across a dense sensor network under varying atmospheric conditions, providing valuable insights for explosion monitoring and advancing understanding of seismoacoustic signal propagation in dynamic environments.

Seismoacoustic Yields of Local to Near-regional Distance Explosions Using Distributed Acoustic Sensing (DAS)

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The high-fidelity and broadband measurements provided by Distributed Acoustic Sensing (DAS) over an extended spatial domain has been shown to be capable of characterizing both traditional seismic sources, such as earthquakes, as well as aerial sources such as bolides. DAS measurements can provide seismic observations which rival those of traditional seismic arrays, while simultaneously providing enhanced constraints on both the atmospheric acoustic and infrasound wavefields, making these measurements uniquely well suited to examine near surface seismo-acoustic sources such as volcanic eruptions and chemical explosions. In this study, we analyze DAS data collected at local to near-regional distances (e.g., ~12 km) from two near surface chemical explosion test series which occurred in May 2024 near Socorro, NM, in which each test series consisted of 4 one-ton TNT equivalent shots followed by a 10-ton TNT equivalent shot. The DAS data captured both seismic and acoustic waves from all the explosions and provides a crucial demonstration of the capabilities of DAS to record surface explosions at local to near-regional distances. We show that the coda spectral ratio method can overcome the azimuthal and unknown ground coupling limitations of using DAS data for the study of seismic source properties and that a rapidly deployed DAS cable can accurately determine the yield of a small chemical explosion (1-10-ton TNT) at distances of ~12 km using both low-frequency seismic (i.e., <20 Hz) and broadband (i.e., 1-100 Hz) acoustic phases.

Possible Double Bolide Measured Across the Idaho National Laboratory Broadband Seismic Network

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On February 21, 2024, the Idaho National Laboratory (INL) Seismic Network triggered on an anomalous seismic event. Upon investigation of this event, it is hypothesized that this event is actually a shockwave from a bolide which passed over the desert of Eastern Idaho. The shockwave was well recorded on at least 60 seismic stations, many of which were three-component broadbands. In addition to the seismometers, the shockwave was also measured on a single infrasound instrument owned and operated by the INL. The pressure wave measured on the infrasound instrument displayed the characteristic N wave usually associated with sonic booms. In addition to the primary N wave, a second N wave was measured about 1.5 seconds following the first. While this second wave was smaller in amplitude and shorter in duration, it is proposed that this second arrival is the result of another source, either two bolides or a single bolide breaking into two pieces. This second arrival was detected on a smaller number of seismic stations, primarily on the Eastern Snake River Plain. Arrival times and wave polarizations are used to model the trajectory of the primary bolide. The source of the shockwave appears to originate directly above the desert footprint of the INL in Eastern Idaho and travels to the northwest. This presentation will show the seismoacoustic signals created from the shockwave, the pressure wave measured on the infrasound station and the grid search method which was used to model the trajectory of the bolide.

Cardinal: Seismic and Geoacoustic Array Processing

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Data collected via seismic and infrasound array deployments are leveraged in the geosciences to detect and characterize a myriad of natural and anthropogenic sources. These deployments consist of many sensors placed in a predetermined configuration to amplify signal strength and improve the efficacy of array processing techniques used to measure signal directionality and waveform coherence. High fidelity feature extraction is often predicated on interstation distance as well as the frequency content and wavelength of an incident signal. Numerous array processing softwares analyze data in sequential frequency bands to obtain a more detailed characterization of a signal. However, current algorithms are limited in their ability to (1) determine optimal array configuration for each band, and (2) mitigate for continuous coherent signals, such as microbaroms or microseisms, that exhibit the propensity to obfuscate signals-of-interest when processing array data.

We introduce an open-source Python code, called Cardinal, to process seismic and infrasound array data in discretized time-frequency space with the option of applying an adaptive array design to determine optimal subarray configuration for each frequency band. To reduce computational time, the array processing step can be run in parallel using multithreading. Furthermore, the software has the capability to aggregate array processing results from different time-frequency pixels to produce separate sets of detections, or families. This approach has added utility via the application of an adaptive semblance threshold which aids in isolating signals-of-interest from coherent background noise. Upon appropriate configuration, Cardinal exhibits the potential to combine distinct seismic and infrasound phases into separate families. We showcase the effectiveness of Cardinal on a variety of sources, including bolide infrasound, earthquake infrasound, and explosion seismology.

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Leveraging Seismic Particle Motion of Air-to-ground Coupled Waves to Investigate the Structure of the Shallow Subsurface

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When low-frequency acoustic (infrasound) waves impinge on the Earth's surface, they can couple into the solid earth and produce measurable ground motion on seismometers. Analysis of seismic particle motion is often used to help identify these air-to-ground coupled waves and can also aid in determining the backazimuth of the infrasound wave. Literature regarding acoustic-seismic coupling often assumes that pressure-induced particle motion is retrograde elliptical, however we show that prograde motion is often observed. Here we explore how to use particle motion to uncover information about the shallow subsurface and the incident acoustic wave at stations with co-located infrasound sensors and 3-component seismometers. We adapt the Normalized Inner Product method (Meza-Fajardo et al., 2015) to quantify the sense of retrograde or prograde motion of air-to-ground coupled waves in the time-frequency domain. We also analyze how the particle motion ellipse is tilted at different frequencies, which may inform identification of the recorded, transmitted wave (body waves, guided waves, etc.). From observations of coupling events, we find that different stations can exhibit broadband retrograde motion, broadband prograde motion, and frequency-dependent particle motion. Previous literature suggests that prograde motion occurs when the subsurface shear wave velocity is less than the acoustic wave speed. However, we also observe prograde motion at low frequencies (0.02 Hz), which are sensitive to structure at depths (> 5 km) where velocities are likely far greater than the speed of sound. To further understand the mechanisms for prograde motion of air-to-ground coupled waves, we model the seismic ground motions induced by pressure waves coupling into a layered subsurface using a matrix propagator technique. We aim to replicate the particle motions observed in real data from chemical and volcanic explosions to understand how the shallow subsurface affects the varying aspects of particle motion.

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Diurnal and Weekly Acoustic Background Noise Fluctuations in the Vicinity of the P-tunnel Complex at the Nevada National Security Site

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Infrasound microbarometers are often subject to background noise from wind and nearby human activity. Wind varies on a diurnal to seasonal cycle, whereas anthropogenic interference has daily to weekly periodicity. This may lead to predictable periods of optimal vs. degraded sensor performance, provided these trends are well understood. Quantifying these fluctuations also gives insight into the micrometerology and human dynamics of specific sites. Here we examine background noise trends on a set of infrasound microbarometers located in complex topography near an active underground facility. Background noise below 10 Hz tends to be lowest around sunset and sunrise. Local anemometer data indicates that this is due to twice-daily wind lulls, a particular regime often found in mountain valleys. Daily variations in higher frequency noise appears to be related to traffic on access roads, while weekly fluctuations are associated with the continuous activity of the tunnel ventilation system from Monday-Thursday. Our study highlights the complex interplay between micrometeorological and anthropogenic noise sources on a daily to weekly scale. These results suggest that performing a background noise assessment should be considered before siting sensors with specific sensitivity requirements.

Advancements in Forensic Seismology and Explosion Monitoring [Poster]

Poster Session • Thursday 17 April

Conveners: Richard Alfaro-Diaz, Los Alamos National Laboratory (rad@lanl.gov); Louisa Barama, Lawrence Livermore National Lab (barama1@llnl.gov); Miles Bodmer, Sandia National Laboratories (mabodme@sandia.gov); Brandon Schmandt, University of New Mexico (bschmandt@unm.edu); Julien Thurin, University of Alaska Fairbanks (jthurin@alaska.edu); Cleat Zeiler, Nevada National Security Site (zeilercp@nv.doe.gov)

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Distributed Acoustic Sensing Technology in Seismological Monitoring: A Validation Through Numerical Modeling of 3D Wave Propagation

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The Comprehensive Nuclear-Test-Ban Treaty (CTBT) International Monitoring System (IMS) is a unique global network designed to detect any source of nuclear explosion underground, underwater or in the atmosphere and verify violations of the Treaty. The network is close to completion and is based on four complementary verification technologies (seismic, infrasound, hydroacoustic and radionuclides) with a total of 321 monitoring stations and 16 laboratories hosted by 89 Countries around the globe. The IMS aims at employing the most effective and latest available technologies, working for constant improvement of the verification regime to ensure a state-of-the-art network.

In the latest years, the use of Distributed Acoustic Sensing (DAS) interrogators has been introduced as a novel tool for studying the Earth systems, spreading in seismic monitoring. DAS instrumentation paired with fiber optic cables offers availability of dense sampling linear deployment of ground motion sensors, enabling unprecedented spatial resolution of seismic measurements. While the analysis of DAS data is still an on-going challenge, both for amount of data and its physical interpretation, the availability of such unique datasets offers new possibilities for studying processes occurring close to the Earth's surface. These reasons seem to indicate the DAS technology as an innovative tool for traditional seismic networks. Investigating its potential use within scientific networks, which might in future complement the information of the IMS network, is a matter of interest.

This study addresses the effectiveness of the DAS technology in recording man-made events, via the synthetic simulation of wave propagation in a layered Earth model and compares the detection potential with respect to a network of seismic stations with similar geometry. The spectral element method for simulating the seismic wave propagation within a volume encompassing crust and upper mantle is used to reconstruct both ground motion and strain-rate time-series at regional distances from the source.

POSTER 83

Characterization of Multi-yield Controlled Chemical Explosions Using Infrasound

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In May and October of 2024, two series of five chemical explosions were executed to investigate atmospheric infrasound propagation at distances up to 200 km. The shots varied in yield, with two pairs of 1-ton TNT-equivalent blasts and a single 10-ton detonation. Approximately 20 ground-based infrasound stations were strategically positioned to acquire records of the acoustic wavefield under varying environmental conditions (spring and fall). This configuration enabled high-fidelity measurements of signal parameters which are viewed as diagnostic markers for characterizing source yield. Here, we focus on determining how measured amplitudes and periods correlate with known yields, thus informing empirical relationships that are used for yield estimation. We are also interested in infrasound propagation effects as a function of season. We will discuss the results in the context of characterization of explosive events.

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POSTER 84

Moment Tensor Inversion Analysis of DPRK6 Nuclear Events Using CTBTO/IMS Data

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The global verification system established under the Comprehensive Nuclear-Test-Ban Treaty (CTBT) is designed to detect all nuclear explosions on Earth. Seismic monitoring, one of the four verification technologies, relies on the International Monitoring System (IMS), a global network of sensor stations, to identify nuclear explosion signals. This study presents an application of Moment Tensor (MT) inversion analysis to assist individual States Parties through expert technical analysis (ETA) of IMS data and any additional datasets provided by the requesting State Party. MT inversion enables precise determination of parameters such as total seismic moment, focal mechanism, and source depth.

To evaluate this approach, we analyzed data from declared nuclear events in the Democratic People's Republic of Korea (DPRK). For the most recent event, DPRK6 (2017/09/03), two methodologies were applied: (1) a regional moment tensor inversion in the time domain (TDMT, Dreger, 2003) and (2) a joint inversion using regional waveforms and teleseismic first-motion polarities (Nayak and Dreger, 2015; Chi-Durán et al., 2024). The analysis included 4 regional waveforms (filtered between 20–50 s) and 81 teleseismic first-motion polarities from CTBTO stations. Known regional velocity models were used to model the synthetic waveforms (Ford et al., 2010; Dreger et al., 2021).

The TDMT approach achieved a high waveform fit and revealed a predominantly isotropic mechanism with a minor double-couple component. These findings are consistent with previous studies using other station datasets (e.g., Alvizuri and Tape, 2018; Chiang et al., 2018). The joint inversion further improved the waveform fit, with the isotropic component remaining dominant. The source-type lune plot confirmed a mechanism primarily characterized by isotropy. Current efforts aim to incorporate additional data, such as teleseismic waveforms, to refine the depth and other characteristics of the event across all declared DPRK events.

POSTER 85

Time-variable Moment Tensor Inversion Applied to Seismic Data Collected at the PE1-A Experiment

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Time-variable moment tensor inversions recover moment function models that capture the evolution of source characteristics instead of a static moment tensor matrix. These inverse formulations are able to better categorize complex sources that change through time, allowing for an estimate of the moment functions for each moment tensor component without requiring *a priori* information regarding the type of source time function. This means that a complex source, such as strike-slip motion on a fault followed by cracking, can be represented in the order these source mechanisms occurred in time, and therefore not subsumed into a scalar representation that might miss one or both aspects of the changing source, as is typically done in traditional, static moment tensor inversions.

We apply our time-variable moment tensor inversion to seismic data recorded as part of the Physics Experiment 1-A (PE1-A). We use various three-component seismic station configurations, as well as filter the seismic data using two different frequency bands to evaluate the performance of our time-variable moment tensor inversion with differing frequency content and recording geometries. Comparison between the recovered moment function results using data filtered between different frequency bands, as well as seismic data from 3 - 21 three-component stations, leads to similar recovered source mechanisms. However, when including fewer stations in the time-variable moment tensor inversions, differing isotropic moments were recovered compared to inversions using data with higher station coverage.

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POSTER 86

Exploring Paired Neural Networks to Identify Similar Waveforms

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Similar event waveforms, such as from repeating earthquakes, aftershocks, or explosions, are often identified using cross-correlation methods. However, these methods can require a careful curation of template libraries or more computational resources than pre-trained, deep-learning models, and this motivates us to explore the effectiveness of using a paired neural network (PNN) to identify similar event waveforms. The PNNs were trained to recognize similar earthquake pairs from a global dataset of real earthquakes augmented with different levels of background noise and showed success when tested against a similar dataset composed of noise-augmented, similar earthquake pairs. When transportability of the PNN model is explored, by testing against a real dataset of repeating earthquake pairs (Schaff and Richards, 2011), we find the PNN model still performs well, but to a lesser degree than when tested against data that are more like the original training dataset. We explore how subsequent PNN model tuning can improve the performance against the repeating earthquake dataset. We also investigate a hyperparameter optimization process and whether it may be used to recognize when a specific training dataset is a good representation of the target test dataset. This Ground-based Nuclear Detonation Detection (GNDD) research was funded by the National Nuclear Security Administration, Defense Nuclear Nonproliferation Research and Development (NNSA DNN R&D). SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

POSTER 87

Using Unsupervised Deep Learning to Denoise Data From Distributed Acoustic Sensing

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Distributed Acoustic Sensing (DAS) has shown promise in supplementing recordings of traditional sensors. DAS has the advantage that it can be deployed in regions that are difficult to access with conventional sensors, thereby improving sensor coverage for seismic event monitoring. However, unlike seismic stations with well-developed installation standards, DAS cables are typically not well coupled to surrounding rock. This leads to a high noise environment that can vary spatially along the cable. We are adapting an unsupervised deep learning algorithm termed "recorrupted-to-recorrupted" approach (R2R, Pang et al., 2021), which was initially developed for image processing, to train a machine learning denoising model for DAS data. The model is trained using teleseismic and local data recorded along the road section of the Sand Hill dark DAS fiber cable beneath Palo Alto, CA. Preliminary results of the evaluation of the denoising model will be presented.

POSTER 88

Accurate Modeling of Seismic Waveforms of PE1-A Explosion

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Our research aims to provide high-fidelity seismic modeling of the PE1-A chemical explosion, conducted in October 2023 at the Nevada National Security Site, with a focus on understanding the coupling of the explosion to the ground. For such modeling, we use the code HOSS developed at LANL to model the near-source regime. HOSS is coupled to two seismic codes to model seismic waveforms at large distances, one based on the reflectivity method (Kennett, 1985) and the other based on the spectral element method, SPECFEM3D. HOSS combines finite-element analysis of continua with discrete-element transient dynamics allowing one to explicitly model fracture and spallation processes. Several material models have been developed to describe the explosion emplacement conditions that are important to accurate modeling of the coupling efficiency of the PE1 chemical explosion series to the ground.

HOSS and the seismic codes are coupled using the representation theorem which states that a seismic source can be replaced by the time-history of the wavefield recorded on a surface surrounding the source volume. The two seismic codes use this recorded information to fully determine the wavefield in the remaining full space. The coupling surface is chosen to be beyond the transition from non-linear to pure elastic domain. This transition is typically less than one hundred meters away from the source centroid. Kinematic energy must be preserved through the coupling for accurate modeling. This may be challenging due to different sampling requirements of the two types of modeling, as well as by the fact that the seismic codes and the hydrodynamic codes may not consider the same velocity model at the coupling surface. HOSS modeling is performed in a layered model based on the local Geological Framework Model which considers multiple Tertiary tuffs. Seismic modeling at distances beyond 10 km will typically use 1D crustal models or 3D regional models that do not incorporate the local layering. In this paper, we will explore the accuracy of our coupling interface and propose a correction to be applied in the case of a velocity model mismatch.

POSTER 89

Recovery and Digitalization of Semipalatinsk Test Site Nuclear Explosions From Legacy Analog Seismograms

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The Institute of Seismology of Academy of Sciences of the Kyrgyz Republic, the National Scientific Center for Seismological Observations and Research of the Emergency Situations Ministry of Kazakhstan, and Michigan State University are recovering, scanning, and digitalizing historic analog seismograms of Soviet Nuclear Explosions that took place at the Semipalatinsk Test Site between the 1960s and 1980s. We are specifically focusing on explosions that occurred in Degelen Mountain. These explosions were well recorded by the regional seismic networks, where thousands of seismograms are still retained. We are working to index these irreplaceable legacy analog seismograms and preserve them against loss for future generations. In the process, we are also generating high resolution scans of the seismograms and digitalizing them for analysis. Along with the seismograms, we are recovering the original station calibrations, responses, and metadata for each station and developed code to generate Dataless SEED files for use with the digitized data. Most seismograms are from short period instruments, and when combined with the correct station calibration information, the digitalization process accurately recovers ground motion signals to at least 5 Hz. The resulting digital waveforms are of sufficiently high quality that they are usable for quantitative research (see Martinetti and Mackey, this conference).

POSTER 90

Source Characterization of Nuclear Tests From Reloaded Tunnels in Degelen Mountain From High-quality Digitalized Seismic Data

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We are recovering and digitalizing regional legacy analog seismograms from nuclear explosion tests in the Semipalatinsk Test Site (STS) to better understand the generation and characterization of nuclear explosion waveforms. Most nuclear testing was conducted during the era of analog seismic recording, thus there are few digitally recorded waveforms available for research. Digitalization of these legacy analog records recorded in Kazakhstan and the Kyrgyz Republic into digital waveforms (see Mackey et al., this conference) provides us with a unique opportunity to study nuclear explosions. Within the STS, nuclear tests conducted in tunnels in Degelen Mountain were often done in pairs, with multiple detonations occurring within the same tunnels, often a few years apart. In a typical case, the first test was conducted in relatively undamaged granitic rock that would create a large fracture zone. The second and subsequent tests were conducted within that fracture zone, perhaps only tens of meters away from the first test. In this study, we aim to characterize differences in the seismic waveforms between both tests using different approaches. We are analyzing spectral amplitude ratios between different seismic phases, corner frequency differences, moment tensor inversions, yield estimation, etc…, all of which can shed light on the difference in the wavefield caused by explosions in damaged vs undamaged rock. Initial results from time-domain full waveform moment tensor inversions show primarily isotropic sources for both explosions, and we continue to characterize multiple aspects of the differences.

POSTER 91

Examination of the Rock Valley Flower Structure Effects on Earthquake Wave Propagation

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The Rock Valley Nevada's fault structure appears to be comprised of a flower structure with many fault strands, which makes accounting for their behavior in synthetic waveform modeling difficult. Fault strands can act as natural wave guides if they are low velocity zones in comparison to surrounding higher velocity country rock, due to a fault experiencing intense fracturing, brecciation, liquid-saturation, and/or high pore-fluid pressure. Separating this behavior from other phenomenon is difficult in Rock Valley given the potential number of fault strands, so to identify the effects we utilize a variety of velocity models to account for possible behavior to see which bests replicates observed waveforms. We perform and contrast three synthetic estimations of waveforms: 1) a simple velocity model, 2) a high-resolution tomography model, and 3) a high-resolution tomography model with low velocity faults within it. For each of these models, we compare the results to the observed waveforms from a couple of selected local earthquakes to see which model accurately reproduces observed waveform phenomena. With the main objective being the investigation of the local fault structures effects on waves propagating across the faults in the Rock Valley which will help to better define the location and structure of those faults.

POSTER 92

Examining Seismicity Surrounding the PE1-A Chemical Explosion With a Dynamic Correlation Processor

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A primary function of seismic monitoring is detecting and characterizing seismic events. Repeating signals and signals that otherwise correlate with each other can provide a wealth of information about an area's seismic activity. A dynamic correlation processor (DCP) is a useful tool for searching for these kinds of signals. The DCP runs over a continuous stream of data, identifying new waveform patterns by applying power detectors from an STA/LTA algorithm as "boot detectors". These signals are used to create new detectors and thereafter applied to the data with the bank of detectors growing in time as more new waveform patterns are encountered. In this study we utilize a DCP to investigate possible aftershocks of the PE1-A chemical explosion as well as other seismicity in the vicinity before and after the explosion. Preliminary results find very few aftershocks detected at the nearby geophone stations. An interesting sequence of very small events was observed before the explosion. Future work will include associating detections from the DCP so that newly detected events can be located and characterized.

POSTER 93

A Comprehensive Analysis on Global Bolide Infrasound

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Under certain entry velocities and initial mass conditions, the interaction of a meteoroid with dense regions of the Earth's atmosphere can produce bolides, which refer to detonating fireballs that explode at resolvable altitudes within the atmosphere. These atmospheric phenomena can generate infrasound at rates which can be processed and subsequently leveraged towards better characterization of meteoroids when other means of observation are not available. Classification of bolide infrasound is regulated by the source geometry, which corresponds to the point along the trajectory which induced a shock wave. Shock waves resulting from a fragmentation event could have spherical or quasi-spherical geometry, whereas infrasound generated via the meteoroid's hypersonic flight has a characteristic cylindrical line source geometry. Infrasound's low-frequency content facilitates long-range propagation at global scales. Interpretation of processing results is oftentimes complicated due to the time-sensitive nature of the atmosphere causing irreversible effects on waveform morphology.

In this study, we utilize a data-driven approach to improve characterization of bolides documented within NASA's Center for Near-Earth Object Studies exclusively with infrasound detected by global arrays. We implement a multi-frequency array processing software, known as Cardinal, to extract directionality estimates and phase velocities, as well as quantify waveform coherence over a broadband frequency range using narrowband spacing. When appropriate, we utilize the adaptive array algorithm to better characterize the signal over sequential frequency bands and subarray configurations. Furthermore, we measure signal delay times using known infrasound propagation velocities and a start time coinciding with bolide peak brightness, typically associated with a fragmentation episode. Our work comprehensively analyzes bolide infrasound as a function of source-receiver distance, signal arrival times, event altitude, and total impact energy.

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POSTER 94

mtuqorg: A Modular Approach to Moment Tensor Estimation and Uncertainty Quantification With MTUQ

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Seismic moment tensors, along with point forces, are used to describe various source mechanisms, including tectonic earthquakes, human-made explosions, and mass movements. Accurately estimating these parameters and rigorously quantifying uncertainties are crucial for enhancing our understanding of seismic sources and reducing ambiguity in their interpretation. The open-source Moment Tensor and Uncertainty Quantification (MTUQ) code provides flexible tools for point-source inversion using seismic waveforms and first-motion polarities, with a focus on balancing computational efficiency and robust uncertainty estimation. We showcase the code's capabilities by revisiting the DPRK nuclear test of September 2017 to evaluate the influence of various data sources on the misfit space, both using a conventional grid-search approach and leveraging the fast Covariance Matrix Adaptation Evolution Strategy (CMA-ES) method. We also demonstrate the modularity of the code by supplementing the CMA-ES optimization with the "increase population restart" strategy, which helps map out the misfit space more efficiently and illuminate local minima. MTUQ accommodates a wide range of Green's function databases (both 1D and 3D and receiver side Strain Green's Function), and integrates with high-performance computing architectures, supporting workflows from single-core optimizations to large-scale grid searches spanning billions of grid points. MTUQ also offers tools for visualizing solutions and uncertainties, facilitating better interpretation of inversion results and aiding reproducibility. New users can engage easily through workshops, online resources, and open development channels, ensuring that MTUQ remains a robust and evolving resource for seismic source characterization and forensic seismology.

POSTER 95

Using Nonlinear Thresholding of Stockwell Transforms to Denoise Seismic Waveforms

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Stockwell transform, commonly known as S Transform (ST, Stockwell et al., 1996) is an extension of the continuous wavelet transform (CWT) and involves an inverse frequency-dependence of the localizing Gaussian window as well as a modulating phase factor, which in contrast to CWT and short-time Fourier transform (STFT), result in frequency-dependent resolution. We are leveraging that advantage by implementing an ST thresholding method for noise suppression in seismic data. Because of the better frequency resolution provided by the ST, combined with the proven efficiency of thresholding methods in improving the signal-to-noise ratio in general, we expect the ST-based thresholding approach to be superior to standard methods and the previously developed CWT thresholding. The approach should lead to better downstream products, including improved signal detection and event characterization.

POSTER 96

Analog Geophysical Data [From Nuclear Tests]: Which Digitization Software Should I Use? How Can I Leverage the Power of AI for Forensic Analysis of Analog Data?

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Digitization of historic analog seismograms from nuclear explosions is an imperative need for the Nuclear Explosion Monitoring community since most recorded observations of nuclear tests are in analog media and conversion to digital format is resource and time intensive, which requires specific expertise. To assess the effectiveness of available digitization software, we identified 4 potential algorithms (out of 33 reviewed references) for further testing and developed a Python toolkit for the generation of synthetic analog helicorder records (synthetic generator). Our evaluation of the selected digitization software uses a tiered approach: synthetic records; scanned & previously digitized data; and scanned, undigitized data.

The synthetic generator creates data in a manner that faithfully represents the complex characteristics (and challenges) of analog seismograms, including variable trace thickness, time marks (WWSSN, USSR), waveform crossover, etc. We also use this toolkit to portray data recorded on digital instruments (e.g., tests from the tail end of the major powers testing era) as if it had been recorded by historic analog instruments. As the number of underground nuclear tests conducted during the digital data era is comparatively small, we can use our synthetic generator to produce and augment AI/ML training datasets for machine learning applications.

We present our initial results for testing of the selected digitization software packages using synthetic data generated by our toolkit. We discuss the data collected for the last 2 phases of our testing framework and explore potential applications for nuclear monitoring of data created by our synthetic generator.

POSTER 97

The Source Physics Experiment on Seismic Waves Generated by Explosions: Results and Future Plans

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The NNSA DNN R&D sponsored Source Physics Experiment (SPE) is a large, multi-institutional (LANL, LLNL, SNL, NNSS and UNR) effort to improve our understanding of how explosions generate seismic waves, particularly shear waves, to improve nuclear monitoring capabilities. The SPE includes a series of chemical explosions in southern Nevada in three Phases, each in a different borehole in contrasting geologies: SPE Phase I (2010-2016) was a saturated granite site; the Phase II (2016-2020) in Dry Alluvium Geology (DAG), and the current Phase III – Rock Valley Direct Comparison (RV/DC) is expected to be in dolomite. For each Phase the explosions vary in size and depth and are recorded on a common network, allowing ratios between events to be formed, canceling path and site effects and illuminating near source effects.

Near-field chemical SPE and historic nuclear data show high-frequency tangential motion is 20-30% of radial amplitudes, although the mechanisms that cause this vary with emplacement media. Within a few kilometers, far-field seismic amplitudes at 1-10 Hz are comparable across the 3 components, and the buried and surface explosions have comparable P/S amplitude ratios - both effects require rapid scattering and conversion to explain. The spectral ratios formed between small explosions used as Green's functions and larger explosions are not well matched by existing explosion models, and the dry alluvium geology produces smaller amplitudes and appears deficient in high-frequency energy relative to explosions in granite. This shows the importance of material effects on explosive wave generation. We are examining factors such as absolute depth, scale depth, and material effects on shear wave generation, P/S and low/high frequency amplitude discrimination performance, and correlation behavior. These results are being used to develop a new explosion spectral model. For the current RV/DC Phase we plan to drill a corehole into a fault producing shallow seismicity to get physical samples and measurements in preparation for a future direct comparison of a shallow earthquake with a chemical explosion.

POSTER 98

Seismoacoustic Explosive Yield Estimation Using Ground-coupled Airwaves Recorded on a Local Seismic Network

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Infrasound waves impinging on the Earth's surface can couple with the ground to create Ground-Coupled Airwaves (GCA), which are frequently observed on seismometers at local distances up to 250 km from a given explosion source. In this study, we explore a method to exploit GCA in estimations of explosive yield at local-scale distances. To develop this method, we evaluate GCA arrivals recorded on seismic sensors from a variety of chemical explosions with known yields, including the Humble Redwood test series: a series of near-surface controlled chemical explosive tests conducted in New Mexico from 2007-2012. We build upon these ground-truth yield data and existing scaling relationships between acoustic propagating waves and their coupling to seismic sensors, including consideration of geologic site conditions at the sensor, to develop reliable scaling relationships between observed GCAs and explosive chemical yield. To supplement yield estimates determined solely by GCAs, we also incorporate seismic arrivals recorded on the same seismic sensors into our technique, noting the varying lithologies that make up the source-receiver paths from event to event. By doing so we account for the fact that some the emplacement conditions of the chemical explosive tests occurred in both alluvium and limestone. Our primary goal in this research is to build a seismoacoustic yield estimation workflow that uses multi-modal seismic and acoustic data obtained from a single seismic sensor.

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POSTER 99

Seismoacoustic Signals from the Tropicana Implosion

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Over the last five years the Nevada National Security Sites (NNSS) has increased the dedicated deployments of infrasound sensor arrays. They have been established in the Las Vegas, NV region and at the NNSS, with the main deployment occurring during the COVID shutdown. The classification of acoustic signals in an urban environment is hampered by the additional municipal noise sources as well as signal reflection caused by infrastructure. During these deployments numerous event sources were collected, including the recent implosion of the Tropicana Hotel on the Las Vegas Strip, which provide a unique opportunity to studies the impacts on signals in a real-world situation. Additional sources, include the Tonga Eruption, OSIRIS-REx, other explosions, and rocket launches signatures for seismoacoustic studies between urban and rural deployments. The varying levels of noise produced during these events and the opportunity to collect unique signatures is the basis for our study. We will show the connection of seismic events to infrasonic signals and demonstrate the utility of augmenting a traditional seismic network with infrasound sensors.

Advances in Reliable Earthquake Source Parameter Estimation

Oral Session • Wednesday 16 April • 8:00 AM Local

Conveners: Oliver S. Boyd, U.S. Geological Survey (olboyd@usgs.gov); Tom Garth, International Seismological Centre (tom.garth@isc.ac.uk); Keith McLaughlin, Leidos (mclaughlin0kl@gmail.com); Colin Pennington, Lawrence Livermore National Laboratory (pennington6@llnl.gov); Thanh-Son Pham, Australian National University (ThanhSon.Pham@anu.edu.au); Natalia Poiata, International Seismological Centre (Natalia.Poiata@isc.ac.uk); Adam Ringler, U.S. Geological Survey (aringler@usgs.gov); Boris Rösler, Ensenada Center for Scientific Research and Higher Education (boris@cicese.mx); William L. Yeck, U.S. Geological Survey (wyeck@usgs.gov); Clara Yoon, U.S. Geological Survey (cyoon@usgs.gov)

Revising the Iaspei Ground Truth List

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Seismic events with well constrained hypocentres, referred to as "Ground Truth" events, are an important resource for benchmarking and testing new seismic velocity models and seismic event location techniques. Ground Truth events are relocated with ISCloc, using stations within 150 km of the event, and are categorised based on major axis of the error ellipse. Events that are determined to within 5 km are considered for the Ground Truth list. The current Ground Truth criteria require that candidate events have a station distribution with a maximum secondary azimuthal gap of 160° and balanced station distribution, as quantified by a ΔU value of less than 0.36. This is designed to ensure that an unbiased event location can be reliably constrained. Additionally, the existing criteria requires that there is at least one station within 10 km of the event, to ensure there is some reasonable depth resolution. We find that it is possible to improve the number of local stations and the secondary azimuthal gap for an event but degrade the ΔU value. As ISCloc and several other modern location algorithms, are able to account for unbalanced station distributions, we propose modifying these criteria in order to make them more inclusive, while not degrading the resulting location quality. In doing so we aim to improve the geographic distribution of events in the Ground truth list.

By replacing ΔU with a new measure referred to as the Cyclic Polygon Quotient (CPQ) we can consider more events for the Ground Truth list, including in areas of very dense seismic network coverage. In addition, the highly exclusive requirement that there is one station within 10 km of the event is augmented with the alternative requirement that there are stations reporting both P & S phase arrivals within 150 km of the event. We demonstrate that by modifying the Ground Truth criteria in this way we can increase the number and improve geographic distribution of Ground Truth events found without compromising the location accuracy of the identified Ground Truth events.

Importance of Accurate Earth Models and Network Geometry for Earthquake Location

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For more than two decades induced seismicity has been an important topic due to the increased number of Oil and Gas well operations (Saltwater disposal and Hydraulic Stimulation). Recently, induced seismicity has become an important issue related to geothermal and Carbon Capture and Storage projects, being one of the top concerns of the public. One of the most challenging problems is the strong dependence of hypocenter location, especially depth, on the velocity model used for the subsurface and the seismic network geometry (i.e. density and azimuthal coverage). At a country/state seismic network operations level it is almost impossible to overcome these problems since, in general: (a) seismic networks do not have a station density equal to the target depth of the human activities, and (b) accurate 3D velocity models for basin and basement structures are not available.

We have developed an approach using 3D models based on sonic log, check shot data and tomography results for the Midland basin, West Texas, to investigate the sensitivity of earthquake location and depth to network geometry and the velocity structure. In a subarea of the basin where the network is dense (interstation distance ~5km) and using at least 5 stations to locate an event, we find that including stations at distances greater than ~12 km shows a strong effect of the basement velocity on the locations. For example, reducing velocities for the basement and using all station data, hypocenters move deeper in the basement. When there are high-impedance velocity contrasts either inside the basin structures or at the basin basement interface, streaks of earthquake location occur, as expected. Due to lack of a dense network in the Midland basin, and in order to avoid the streaks and large time residuals we have incorporated an approach based on simplified wide angle refraction seismology to optimize the sub-basement velocity to create an improved reference 3D velocity model. We used this 3D reference velocity model to relocate the seismicity in the Midland basin area and identify the bias on hypocentral depth compared to 1D velocity models.

Improving First-order Seismic Characterization Through Calibrated Earthquake Locations

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Accurate earthquake locations are foundational to seismic research and rapid hazard assessment. Despite being a well-established inverse problem, earthquake location estimates remain inherently complex due to factors such as unknown Earth structure, phase-pick uncertainties, and inconsistencies in station distributions. Single-event location methods are computationally more efficient, but they often suffer from significant inconsistencies introduced by these limitations. In contrast, multiple-event location techniques leverage statistical relationships among events to better estimate hypocenter uncertainties and address inconsistencies from poor network configurations. However, multiple-event methodologies still suffer from location bias due to unknown velocity structure, typically several km when using local observations and >10km when using regional/teleseismic observations.

We highlight the application of MLOC, a specialized multi-event earthquake location procedure, in generating the Global Catalog of Calibrated Earthquake Locations (GCCEL), which is updated and published online by the USGS. This catalog includes ~28,000 hypocenters in 366 event clusters that are geographically well-distributed, leveraging global and local networks, as well as temporary deployments where available. Calibrated hypocenters are minimally biased by unknown Earth structure due to careful selection of data at short epicentral distances for estimating the absolute locations and procedures to minimize misfit of the local velocity model, while the associated hypocentral parameter uncertainties are fully quantified with empirically determined data variances. GCCEL serves as a benchmark dataset, supporting improvements in routine earthquake monitoring and advanced seismic research, including development of 3D and regional specific velocity models and improved statistical frameworks for seismic monitoring. This presentation will emphasize the importance of calibrated locations and the challenges of absolute location accuracy, demonstrating how GCCEL could address these complexities to enhance first-order seismic observations.

The Body-wave Magnitude mb: An Attempt to Rationalize the Distance-depth Correction Q(delta, H)

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Because it is measured on first-arriving *P* waves, the body-magnitude m_b remains an important metric of earthquake sources, especially smaller ones. Its algorithm uses a distance-depth correction, *q(DELTA, h)*, introduced 80 years ago by B. Gutenberg, and still in use today. However, this function was derived by the founding fathers without a proper command of either the physical nature of an earthquake source as a double-couple, or the structure of the interior of the Earth, in particular the existence of mantle discontinuities leading to triplications, or even the existence of anelastic attenuation. Thus, the exact origin of *q(DELTA, h)* remains largely mysterious.

In this work, we use modern models and theory to synthesize a dataset of more than 30 million seismograms, which we then process through the exact algorithm mandated under present-day seismological practice, to build our own version, q_{SO}, of the correction, and compare it to the original ones, q_{45} and q_{56}, proposed by B. Gutenberg and C.F. Richter. While we can reproduce some of the large scale variations in their corrections, we cannot understand their small scale details. We discuss a number of possible sources of bias in the data sets used at the time, and suggest the need for a complete revision of existing m_b catalogues.

Extending Coda Envelope Moment Magnitudes to Remote Regions of Canada for Improved Hazard Assessment

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To achieve uniform seismic hazard assessment throughout a region, it is crucial that the input parameters are uniform. Canada is a tectonically diverse country with non-uniform seismicity and station coverage. Although modern hazard assessment tools are able to consider multiple input parameters, magnitude recurrence rates remain the backbone of seismic hazard calculations. A first step toward uniformity of magnitudes in Canada was the development of conversion relations to convert the myriad of magnitude types in the database to moment magnitude. However, the conversion relations are based on moderate to large events and may not be valid for smaller earthquakes, which control the shape of the recurrence curve. The coda envelope moment magnitude method (Mayeda et al, BSSA, 2003) proved successful in lowering the moment magnitude threshold for direct calculation from ~3.5 to ~1.5 in the seismically active regions of southeastern Canada, below the M2.5 minimum used in hazard assessment in Canada. Thus, the reliance on converted magnitudes has been reduced. The need cannot be completely eliminated as the coda envelope method cannot be used for analog data unless it is digitized. The method requires calibration on a regional scale and thus the calibration for one region cannot be applied to another, which may have different attenuation and stations. Extension of this method into the adjacent Appalachian region was also successful. The use of this method has been extended to remote and/or less active regions of eastern Canada: the northern Canadian Shield, the Arctic and the eastern offshore (Laurentian Channel and Labrador Sea). Challenges in these regions include sparse station coverage and small numbers of suitable ground truth events. In the offshore regions, it is also critical to separate those events occurring in continental and oceanic crust as the coda consists predominantly of Lg waves in the former and S in the latter. Results indicate that the current conversion relations are not valid for smaller events and need to be reevaluated and provide an improved data set to that end.

Sparse Fault Representation Based on Moment Tensor Interpolation

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Accurate representations of large earthquake sources are crucial for understanding rupture processes and improving seismic hazard assessments. Although finite-fault models can represent complex slip distributions, they are often overparameterized and require strong regularization. Conversely, multiple point-source approaches offer considerable simplicity but struggle to reproduce near-field static displacements and high-frequency signals. We present a sparse fault parametrization that bridges the gap between classical finite-fault and point-source models by leveraging the geometric structure of the seismic moment tensor. Using a few "key" tensors as centroids of a continuous tensor field, we show that interpolating eigenvalues and eigenvectors separately preserves source type and provides smooth transitions between orientations. This interpolation framework enables us to (1) approximate detailed finite-fault models—which we demonstrate on the USGS NEIC slip for the 2024 Noto earthquake—with a few key moment tensors and (2) upscale these sparse models for forward simulations in 3D spectral-element solvers, preserving both the dynamic and static components of the wavefield. Our results confirm that this sparse representation can provide comparable displacement fields to finite-fault models despite requiring fewer parameters. These advances highlight the potential of sparse, moment-tensor-based models for rapid-response earthquake source characterization and high-fidelity forward modeling in complex 3D Earth structures.

Numerical Simulations Reproduce Characteristics of Distributions of Non-double-couple Components in Global Moment Tensor Catalogs

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Non-double-couple (NDC) components of seismic moment tensors (MTs) describe earthquake source processes beyond the double-couple components representing slip on planar faults. MTs from global and regional catalogs find pervasive NDC components with a mean deviation from a double-couple (DC) source of around 20%. Their distributions vary only slightly with magnitude, faulting mechanism, or geologic environments. This consistency suggests that for most earthquakes, especially smaller ones, NDC components are largely artifacts of the MT inversion procedure. We generate synthetic seismograms for the DC components of earthquakes around the world using one Earth model and inverting them with a different model. To match the waveforms with a different Earth model, the inversion changes the mechanisms to include a substantial NDC component while largely preserving the fault geometry (DC component). The resulting NDC components have a size and distribution similar to those reported in global catalogs. MT inversions not adequately accounting for the effects of laterally varying Earth structure can also cause the NDC components of MTs to have a preferred polarity for large shallow thrust- and normal-faulting earthquakes. MT catalogs show that strike-slip earthquakes have predominantly negative NDC components, whereas simulations show equal likelihood for negative and positive NDC components. Hence the preferentially negative NDC components for strike-slip earthquakes could reflect global fault geometry. These NDC components could also be additive, reflecting near-simultaneous strike-slip and dip-slip faulting, such that more common normal-faulting contributions give rise to negative NDC components whereas contributions of thrust-faulting yield positive NDC components. The mean NDC components of earthquakes of all faulting types tend to zero with increasing magnitude, supporting the hypothesis that the different polarities for earthquakes with different faulting types is largely due to lateral heterogeneity of Earth structure to which the longer wavelengths used in the inversion of larger earthquakes are less sensitive.

Moment Tensor Uncertainty Analysis for the 2017 Hojedk, Central Iran, Earthquakes Using 1D and 3D Green's Function

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Uncertainty analysis is crucial for determining the reliability of a moment tensor solution. Traditional inversion approaches usually provide a single best-fitting solution, ignoring other solutions that may fit the data similarly well. For example, inaccuracies in location and velocity model and signal-to-noise ratio issues can lead to a poor fit between observed and synthetic seismograms such that a wide range of solutions, including those with spurious non-double couple components (ndcc), may fit the data quasi-equally. We use a grid search approach to systematically estimate moment tensor parameter resolution, re-analyzing events from a moment tensor catalog for the Hojedk region in central Iran using the Moment Tensor Uncertainty Quantification (MTUQ) code. The code explores moment tensor solutions through regular grid searches or sampling methods. It also includes statistical analyses to calculate the likelihood distribution of finding the true moment tensor near the best-fitting solution. For a reliable solution, the cumulative likelihood for the assumed correct solution increases rapidly in a short angular distance from the preferred moment tensor. We performed the uncertainty analysis using two velocity models: a 1D model developed for Iran and a regional-scale 3D model for the Middle East. For events above M_w 5.0, we found that the 3D model outperforms the 1D model at long periods (T≥25-30s), requiring smaller time shifts, resulting in lower misfits, reduced spurious ndcc, and yielding more stable solutions. However, for events smaller than M_w 4.0 that require analysis at short periods (T<15 s), where a 3D model would be most beneficial, the 3D model did not outperform the 1D model, with both working well. This is due to the limitations of the current 3D model, which was developed using T≥30s waveforms. Nevertheless, this work represents a step towards implementing more realistic velocity models for waveform modeling in the Middle East. We plan to contribute more in-country data and reliable regional moment tensor solutions to improve the 3D velocity model resolution in the Middle East.

Determining Small Earthquake Focal Mechanisms Using 360° S-wave Polarization

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Accurate earthquake focal mechanisms are essential for providing insights into subsurface faulting geometry and stress states. Conventionally, P-wave first-motion polarities and/or S-/P-wave amplitude ratios are used to determine the focal mechanisms; nonetheless, their accuracy, particularly for small (M<3) earthquakes, heavily depends on the station coverage. We introduce a novel approach for utilizing 360-degree S-wave polarizations to determine the focal mechanisms. Using data from the Gyeongju Hi-Density Broadband Seismic Network (GHBSN) in the southeastern Korean Peninsula, we assess the performance of the focal mechanism estimation with three different datasets: P-wave first-motion polarities, S/P amplitude ratios, and S-wave polarizations, incorporating different levels of measurement errors. The results indicate that utilizing the S-wave polarizations with the correction of S-wave splitting effectively lowers the minimum number of stations needed. For an M_L 2.9 event recorded by the GHBSN, with a 6-degree measurement error in S-wave polarization, the solution could be obtained using only two stations, with an average error of 12 degrees. With a 12-degree measurement error in S-wave polarization for smaller (M_L~1.0) events, an average error of 15 degrees in the focal mechanism solution is achieved for strike-slip events using three stations and for dip-slip events using four stations. A performance comparison for earthquakes with magnitudes between 0 and 3 using the HASH program, the most widely used program in the seismological community, shows that our method provides more accurate solutions as the earthquake magnitudes decrease. These findings highlight the robustness of our method in determining focal mechanisms for small earthquakes, even with fewer stations, providing a valuable tool for analyzing microseismicity.

How S/P Amplitude Ratio Data Can Bias Focal Mechanism Estimates

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Earthquake focal mechanisms provide crucial information about fault geometry and stress orientations in the Earth's crust. For small earthquakes, focal mechanisms are typically inferred through analysis of seismic radiation patterns, for example by using P-wave first-motion polarities to identify the mechanism's nodal planes. In recent years, it has become common to incorporate S/P amplitude ratio data alongside P-wave polarities to further refine the mechanism solution. The motivation for this procedure is well-founded, as P- and S-wave radiation patterns depend systematically on the fault orientation, and thus S/P amplitude ratios provide potentially useful observations for the inference of focal mechanisms. However, in practice, S/P amplitude ratio measurements can be noisy and strongly influenced by factors that are unrelated to the source mechanism. In this study, I characterize several underappreciated and systematic issues with S/P amplitude ratio data that are relevant to the focal mechanism inversion problem. The analysis combines synthetic tests with new measurements of waveform amplitudes from tens of thousands of well-recorded M_L 1.0 and greater earthquakes in Nevada and eastern California. Key findings include that (1) the statistical distribution of S/P amplitude ratio data differs markedly in shape and width from the theoretical expectation, (2) S/P amplitude ratios decay systematically with distance beyond ~ 60 km or so, (3) this distance effect is more severe for small earthquakes than for large ones, and (4) modifying the frequency band in which amplitudes are measured can shift the observed amplitude ratio distribution but does not significantly mitigate issues (1) through (3). Taken together, these findings indicate that S/P amplitude ratios measurements are significantly influenced by differential path attenuation and signal-to-noise effects that are not easily accounted for with existing workflows. Unless handled with care, S/P amplitude ratio data may hinder rather than facilitate robust mechanism solutions.

A Deep Learning Approach for Non-binarizing the Impulsive/Emergent Phase Labels

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The impulsiveness of an arrival is one of the metrics that are often labeled along when picking seismic phase arrival times. This can be considered as the slope of the seismogram at the arrival, which can theoretically (but not realistically) range between 0 (perfectly emergent or parallel to the time axis) and 1 (perfectly impulsive or perpendicular to the time axis). However, due to the broad frequency contents and the noise in seismograms, the slope cannot be measured with confidence in most cases. Hence, this continuous value has been labeled subjectively by choosing from a set of choices – typically either impulsive or emergent (i.e., binary). Here, we propose a simple approach for converting these binary labels to continuous values. We train neural networks for binary classification using the binary impulsive/emergent labels. We show that the two classes cannot be separated even if we optimize the hyperparameters of the models to maximize the classification accuracy, which demonstrates the measure of impulsiveness is indeed a continuous value. We also show that different neural networks output almost consistent classification scores with most samples having a standard deviation of less than 0.1. We further evaluate the approach by altering the impulsiveness and signal-to-noise ratio of an arrival and show that the changes in classification scores align with our intuition. This classification score (or the 'impulsiveness') can serve as a measure of difficulty for phase arrivals, which can be used as weights when training phase picking models or for various geophysical inversion problems that rely on arrival time measurements.

Coda Calibration Technique for Reliable Moment Magnitudes and Source Characterization in SW USA and NNSS

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Reliable estimates of moment magnitude and source mechanism for seismic events are essential parts of understanding a seismic region and source characterization of earthquakes and explosions. Although waveform modeling-based methods (e.g. moment tensor inversion) is routinely used for moderate-sized and larger earthquakes (M>4 for regional catalogs), these inversions require good azimuthal distribution of stations and very good knowledge of the Earth's structure in the region, which makes waveform modeling difficult to perform on smaller earthquakes. Robust regional-specific seismic event characterization requires well-calibrated regional seismic stations to produce reliable and stable estimates of earthquake source parameters which can be derived using the coda wave calibration method. The Coda Calibration Tool (CCT) is an application designed for calibrating 1D shear wave coda measurement models to observed data using a small set of reference moment magnitudes calculated from other methods, such as moment tensor inversion. These calibrated measurement models can then be used to generate coda moment magnitude (M_W) and apparent stress estimated from stable source spectra.

In this presentation, we describe the methodology of using CCT for calibrating a region of seismic stations encompassing and surrounding the Nevada National Security Site (NNSS), a region of interest due to previous multi-physics experiments. The results from applying this calibration on earthquakes (with a range of magnitudes) and on chemical explosions, exemplify the stability of the calibration that we hope to be used to facilitate reliable estimates of moment magnitude and source mechanism for seismic events at local and regional distances in Nevada and surrounding regions in the future.

Using 3D Crustal Velocity Models and Multiazimuth Back Projection to Image Rupture Processes of Intermediate-sized Earthquakes

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We have developed a multiazimuth backprojection method, which allows us to image intermediate-sized earthquake rupture processes by using regional networks, 3D crustal velocity models, and may achieve depth resolution. We applied this approach to two earthquakes occurred in 2019 and 2020. The time-integrated images for the M_w6.4 foreshock and M_w7.1 mainshock agree with the fault geometry delineated by the aftershock distributions. Backprojection images at different times illustrate the detailed rupture processes for these two events. For instance, the M_w6.4 foreshock initialized close to the hypocenter, then the rupture propagated along a northwest trending fault with an average velocity of 1.0 km/s, and finally jumped to a southwest trending fault and propagated about 20 km with a velocity about 1.5 km/s. In contrast, the M_w7.1 mainshock initialized near the hypocenter, then propagated to the northwest upon reaching the Coso volcanic field with an average velocity of 1.4 km/s, and later turned to the southeast and propagated along the main fault zone with a complex bilateral process and a velocity about 0.6 km/s.

For the 2020 Mw 6.5 Stanley earthquake, more than 35% nondouble-couple component in long-period point-source solutions indicate a more complex source than slip on a planar fault. Combining backprojection, finite fault inversion and InSAR analysis, we find that the Stanley earthquake ruptured a pair of opposing-dip faults offset by a 10-km-wide step, including an unmapped northern subfault with predominantly strike-slip faulting and a southern subfault subparallel to the Sawtooth fault with predominantly normal faulting. This study reveals that a composite rupture process with strike-slip and normal faulting is typical for earthquakes located near the northern boundary of the Centennial Tectonic Belt (CTB), which is distinct from the predominantly normal faulting in the central CTB.

Broadband Spectral Characteristics of Moderate-sized Earthquakes Using Nearby Recordings

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We propose characterizing earthquake source spectra using three measures: seismic moment M_0, apparent stress σ_a, and stress parameter $\Delta\sigma_B$, corresponding to frequencies less than the corner frequency f_c, bracketing f_c, and much higher than f_c. To minimize path effects, σ_a and $\Delta\sigma_B$ are estimated using S wave records within 50 km. Depth dependent variations in velocity and density at the source are accounted for. The results are calibrated using observations at rock sites. We model near-surface impedance as a function of frequency using a generic model created using the corresponding Vs30 measure. We conduct a grid search with F-tests to constrain a frequency-dependent crustal Q model ($Q(f)=q_0 f^\alpha$) and a site attenuation constant κ_0 for each station, assuming Aki's ω^{-2} model.

We use this approach to study the Ridgecrest earthquake sequence. Taking advantage of high signal-noise-ratios (SNR) in lower (<0.5 Hz) and higher frequencies (~10-40 Hz), we first use 42 relatively larger Ridgecrest events (4.0≤M_w≤5.4) to construct the attenuation models: q_0=60, α=0.675, and κ_0 ranging from 0.01s—0.05 s among different stations. We subsequently use them to retrieve the source spectra of 122 3.5≤M_w≤5.4 Ridgecrest earthquakes. We validate our approach by inspecting the high frequency falloff rate γ, estimated using the stacking spectra for frequency ranging from 15 Hz to 36 Hz. For Mw≥4.0 earthquakes, γ is 2.0±0.20 as expected. For 3.5≤Mw≤3.9 events, γ decreases to 1.8±0.30, correlated with the decrease in SNR ratios. The scaling of σ_a and $\Delta\sigma_B$ with magnitude follow the relationship 10^(c×Mw) with c ~ 0.24 for σ_a and 0.30 for $\Delta\sigma_B$. Geometric mean σ_a and $\Delta\sigma_B$ for Mw 4.6 events with centroid depths ≥ 6 km are 1.0 MPa and 2.9 MPa, respectively, approximately 4 times larger than the geometric means σ_a and $\Delta\sigma_B$ for events of the same magnitude but with centroid depths < 6 km. The ratios of $\Delta\sigma_B/\sigma_a$ increase with magnitude slightly and have a geometric mean of 2.9, suggesting the source spectrum in this magnitude range is close to a Boatwright single-corner spectral model.

Random and Systematic Uncertainties in EGF Spectral Ratio Analysis and Their Implications for Source Scaling

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Most estimates of earthquake stress drop, and any resulting magnitude dependence are made by modeling amplitude spectra. Trade-off between high-frequency attenuation (path and site) and source shape leads to systematic differences in estimates of spectral stress drop for small earthquakes, leading to different scaling relationships between with magnitude or depth. Spectral ratio, empirical Green's function (EGF), techniques in which the amplitude spectrum of a larger earthquake is divided by that of a closely located smaller earthquake to obtain estimates of their corner frequencies, moment ratio, high-frequency asymptote, and hence spectral stress drop, are widely used. In theory, these techniques remove propagation effects without requiring a reference site effect or source spectral shape inherent in generalized inversion and spectral decomposition techniques. In practice, source model assumption, and data quality and availability have all limited the resolution and reliability of results. Some studies treat both corner frequencies and spectral stress drop as equally well resolved, and others do not, leading to different conclusions concerning earthquake source scaling. The well-studied data set of the Ridgecrest Community Stress Drop Validation Study provides an opportunity to identify whether there is systematic bias or large random uncertainties in the small event corner frequency. We select closely-located clusters of earthquakes that have a wide enough magnitude range for some events to form both the numerator and denominator in different spectral ratios. Initial results show that the corner frequency obtained for an individual event is systematically lower when it is the denominator, compared to the numerator, in a spectral ratio. We compare three independent approaches to spectral ratio analysis, varying time window selection, wave-type and assumed source model to determine under what conditions the estimates of spectral stress drop for both earthquakes in a ratio are reliable and comparable, and what causes systematic differences observed in preliminary tests.

Advances in Reliable Earthquake Source Parameter Estimation [Poster]

Poster Session • Wednesday 16 April

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POSTER 21

Earthquake Source Spectra Estimates Vary Widely for Two Ridgecrest, California, Aftershocks Because of Differences in Attenuation Corrections

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Differences in stress-drop estimates among groups of scientists for the same earthquakes suggest disagreement in the shape of the source spectra that are used to measure corner frequency. A critical step in characterizing source spectra involves applying empirical corrections for site effects and the loss of high-frequency energy that occurs along the source-receiver path. As part of the Ridgecrest stress drop validation study, we compare path-corrected source spectra among different methods for two nearly co-located M3 earthquakes and investigate whether systematic differences in the applied path corrections are affecting corner-frequency estimates. We find substantial disagreements in the path corrections, which are well-approximated with a simple exponential function related to the strong ground motion parameter kappa. These kappa ;differences are strongly correlated with corner-frequency estimates for path-corrected spectra, suggesting they are a large source of systematic differences in corner frequency (and inferred stress drop) among the methods, reflecting varying tradeoffs between the source and path contributions to observed spectra. Because each method presumably fits the data it uses sufficiently well, these results indicate the limitations of existing purely empirical techniques to estimating path corrections and the need for new approaches.

POSTER 22

Update and Future Plans for the International SCEC/USGS Community Stress Drop Validation Study

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We present the results to date of the Statewide California Earthquake Center/U. S. Geological Survey Community Stress Drop Validation study. The Community study has engaged a wide international group since its conception in 2021, focused on using a common dataset of the 2019 Ridgecrest, California earthquake sequence. The aim of the collaboration is to improve the quality of stress drop and earthquake source parameter estimates and their uncertainties, to enable more reliable ground motion forecasting, and towards a better understanding of earthquake source physics.

To date, we have received 56 unique community submissions, consisting of spectral corner frequencies (or source durations), moment magnitudes, and spectral stress drops. Initial analysis reveals significant scatter of spectral stress drops spanning over six orders of magnitude. Averaging submissions for a prioritized subset of 56 events results in a minimal standard deviation between spectral stress drops, indicating overall consistency. Lack of correlation between methods for magnitudes less than ~2.5 indicates that obtaining reliable spectral stress drop values for events this small is difficult, at least within the frequency range of the data. We use submitted moments to study the relationship between seismic moment and both catalog local and moment magnitude to develop a consistent magnitude scale for comparison. Considering the trends in magnitude and depth for each set of submissions demonstrates consistent trade-offs. We examine the spatial and temporal distribution of averaged, de-trended values to investigate relationships with the M7.1 mainshock rupture.

The results to date will be published in the coming Special Issue of the *SSA Bulletin*. The next stage of the community endeavor will likely include an experiment involving synthetic data. We welcome new members to the study, wishing to observe, learn or more actively participate. Visit https://www.scec.org/research/stress-drop-validation for more information.

POSTER 23

Focal Mechanism and Uncertainty Estimation in Data-sparse Settings

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An assumed double-couple focal mechanism can be inferred by inversion of observed body wave amplitudes when given waveform data from one three-component seismometer with *P*, *SV* and *SH* signals. Since *P* and *S* waves have different noise levels, asymmetry of uncertainty in the observed data propagates to the estimated source mechanism parameters. For the general case where we need to interpret relative amplitudes rather than absolute amplitudes, inversion leads to an entire class of focal mechanisms which produce body waves whose amplitude vectors, represented in 3D space, point in the same direction as the observed amplitude vector. This approach is especially useful for data-sparse regions because it accounts for amplitudes, polarities and uncertainties in a simple and geometrically elegant way.

Most existing methods for focal mechanism inversion use some form of brute force, commonly grid search. We have developed a hybrid of brute force (random search) and directed search (gradient descent) methods to trace out the best-fitting class of mechanisms in different 3D spaces capturing parameters like strike, dip and rake or T-axis and P-axis orientations. Gradient descent with randomly sampled starting points not only allows for the computation to be time efficient, but also for systematic exploration of multiple minima. We show that some parameter spaces can capture these classes of mechanisms in a more concise and interpretable way, as well as provide an advantage when propagating the associated uncertainty using Monte Carlo methods.

The broad aim of our research is to demonstrate the utility of the new inversion and uncertainty estimation methods compared to others commonly used, provide an analysis of the pros and cons of our method and show example cases using data from Uganda: focal mechanisms of East African rift earthquakes which occurred before and during a dense deployment of temporary seismometers.

POSTER 24

Source and Along-path Seismic Parameters of S-waves From Earthquakes in the Central-northern Gulf of California, Mexico

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I used 114 S-wave recordings from 27 earthquakes with epicenters in the central-northern Gulf of California (GoC), Mexico, and applied a one-step least-squares inversion approach to separate source and path effects from the amplitude Fourier acceleration spectra of the vertical components of ground motion. I then parameterized the nonparametric source and along-path spectra using Brune's (1970, 1971) ω^2 source model and an exponential function containing the S-wave Quality factor (Q_S), respectively. I found evidence that the stress drop values, on average, follow self-similar scaling behavior, although the number of recordings in my database is limited. Furthermore, earthquakes with lower stress drops tend to occur near the Canal de Ballenas Rift and Basin, an extensional zone within the central-northern GoC, whereas earthquakes with relatively higher stress drops tend to occur along the Salsipuedes Transform Fault, a zone characterized by right-lateral strike-slip events. Overall, I found a median stress drop of 15.3 MPa. Finally, I estimated an average $Q_S = (98.3 \pm 2.9)f^{(0.64 +- 0.01)}$ when assuming a geometrical spreading of $r^{-1.0}$ for $r \leq 80$ km and $r^{-0.5}$ for $r > 80$ km. I expect my results to contribute to the ongoing debate on scaling behavior and lateral variability of the stress drop. Furthermore, these findings enhance our understanding of the physics governing earthquakes and ground motion in the central-northern GoC.

POSTER 25

The International Seismological Centre (ISC) Earthquake Toolbox for MATLAB: Interactive Access to Earthquake Observations and Parameters

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The ISC Earthquake Toolbox for MATLAB is designed to offer access to parametric earthquake data curated by the International Seismological Centre (ISC). The ISC produces the definitive global earthquake catalogue by combining seismic phase arrivals from ~150 agencies in ~100 counties. The ISC Bulletin also includes earthquake parameters, reported by many agencies, such as hypocentres, magnitudes, and moment tensors, and is freely accessible, searchable and downloadable in a range of widely used seismic formats through the ISC website (www.isc.ac.uk/iscbulletin). The ISC Earthquake Toolbox for MATLAB allows users to query the ISC Bulletin via a graphical user interface (GUI) within the MATLAB environment.

The GUI replicates the search options of the ISC website and reads the parametric earthquake data into MATLAB data. Several live scripts are included to demonstrate to the user how to interrogate the ISC Bulletin data. Examples include comparing different magnitude types and authors, and plotting moment tensors from the ISC Bulletin. The toolbox enables the unrestricted exploration of earthquake location data, phase arrivals, magnitudes and amplitude measurements as well as earthquake moment tensors. The toolbox also allows 3D visualisation of earthquake distributions, 2D and 3D moment tensor plotting, as well as introducing new functionalities such as plotting moment tensors within MATLAB mapping toolbox figures. It is anticipated that the ISC Earthquake Toolbox for MATLAB will be used as a teaching tool to explore the wealth of earthquake data available at the ISC, as well as a tool for researchers to build more complex applications upon. The toolbox is publicly available to download via GitHub (github.com/tomgarth/ISC_Earthquake_Toolbox) and MathWorks file exchange (https://uk.mathworks.com/matlabcentral/fileexchange/167786-isc-earthquake-toolbox).

POSTER 26

Upper Plate Control on Earthquake Stress Drop: Comparison Between High and Low Ground Velocity Zones in Costa Rica

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Despite its small area, Costa Rica's tectonics is highly complex and geophysically diverse. Upper plate dynamics (crustal deformation and seismicity) is strongly influenced by the interaction of four tectonic plates: The Cocos plate, the Caribbean plate, the Panama microplate and the Nazca Plate, modulating the generation of M+7 megathrusts every 40 to 50 years, the abundant microseismicity, intermediate magnitude earthquakes, Slow Slip Events, Low Frequency Earthquakes (LFEs) and Landslides. The notorious presence of sedimentary basins, a large shear zone located in the Central Valley and active volcanic chains, lead the region to a wide range of peak ground velocity (PGV) measures following the occurrence of earthquakes at short and large distances. For example, we analysed the records from 25 teleseismic events with magnitudes between 7.0 and 7.5, using a very dense broadband seismic network operated by the Volcanological and Seismological Observatory of Costa Rica (OVSICORI), we observed that the Talamanca Mountain Range, predominantly composed of well-consolidated Miocene volcanic rocks, represents an area with low PGV. In contrast, the Tilaran Range, mainly consisting of poorly consolidated Pleistocene volcanic rocks, exhibits anomalously high PGV values. Both the Talamanca Mountain Range and the Tilaran Range show clustered and well-aligned seismicity between 0 and 20 km depth that is poorly studied. Understanding the source of variability in the amplitude of ground motion across Costa Rica is essential for improving building codes, fine-tuning Ground Motion Prediction Equations (GMPEs) and characterizing which regions are more susceptible to damage from earthquakes. This on-going study explores the variability in earthquake stress drop within these two distinct regions. We seek to better understand how the mechanical properties of the rocks in the Talamanca Mountain Range and the Tilaran Range influence the earthquake rupture mechanics and radiation of wave fields at frequencies compared to those responsible for negatively affecting buildings and infrastructures.

POSTER 27

Micro-EQpolarity: Transfer Learning for Microseismic P-wave First-motion Polarity Determination and Its Application in the Western Canada Sedimentary Basin (WCSB)

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Microseismic focal mechanism solutions (FMSs) are essential for understanding reservoir stress state and rock fracturing during hydraulic fracturing. Focal mechanism inversion based on P-wave first-motion polarity (FMP) has been widely utilized due to the deployment of dense seismic arrays. However, preparing high-quality polarity data is highly labor-intensive and time-consuming, making focal mechanism inversion for extensive microseismic events challenging. While existing artificial intelligence (AI)-assisted workflows, which have been trained on data from moderate to large earthquakes, have demonstrated efficiency and reliability in applications, their performance diminishes when applied to microseismic events. This decline is likely due to differences in signal-to-noise ratio (SNR) and rupture mechanisms between microseismic events and larger earthequakes. Thus, a clear need exists for an AI-based model tailored for microseismic FMP determination.

We propose Micro-EQpolarity, a fine-tuned extension of the recently proposed deep learning model EQpolarity, which leverages transfer learning to determine the P-wave FMP of microseismic events. The model was initially trained on the Southern California Seismic Network (SCSN) dataset and subsequently fine-tuned using the Tony Creek Dual Microseismic Experiment (ToC2ME) - a dataset from western Canada, encompassing a hydraulic fracturing well-pad. Specifically, we manually picked 19,724 FMPs from representative microseismic events to fine-tune the pre-trained model. The resulting model achieves 99.19% accuracy, showing a significant improvement of 29.26% over the baseline pre-trained model. When applied to the full ToC2ME dataset, Micro-EQpolarity successfully determines FMSs of 2,519 events with magnitudes as low as -1.4. This new catalog contains four times more FMSs than previously reported 530 events and reveals four distinct types of FMS. These focal mechanisms enable illuminating fine-scale fault structures (e.g., a well-defined en-echelon structure) at an unprecedented resolution and offer new insights into the complex regional fracture network.

POSTER 28

Refining Stress Drop Measurements Using Spectral Asymptotes: Insights From the Ridgecrest Sequence

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In the community stress drop validation study (Abercrombie et al., 2024), stress drop was estimated for the Ridgecrest earthquake sequence. Significant variation in stress drop between research groups using various methods was observed. Much of this variability can be traced to differences in corner frequency estimates, often caused by even slight discrepancies in accounting for the path and site effects. The cubic dependence of stress drop on corner frequency makes obtaining accurate measurements critical for reducing uncertainty.

Recent work has shown promise for a method that uses the asymptotes of the spectral ratio for pairs of events. In this method, the low-frequency end represents the moment ratio and the high-frequency end represents the slip ratio. By eliminating the need for direct corner frequency measurements this approach reduces potential sources of uncertainty. We apply this method to a subset of larger events in the Ridgecrest catalog and compare the results to those from the community study. Additionally, we explore the effectiveness of different methods (both automated and manual) for determining asymptotes and assess whether these asymptotes can be measured with sufficient precision to preserve the advantages of this approach.

POSTER 29

Earthquake Energy Calculations From Seismogeodetic Data

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This research extends the RTergpy program, originally developed by our group, to evaluate novel seismogeodetic data and enhance its capabilities for the calculation of radiated seismic energy, particularly in the near-field where traditional weak-motion seismometers can quickly go off scale during strong shaking. Seismogeodetic data is a combined data product that incorporates both real-time positioning from GNSS with high-rate accelerations from collocated accelerometers and has been shown to approximate the moment magnitude of nearby offshore ruptures accurately and rapidly. This data stream provides an opportunity to synchronously calculate radiated energy that can be compared with seismic moment to assess whether an event is likely to be a slow rupturing tsunami earthquake through the log of the energy-to-moment ratio, described as the Theta parameter (Newman and Okal, 1998). In addition to energy, RTergpy includes functionality for evaluating the change in energy over time for a per-second assessment of rupture behavior. In the far-field, we have shown this method to be beneficial for additionally estimating earthquake rupture duration (another parameter that identifies slow tsunami earthquakes). RTergpy directly incorporates one such estimate called at the maximum of the Time-Averaged Cumulative Energy Rate (TACER) as described in Convers and Newman (2013). We are directly assessing the performance, and any process improvements needed for utilizing seismogeodetic data for such calculations. The data is being processed similarly to seismic data, only ignoring instrument response as the seismogeodetic data is pre-processed. This indicates no additional calibrations should be needed. Preliminary results show that near-field outputs from seismogeodetic data closely match those from seismic data for smaller events. These new tools are proving extremely valuable for improving rapid earthquake and tsunami risk assessments.

POSTER 30

Mb Magnitude Station-station Spatial Correlations and Station Mb Biases

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Station mb's from ISC (2000-2020) and NEIC (2017-2021) catalogs are examined for station effects (station amplitude biases). Analyses include a General Linear Model (GLM) as well as statistics of station residuals w.r.t. the network average. Residuals were examined versus epicentral distance, network magnitude and with time. Consistent station biases are observed in both catalogs with regional spatial correlation and consistent over time. That is, most stations systematically report a magnitude higher or lower w.r.t. the network average. The station biases exhibit spatial patterns that correlate to geophysical/tectonic provinces and may contain valuable geophysical information. A global station-station correlation structure may be extracted. That is, mb's reported by two stations within 100 km will generally have a correlation coefficient >50%. While the mb network standard deviation is generally 0.35-0.4 units, any two stations less than 100 km apart will likely report station-station standard deviation 0.17-0.2. Station biases for most sites are remarkably stable over time with events from multiple source regions. This implies the leading bias mechanism is the local mantle-crust response. The distribution of station biases closely resembles the distribution of network residuals. Past work in world-wide explosion seismology observed reciprocal relationships between regional station mb biases and explosion teleseismic mb biases. Consequently network mb magnitudes may exhibit regional baseline biases due to these mantle-crustal responses.

POSTER 31

The Influence of 3D Velocity Models on Seismic Moment Tensor Estimation in Alaska

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The EarthScope Transportable Array of seismic stations in Alaska and western Canada peaked in 2017 and has provided excellent data coverage in Alaska and western Canada, leading to a new generation of seismic velocity models, many of which are archived at the EarthScope IRIS EMC. We use five of these models to examine how 3D structures impact the estimation of moment tensors for a set of five representative Alaska earthquakes. We use the software package SPECFEM3D_Globe to generate Green's function databases for each model, and then use the Python-based package MTUQ to perform moment tensor inversions. Using a set of goodness-of-fit metrics, we quantify the performance of each velocity model, as well as the differences among the estimated moment tensors. The testing will allow us to carefully choose the best starting model for a future adjoint tomography study in Alaska.

POSTER 32

Joined Double Difference Earthquake Location and Estimation of Vp/Vs-Ratio from Earthquake Clusters

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A commonly used method to determine the vp/vs ratio within spatial closely distributed earthquakes is the approach proposed by Lin and Shearer (2007). There, pairs of differential P- and S-arrival times measured at the same station are used to estimate the vp/vs ratio within the earthquake cluster. The vp/vs

ratio is the slope of a line fitted to differential P- and S- times after subtraction of the mean value over all stations. This statistical approach is highly dependent on the geometry of the earthquake locations and the station distribution. Only in a medium with a homogeneous vp/vs ratio, the estimated vp/vs ratio has no bias, as shown by Palo et al. (2016) and cannot be accurately accounted for, which limits the usage of “Lin and Shearer”.

Here we present a new method to overcome these limitations as we invert directly for the vp/vs ratio after a precise location, e.g. with the double-difference earthquake location of Waldhauser and Ellsworth (2000). Our approach is based on the ansatz of the relative location presented by Fréchet (1985). We use P and S differential times and invert directly for P-velocity and vp/vs ratio. We can combine the double difference relocation of the earthquake hypocentres with our estimation of the vp/vs ratio in an iterative inversion process to improve locations and velocity estimates. We test our method with synthetic data in a 2D and 3D subduction zone setting and apply it to a dataset of an earthquake cluster at the seismogenic interface in the subduction zone offshore Ecuador.

POSTER 33

Kinematic Slip Model of the Mw7.0 December 5, 2024 Offshore Cape Mendocino Earthquake

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The M7.0 December 5, 2024 Offshore Cape Mendocino earthquake is the largest earthquake in the triple junction area since the Mw7.2 April 25, 1992 Cape Mendocino earthquake. Focal mechanisms of the mainshock and largest aftershocks are consistent with right-lateral strike slip on the ~east-trending Mendocino fracture zone (MFZ). The December 2024 rupture closely follows the December 2021 Petrolia Mw6.1 and Mw6.0 earthquake doublet, which also initiated on the MFZ, and the Mw6.4 December, 2022 Ferndale intraslab earthquake (Yoon and Shelly, 2024). In order to clarify the location and amount of slip in the December 2024 earthquake, we assemble three-component broadband seismograms from 91 regional stations within 300 km of the main shock epicenter, combined with 89 horizontal coseismic offsets derived from Global Navigation Satellite System (GNSS) time series and a Sentinel-1 ascending interferogram. These data are interpreted with a model of slip distributed on two vertical fault planes with slightly different strikes, representative of the eastern MFZ and spanning the ~70 km length of aftershocks. Assuming right-lateral strike slip, we find that slip occurs in two distinct pulses. The first occurs within ~4s of the origin time and is isolated near the USGS-determined hypocenter at the western end of the rupture zone, and the second occurs ~10s after the origin time near the initial locus of slip, followed by unilateral rupture propagation towards the east. This model is consistent with two distinct direct P arrivals observed in three-component record sections. We shall investigate the precise nature of the temporal gap in initial slip as well as any possible relationship between the spatial distribution of net coseismic slip and the slip of the first (Mw6.1) of the 2021 Petrolia earthquakes.

POSTER 34

Evaluating Scaling Relationships From Reliable, Insar-derived Earthquake Source Parameters

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Scaling relationships between earthquake source parameters (e.g. fault length, fault width, slip, and seismic moment) have strong implications for earthquake physics and seismic hazard. Questions remain about the existence of a power law (or not), in length-moment scaling, whether small and large earthquakes scale similarly, and whether scaling differs for different tectonic regimes and event types. Source parameters estimated by different groups, and from different data sources, can show significant epistemic uncertainty, which can affect the quality of the scaling relationships obtained.

In this study we aim to use more robust estimates of source parameters by focusing on earthquake models constrained by InSAR. InSAR has been used to study earthquakes over a wide range of magnitudes (4.9 ≤ Mw ≤ 9.0) and can directly constrain estimates of key source parameters (e.g. rupture length) for shallow earthquakes. We compile an InSAR-based source parameter dataset by mining published studies that used InSAR data. For well-studied events, such as the 2015 Gorkha, Nepal and 2019 Ridgecrest, CA earthquakes, we use the range of models to assess source parameter epistemic uncertainties. We supplement this compilation with our own InSAR-constrained models of recent earthquakes absent from the literature. Our final dataset contains parameters from over 200 earthquakes, from 1992 to present.

To evaluate scaling relationships, we use regression analysis to quantify the relationships between key parameters, such as fault length, L and seismic moment, M0. We find that different event types have different length-moment scaling relationships – for thrust faults, we find M0 ∝ L2.2, whereas for strike-slip faults, M0 ∝ L1.9. We do not find a statistically significant improvement to data fit if we include a change of scaling between smaller and larger earthquakes.

POSTER 35

Regionalized Earthquake Source Models of Subduction Interface Earthquakes

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In Skarlatoudis et al. (2016; Sea16), we established global scaling relations between seismic moment (M_0) and physical source properties such as earthquake rupture area (S), total asperity area (S_a), slip (D), and fault width (W) for large subduction interface events. These relations significantly reduced the variability in predicting these source parameters. Since their publication, researchers and institutions worldwide have utilized these scaling relations to forecast ground motions and tsunamis from significant subduction earthquakes for various applications, including the US National Seismic Hazard Maps.

Since the creation of the Sea16 database, and by using the Slab2.0 (Hayes, 2018) subduction zone geometries, we identified 79 additional subduction interface events with published finite fault solutions that have been catalogued in the USGS Finite Fault database, the Online Database of Finite Fault Rupture Models (SRCMOD; Mai and Thingbaijam, 2014), and the Next Generation Attenuation Subduction (NGA-Sub) database, nearly tripling the available data. We expanded our existing database of subduction interface events with these additional models and developed an updated set of global scaling relations enhancing predictions of various source properties and reducing uncertainties.

The differences between the regression coefficients from this study and Sea16 were generally small. However, we showed that rupture length has a linear scaling relationship with seismic moment, but rupture width saturates, causing a decrease in scaling of rupture area, which is offset by an increase in slip. This is analogous to the saturation of rupture width, identified in shallow crustal earthquakes. Furthermore, for subduction zones with an adequate number of earthquakes in our database, we examined regionalized versions of the scaling relations and explored possible explanations for the observed regional differences in subduction interface ground motions by seeking correlations with various parameters such as trench-normal trench velocity, thrust dip angle and subduction partitioning.

POSTER 36

Quantitatively Assessing the Importance of Three-dimensional Structure for Finite Fault Inversions

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Accurately producing earthquake inversions is fundamental to understanding source processes and hazards related to large earthquakes. Unfortunately, uncertainty and nonuniqueness is inherent in the inversion process. Traditional kinematic inversions rely on 1D structural models; however, for tectonically complex regions like subduction zones, this assumption may lend to unaccounted “path effects” that may be inappropriately mapped into output source models. This then may hinder our ability to accurately image and understand large earthquakes. The simplification is often justified by assuming crustal deformation results from lower-frequency shaking that is less sensitive to structural heterogeneities. Recent work, however, demonstrated accounting for 3D structure can impact time-dependent crustal deformation. One step further, if we apply 3D structure into the inversion framework, how does this impact our ability to resolve large earthquakes and their physics? Unlike the “traditional” approach, we compute 3D Green's Functions (GFs) for application into the inversion process. We focus on the Japan Trench and the rupture area from the 2011 M7.9 Ibaraki earthquake to assess the impact of incorporating 3D structure into the workflow. To understand the impact of 1D vs. 3D structure, we create synthetic stochastic slip rupture models based on the 2011 Ibaraki earthquake and model the surface deformation resulting from each event at GNSS stations across Japan. We then produce source inversions assuming either a 1D or 3D layered earth model and assess the dissimilarity of kinematic inversions to synthetic ruptures to quantitatively compare models. We also run inversions varying the azimuthal range that highlights or neglects regions of structural complexity and assess the coverage impact on resultant models. We find nearly all inversions from 3D GFs have lower dissimilarity values than those produced using traditional 1D GFs. This work demonstrates the importance of considering 3D structure specifically when studying crustal deformation.

POSTER 37

Using a High- to Low-frequency Spectral Ratio to Distinguish Variations in Earthquake Source Properties

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Earthquakes radiate energy across a range of frequencies and the shape of the source spectrum can reveal details about earthquake mechanics. However, interpreting observed spectra is complicated by hard-to-resolve tradeoffs between source and path effects, i.e., an earthquake with less high-frequency energy might have the same observed spectrum as an earthquake whose waves passed through a more attenuating region. Often, analyses that attempt to correct observed spectra for path and site effects to estimate parameters like stress drop suffer from large uncertainties and show poor agreement among different studies. Here, we introduce a method to address this ambiguity by studying a new parameter, β, defined as the ratio of the average spectral amplitude in a high-frequency band to that in a low-frequency band. For a single station and sufficiently distant earthquake region, the path and station effects are roughly constant and are removed by applying a correction using small, local calibration events. Variation in corrected β values for earthquakes of similar magnitude therefore reveals changes in source mechanics. We identify spatial variations in corrected β values for southern California seismicity that correlate with spatial distributions of stress drop; since higher stress drop regions have comparatively more high-frequency radiation for equal magnitude earthquakes, they have a higher β. Our simple approach can robustly identify variations in high-frequency energy from different source regions without the need to apply path corrections, as the results are insensitive to path effects. Thus, our proposed β analysis provides an alternative to more complicated spectral analysis methods, such as spectral decomposition, for identifying variations in high-frequency radiation. We compare our results for different datasets to those of previous stress-drop studies, explore some synthetic examples, and discuss implications for earthquake dynamics and fault properties.

POSTER 38

Source Characterization of Complex Earthquakes via Subevent Decomposition: Application to Apparent-repeating Earthquakes

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Stress drops of small earthquakes are often estimated under the assumption of a simple rupture process. However, some real rupture processes exhibit significant complexities, with multiple shocks being one example. Repeating earthquakes are considered to result from intermittent seismic slip on isolated earthquake patches and are generally assumed to involve a simple rupture process. However, it is also known that they can exhibit complex behaviors, such as magnitude variations, especially after large earthquakes. Advancing the understanding of these rupture processes is crucial for improving insights into the earthquake propagation process. We investigated the characteristics of the rupture processes for several sequences of repeating earthquakes along the Japan Trench that exhibited significant magnitude variations.

The sequence introduced here consists of approximately 50 earthquakes with magnitudes varying between Mw 3 and 4. By performing deconvolution using the waveforms of a nearby smaller earthquake, the apparent moment-rate function (AMRF) was estimated. The results show that events with Mw <3.6 exhibited a single-pulse rupture, while those with Mw >3.6 generated an additional rupture. Depending on the loading rate, the final magnitude, slip amount, and the number of patches appear to vary.

Rupture separation was performed using Kikuchi & Kanamori's (1982) method, placing candidate sources on a planar fault consistent with the plate boundary. This approach determined the locations, onset times of up to two sources, and a common duration. Based on the obtained duration and seismic moment, stress drops for each patch were estimated using Brune's (1970) model, ranging from 20 to 50 MPa. These values exceed typical estimates for small earthquakes in Japan but align well with Nadeau & Johnson's (1998) empirical relationship for this magnitude range. If the stress drop were around 3 MPa, the patches would become too large and overlap significantly, suggesting the targeted downdip repeating earthquakes may genuinely have high stress drops.

POSTER 39

Robust Earthquake Location Using Random Sample Consensus (RANSAC)

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Accurate earthquake location, which determines the origin time and location of seismic events using phase arrival times or waveforms, is fundamental to earthquake monitoring. While recent deep learning advances have significantly improved earthquake detection and phase picking, particularly for smaller-magnitude events, the increased detection rate introduces new challenges for robust location determination. These smaller events often contain fewer P- and S-phase picks, making location accuracy more vulnerable to false or inaccurate picks.

To enhance location robustness against outlier picks, we propose a machine learning method that incorporates the Random Sample Consensus (RANSAC) algorithm. RANSAC employs iterative sampling to achieve robust parameter optimization in the presence of substantial outliers. By integrating RANSAC's iterative sampling into traditional earthquake location workflows, we effectively mitigate biases from false picks and improve the robustness of the location process. We evaluated our approach using both synthetic data and real data from the Ridgecrest earthquake sequence. The results demonstrate comparable accuracy to traditional location algorithms while showing enhanced robustness to outlier picks.

Advancing Seismic Hazard Models [Poster]

Poster Session • Thursday 17 April

Conveners: Vedran Lekic, University of Maryland, College Park (ved@umd.edu); Victor Tsai, Brown University (victor_tsai@brown.edu)

POSTER 55

Subduction Zones in USGS National Seismic Hazard Models

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Shaking caused by subduction zone interface and intraslab earthquakes can be a large contributor to overall earthquake hazard in U.S. Geological Survey (USGS) National Seismic Hazard Models (NSHMs). Recent and ongoing efforts to characterize hazard from subduction zones across the U.S. and its territories have shown that it is difficult to apply the same earthquake rupture forecast (ERF) modeling techniques everywhere. Furthermore, ergodic global and regional partially non-ergodic ground motion models (GMMs) are often difficult to reconcile with local data that may not have been considered during GMM development. For example, in the conterminous U.S. NSHM, the slow-slipping Cascadia subduction zone is characterized by a reliable geologic and paleoseismic record of large, zone-rupturing earthquakes, but the earthquake catalog is depleted in M<8 events. The subduction zone ERF is therefore limited to large M8+ events and localized patches of low-rate subduction intraslab events. The complex and uncertain structure of deep basins in high exposure areas like Seattle required their careful consideration during development of the GMMs. In contrast, the fast-slipping Alaska-Aleutian subduction zone (AASZ) is constrained by a modest paleoseismic record; high slip-rates permit development of geodetically derived slip-deficit rates. The AASZ also includes a rich catalog of smaller earthquakes, so the ERF also includes gridded seismicity-based ruptures (M5-8). In the 2023 Alaska NSHM, regional partially non-ergodic GMMs for subduction interface events were found to be at odds with recent earthquake data and were therefore disregarded in favor of data-adjusted global models. Here, we compare the different subduction zones considered in the USGS NSHMs in terms of geometry, geologic and paleoseismic constraints on historic ruptures, and earthquake catalog rates. We also discuss ways to improve the consistent representation of epistemic uncertainty across subduction zone ERF and GMM components.

POSTER 56

Geologic and Seismotectonic Data for the 2026 American Samoa and Mariana Islands National Seismic Hazard Model Update

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A primary responsibility of the National Seismic Hazard Model (NSHM) Project of the U.S. Geological Survey is to model the ground shaking hazard from potentially damaging earthquakes for U.S. territories. The previous and initial assessments for American Samoa, Guam, and the Commonwealth of the Northern Mariana Islands were completed in 2012, and significant updates are currently being planned for a release in 2026. The research and development process is consistent with past NSHM workflows and includes compiling new earthquake catalogs for the regions, reviewing possible new fault sources, and revising previously included fault sources, all in order to develop earthquake rupture forecasts (ERF) for the NSHMs. To support the 2026 update, we examined available geological and geophysical data on the islands and the surrounding ocean floor, and we developed a geodatabase that summarizes the fault section inputs. New inputs for the ERF component of the model include updated and additional crustal fault sections. The areas of interest have been adjusted from the 2012 update, but they still cover significant regions of Micronesia (Guam and the Northern Mariana Islands) and Polynesia (American Samoa). The previous extent of the Micronesia subregion is largely retained, including the major features of Mariana subduction zone. The area of interest for American Samoa in the update will be smaller than the assessment from 2012: the Tonga subduction zone is included with an area of backarc spreading, but only the northernmost section, whereas the previous work included Fiji and islands of New Zealand. The area also extends far enough north to capture seismicity related to the Samoan hotspot track. Development of the geological and geophysical inputs for the 2026 NSHM represents a catalyzing step in the workflow that informs the ERF and other components of the source and ground motion models for the probabilistic seismic hazard assessment.

POSTER 57

Sensitivity of Seismic Hazard Models to Catalog Magnitude Conversion Relations

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The 2023 U.S. National Seismic Hazard Model (NSHM) showed that hazard estimates can be extremely sensitive to changes in magnitude. Hazard is typically computed for earthquakes above a minimum magnitude (e.g., M_{min}=5), but smaller magnitude earthquakes are used to 1) develop the spatial kernel that forecasts where damaging earthquakes are likely to occur in the future, and 2) determine the Gutenberg-Richter *b*-value that is used to extrapolate the occurrence rate of the more common smaller events to the rate of M_{min} earthquakes. Changes in the magnitudes, whether due to revised estimates or changes in how various magnitude types are converted to a uniform moment magnitude, can therefore affect forecasts of both where and how often damaging shaking is expected to occur in the future.

Here we focus on the sensitivity of the gridded seismicity model to the catalog conversion equations in the eastern United States. In the 2023 NSHM, magnitudes of various types were converted to moment magnitudes using equations developed by the Central and Eastern United States Seismic Source Characterization for Nuclear Facilities, based on linear regressions made using data from a catalog containing events up through 2008. We update these regression equations using more recent earthquakes from 2000 through 2023. Also, rather than the least squares regression used previously, we adopt orthogonal regression, following Arabasz et al. (2016), which accounts for uncertainties in both dependent and independent regression variables (observed moment magnitude and alternative magnitude type, respectively). We compare the spatial distribution of annual M≥5 rates, which directly feed into the hazard computation, using 3 different models: 1) the previous 2023 NSHM conversions, 2) our updated conversions, and 3) no conversions at all. We find that the choice of conversions can lead to significant differences in the rate forecasts, which can greatly impact the seismic hazard model, particularly in regions with low seismicity rates like the eastern U.S. where the hazard is dominated by gridded seismicity rather than a fault model.

POSTER 58

The USGS 2025 Puerto Rico and U.S. Virgin Islands Earthquake Rupture Forecast

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We present the preliminary 2025 U.S. Geological Survey (USGS) time-independent earthquake rupture forecast (ERF) for Puerto Rico and the U.S. Virgin Islands (PRVI). This model updates the prior 2003 ERF and includes expanded geologic and seismologic input data, as well as methodological improvements based on the 2023 National Seismic Hazard Model (NSHM23) for the conterminous U.S. Development of the ERF is overseen by a 16-member participatory review panel. The model is expected to be released in December 2025.

The crustal on-fault portion of the ERF includes substantial updates to the fault inventory (increasing from 3 to 35 fault sections) and a new geologic deformation model that captures uncertainties in fault slip rates. We use the inversion approach to solve for rupture rates matching those slip rate data in an interconnected fault-system following the methodologies established for the western U.S. in NSHM23. The statistical seismology model largely follows the methods used in NSHM23, but includes an updated rate uncertainty estimation method that is more appropriate for regions where completeness magnitude is near or above the minimum magnitude considered for hazard calculations (as is the case for PRVI). We find that earthquake activity rates calculated for crustal faults exceed best-estimate extrapolations from observed seismicity, i.e., there is a "bulge" in the regional magnitude-frequency distribution. This indicates a potential inconsistency between the data, assumptions, and/or methodologies used for the crustal fault and statistical seismology models. This is an outstanding issue that warrants further investigation in future models, including identifying any biases in fault slip rates and regional seismicity rates. The ERF for subduction sources also uses the fault-system inversion methodology to solve for rates of large interface ruptures and match slip rate data. This is a first for U.S. subduction ERFs, and paves the way for future updates for Alaska and Cascadia. It includes uncertainties in coupled interface geometry and slip rates, rupture scaling, and *b*-value.

POSTER 60

Comparing Site-specific Seismic Hazard Analyses with the National Seismic Hazard Model for the Central and Eastern U.S.

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There are ongoing discussions on whether the site-specific hazard of the new generation of nuclear reactors can be evaluated and licensed through a scaled-back effort using the USGS National Seismic Hazard Model (NSHM). The objective of this analysis is to explore the feasibility of that idea. We have performed site-specific probabilistic seismic hazard analyses (PSHA) and site response analyses for 16 proposed and existing critical and important facilities distributed throughout the central and eastern U.S. (CEUS) including LNGs, bridges, mine tailing facilities, power plants, and petroleum and chemical storage sites. For each site, we have compared our site-specific results with the 2023 NSHM to understand potential differences. The inputs into the hard rock PSHA include the 2012 EPRI/DOE/NRC CEUS seismic source characterization model and the NGA-East ground motion models. To adjust the hard rock hazard to foundation/ground surface level, we performed 1D equivalent-linear site response analysis using a stochastic point-source model and random vibration theory. This approach has been used for most of the nuclear power plants in the CEUS.

The hard rock site-specific PGA and 1.0 sec SA hazard is about 33% lower on average (range of 4 to 83%) than the 2023 NSHM when the hazard is controlled by the gridded seismicity due to differences in the gridding parameters (CEUS-SSC versus NSHM). The CEUS-SSC parameters are defined for site-specific use. For sites near Quaternary faults e.g., New Madrid, Charleston, or Meers fault systems, the site-specific hard rock hazard is generally within 20% of the NSHM. The differences at the ground surface/foundation level can be even more significant due to the differences between the site-specific site response analyses and the USGS use of generic amplification factors. These differences are frequency-dependent and can range up to a factor of two with no systematic bias. Differences between a site-specific approach to site effects and generic amplification factors are to be expected as the goals of the NSHM for building design are different than those for a critical facility.

POSTER 61

Update of the Lower Seismogenic Depth Model for Western U.S. Earthquakes

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We present an updated model of the lower seismogenic depth of earthquakes in the western United States (WUS), estimated using the hypocentral depths of events with magnitudes greater than 1, a crustal temperature model, and historical earthquake rupture depth models. The earthquake locations are sourced from the Advanced National Seismic System Comprehensive Earthquake Catalog (ComCat) spanning from 1980 to 2024. This data is supplemented with relocated seismicity in southern California (Hauksson et al., 2012) for higher precision and better resolution. We calculated the average depth of the deepest 10% of the events in the merged catalog using an adaptive radius (R) instead of a fixed 50 km. This initial R is determined based on the best depth location errors. Our findings show a strong correlation between this updated depth model and rupture depths derived from the coseismic slip of large earthquakes across the region. Generally, our estimated earthquake depths are deeper than the seismogenic depths previously determined for the Uniform California Earthquake Rupture Forecast version 3 (UCERF3) model, which was based on work by Petersen et al. (1996) using seismicity cross-sections along major fault zones in California. We also updated the brittle–ductile transition model using the WUS crustal temperature models by Blackwell et al. (2011) and Boyd (2020), applying it to the seismogenic depths in the model east of the Intermountain West Seismic Belt, where the seismicity rate is low. This updated depth model is valuable for recalibrating the lower geologic fault rupture depths and for constraining deformation and seismicity source models in updates to the U.S. Geological Survey National Seismic Hazard Model.

Advancing Time-dependent PSHA and Seismic Risk Assessment: Accounting for Short- to Medium-term Clustering

Oral Session • Tuesday 15 April • 10:30 AM Local

Conveners: Edward Field, U.S. Geological Survey (field@usgs.gov); Matt Gerstenberger, GNS Science (m.gerstenberger@gns.cri.nz); Kenny Graham, GNS Science (k.graham@gns.cri.nz); Maximilian Werner, University of Bristol (max.werner@bristol.ac.uk)

Exploring Long and Short-term Time Dependencies in Earthquake Risk Modeling

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State-of-practice earthquake risk modeling involves several important simplifications, which neglect (1) interactions between adjacent faults; (2) the long-term elastic-rebound behavior of faults; (3) the short-term hazard increase associated with aftershocks; and (4) damage accumulation in assets due to the occurrence of multiple earthquakes in a short time window. Several recent earthquake events (e.g., 2010 Canterbury earthquakes, New Zealand; 2019 Ridgecrest earthquakes, USA; 2023 Turkey-Syria earthquakes) have emphasised the need for models to account for the aforementioned short- and long-term time-dependent characteristics of earthquake risk. This work specifically investigates the sensitivity of earthquake risk metrics to these time dependencies for a case study portfolio in Central Italy. The end-to-end approach for time-dependent earthquake risk modeling used in this study incorporates (a) recent advancements in long-term time-dependent fault modeling and aftershock forecast; (b) vulnerability models that account for damage accumulation due to multiple ground motions occurring in a short time; and (c) consideration of time-dependent catastrophe risk insurance features. The sensitivity analysis results provide valuable guidance on the importance and appropriate treatment of time dependencies in regional (i.e., portfolio) earthquake risk models. We find that the long-term fault modeling and whether or not aftershocks are accounted for are the most important features to constrain in a time-dependent seismic risk model. If a large proportion of the assets in the portfolio has a high deductible, then accounting for damage accumulation also becomes important.

Who Needs ETAS-based Seismic Hazard?

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Earthquakes typically occur in space-time clusters, each identifying a seismic sequence. Nevertheless, because of catalog de-clustering/completeness and calibration easiness, classical probabilistic seismic hazard analysis (PSHA) only accounts for the largest magnitude event within the sequence, which is recognized as the *mainshock*. PSHA models the mainshock occurrence over time according to a homogeneous Poisson process (HPP), which is defined by its time-invariant rate, while it neglects *foreshocks* and *aftershocks*, that is, those events within the sequence preceding and following the mainshock, respectively. This means that seismic hazard is underestimated, and that risk assessment cannot contemplate structural failure due to non-mainshock events or damage accumulation within each sequence. Because of some recent advances in PSHA, it is now possible to include aftershocks in the long-term seismic hazard assessment through sequence-based PSHA (SPSHA), which still has the advantages of using de-clustered catalogs. SPSHA assumes that the mainshocks-aftershocks sequences occur following the HPP adopted for mainshocks, whereas the occurrence of aftershocks, within each sequence, is described via a non-homogeneous Poisson process, whose rate decreases with the time elapsed from the mainshock according to the modified Omori law. A – trendy and computationally more demanding – alternative for modelling seismic clusters, is represented by the epidemic-type aftershock sequences (ETAS) models. In the ETAS framework, starting from a background HPP, each event within the sequence may generate its own Omori-type sequence. In the presented study, the close links between SPSHA and ETAS-based hazard are discussed. Furthermore, a comparison between ETAS and SPSHA, in terms of seismic hazard and structural risk assessment – with and without seismic damage accumulation – is addressed, considering two sites in Italy exposed to high and low hazard and state-of-the art structural models. The final goal is to determine whether ETAS models are necessity for earthquake engineering applications or more a research trend in seismology.

Risk Implications of Poisson Assumptions and Declustering Inferred From a Fully Time-Dependent Earthquake Forecast

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We use the 3rd Uniform California Earthquake Rupture Forecast ETAS model (UCERF3-ETAS), which is fully time-dependent in terms of including spatiotemporal clustering, to evaluate the effects of the Poisson assumption and declustering algorithms on statewide loss exceedance curves. The model is simulation-based, meaning it produces synthetic catalogs that exhibit realistic behavior with respect to aftershocks and finite-fault ruptures (including muti-fault earthquakes). A Poisson version of the model was constructed by randomizing event times, and the influence of two declustering algorithms was also examined. We demonstrate that for curves that specify the probability of one or more loss exceedances, the Poisson model implies greater risk because it has fewer seismically quiet time periods. The discrepancy is up to a factor of 32% but varies depending on the loss threshold (the x-axis value) and the forecast duration (we examined a range between 24 hours and 50 years, with the discrepancy for the latter being negligible). We discuss how the one-or-more loss exceedance metric is questionable because it ignores all but the maximum loss experienced in each timeframe. An alternative metric based on total aggregate loss in each time window was also examined, for which the Poisson model again implies higher risk at intermediate losses, but lower risk at higher losses (because large, triggered events now contribute to total aggregate losses for the fully time-dependent model). We also argue that declustering is not a scientifically justifiable way to deal with full time dependence, in agreement with a chorus from other recent studies. It is difficult to draw generally applicable conclusions from our research, in part because application-specific details will likely be important, but we hope to have exemplified how full time dependence can easily be reckoned with once authoritative forecast models are made available.

Accounting for Earthquake Sequences in Probabilistic Seismic Hazard Assessment

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Probabilistic seismic hazard analysis (PSHA) generally assumes a time-invariant Poisson process on mainshocks, not accounting for aftershocks. The removal of these events is largely subjective, as it depends on the chosen declustering procedure, and it may also result in an underestimation of the seismic hazard. In fact, recent earthquake sequences proved that aftershocks can significantly contribute to ground shaking.

The present study proposes a new methodology to include earthquake sequences in PSHA. With respect to the procedures used so far, we achieve a good level of consistency and accuracy for different return periods, as well as the generation of synthetic catalogs that exhibit the same features of a real earthquake catalog. We account for aftershocks using the Epidemic-Type Aftershocks Sequence (ETAS) models in order to have a complete and homogenous distribution of events. In particular, we employ the SimplETAS algorithm to create a large number of synthetic catalogs, each spanning 50 years. We associate a plausible seismogenic structure for the epicentral area to each earthquake in the synthetic catalog, and then we calculate the fault-to-site distance. This is critical for assigning a possible ground-shaking value to that earthquake. Eventually, we calculate the probability of exceeding a given threshold of ground shaking intensity as the fraction of catalogs where the intensity is exceeded at least once, without relying on the Poisson distribution.

In this first application, we obtain seismic hazard curves for the next 50 years for four Italian cities spanning from north to south and with different seismicity levels: L'Aquila, Firenze, Reggio Calabria, and Milano. Finally, we compare them and discuss the differences with the official hazard curves from the national model for Italy.

Seismic Models for the Taiwan Probabilistic Seismic Hazard Assessment: Tradition and Innovation

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To develop the official probabilistic seismic hazard assessment (PSHA) for Taiwan, the Taiwan Earthquake Model (TEM) updated earthquake catalogs and seismogenic structure databases to refine seismic source parameters. The areal sources surrounding Taiwan were divided into 30 zones to estimate seismic hazards, integrating seven earthquake catalogs spanning from 1900 to 2023. Background seismicity was calculated, based on the assumption of a Poisson distribution, after excluding foreshocks and aftershocks. Both onshore and offshore seismogenic structures were updated in the model, incorporating newly identified multiple-structure ruptures based on Coulomb stress criteria and historical evidence. The analysis procedure of this model meets engineering requirements and its outcomes contribute to advancing disaster prevention strategies in the public sector, including the development of earthquake scenarios, disaster evacuation plans, and rescue drills.

However, the assumptions of a traditional PSHA diverge from observed seismic behaviors. To address these challenges, we utilized the Seismic Hazard and Earthquake Rates in Fault Systems (SHERIFS) model, which accommodates multiple-structure ruptures and can anticipate larger seismic events than typically expected. The model not only reflects the occurrence of the 2024 M_w7.5 Hualien earthquake but also aligns with historical seismic activity. Moreover, traditional PSHA assumes events are independent, making it unsuitable for quantifying hazards arising from earthquake sequences. Recognizing the limitations of traditional models for short-term forecasting, we integrated the Epidemic-Type Aftershock Sequence (ETAS) model. Model credibility was validated by comparing predicted ground shaking exceedance probabilities with maximum observed ground shaking at strong-motion stations during a short observation period. These innovative methods highlight the importance of integrating multiple seismic models to achieve precise and comprehensive seismic hazard assessments.

Advancing Time-dependent PSHA and Seismic Risk Assessment: Accounting for Short- to Medium-term Clustering [Poster]

Poster Session • Tuesday 15 April

Conveners: Edward Field, U.S. Geological Survey (field@usgs.gov); Matt Gerstenberger, GNS Science (m.gerstenberger@gns.cri.nz); Kenny Graham, GNS Science (k.graham@gns.cri.nz); Maximilian Werner, University of Bristol (max.werner@bristol.ac.uk)

POSTER 71

A Comparison of Earthquake Risk in the Western U.S.: Time-independent vs. Time-dependent Approaches

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Although the science has shown for over a century that earthquakes are fundamentally a *time-dependent* process, hazard and risk analyses have generally been stuck in a *time-independent* framework. At CoreLogic, we have implemented time-dependent hazard and vulnerability models that provide a better assessment of the risk earthquakes pose. We will present our 2025 time-dependent earthquake model and compare it to the time-independent approach in California and the Pacific Northwest. We will show how hazard and loss change between the two models in regions of high risk, like Los Angeles, the San Francisco Bay area, and the Pacific Northwest. We also show how memory can be incorporated into vulnerability functions to better assess the cumulative damage effects of a mainshock and its subsequent aftershocks.

POSTER 72

What If? – A Look at How Partial Ruptures and Stress Transfer Can Be Incorporated Into Time-dependent PSHA

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In a time-independent PSHA model, a rupture has no impact on other ruptures so the subsequent hazard would remain unchanged. However, in a time-dependent PSHA framework, the hazard should change, but how it should change is an unresolved question. Traditionally, in a time-dependent approach, when an earthquake occurs, the clock resets. But what if only part of the fault ruptures? How should the hazard change on other sections of the fault and for larger ruptures? Likewise, how should ruptures on one fault impact the hazard from nearby faults through stress transfer? Here we will present different strategies for addressing these questions (focusing on the San Francisco Bay area and Pacific Northwest) and the potential impact on expected losses.

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Clustering in PSHA: A Study on Short Return Period Risk Assessments

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Probabilistic seismic hazard assessment (PSHA) typically employs a Poisson assumption, i.e., random and independent events. However, the Poisson assumption fails for highly clustered processes such as aftershock sequences and earthquake swarms. PSHA often handles these processes by declustering earthquake catalogs in an attempt to remove non-Poissonian behavior. An alternative approach used in the U.S. Geological Survey (USGS) National Seismic Hazard Model (NSHM) 2023 combines full catalog rates and a Poisson model with the spatial pattern from a declustered catalog. This method is less dependent on declustering methods and is an acceptable approximation for low probabilities of exceedance (e.g., 2% or 10% in 50 yr) used in the USGS NSHM 2023 hazard metrics (Field et al., 2021; Marzocchi & Taroni, 2014). However, for shorter forecast durations that are applicable for the insurance industry, the limitations of the Poisson assumption are apparent and have significant impacts on hazard (Field et al., 2021). In this study, we investigate the sensitivity of earthquake rate estimates at shorter forecast durations using full catalogs with both Poisson and non-Poisson (i.e., time-varying) models. The key questions are how hazard intensities and losses change when using full catalogs with a Poisson assumption versus non-Poisson models at short return periods, and whether non-Poisson models are sufficient when using full catalogs or if fully time-dependent models are required to capture the behavior of shorter forecast durations. Building on recent work evaluating the impact on short return period losses in Puerto Rico when using full catalogs (Farghal & Velasquez, 2024), we compare the performance of the Poisson model in the western US from the USGS NSHM 2023 with non-Poisson models, such as the ETAS model and the negative binomial distribution. The outcomes of this analysis aim to 1) evaluate the impact of the Poisson assumption at shorter forecast durations using full catalogs, and 2) help determine whether fully time-dependent models are warranted for shorter forecast durations in seismic hazard and risk assessments.

POSTER 74

Integrating Earthquake Clustering Into Probabilistic Seismic Hazard and Risk Assessments

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Conventional probabilistic seismic hazard analysis (PSHA) and risk assessment often do not fully capture the dynamic nature of earthquake clustering, including phenomena such as foreshocks, aftershocks, extended sequences, and the cumulative impacts of multiple seismic events. Recent earthquakes, such as the 2010/2012 Canterbury sequence in New Zealand, the 2019 Ridgecrest sequence in the USA, and the 2023 Turkey-Syria earthquakes, highlight the critical need to refine these methodologies to address the complexities of earthquake behaviour.

PSHA has long been a cornerstone for governments and industries, guiding the development of hazard maps, building codes, earthquake insurance policies, and safety standards for critical infrastructure. However, seismic hazard models must evolve to incorporate the full dynamic nature of earthquake clustering to advance disaster risk reduction and enhance seismic resilience.

We examine advancements in time-dependent probabilistic seismic hazard analysis (PSHA) and risk assessment, emphasising clustering effects such as spatiotemporal variations in earthquake activity. This includes methodologies that incorporate time-dependent fragility curves and damage accumulation to capture the evolving vulnerabilities of structures exposed to multiple seismic events. We aim to review state-of-the-art methodologies in time-dependent seismic hazard analysis and risk assessment, address implementation challenges, and examine real-world applications.

Incorporating time-dependent factors into PSHA and risk assessment is critical to advancing disaster risk reduction strategies and strengthening community resilience. Although challenges such as model complexity, data limitations, and computational demands persist, these approaches offer significant benefits by providing valuable insights for more effective risk management.

POSTER 75

Seismic Hazards in the Makran Accretionary Wedge, Pakistan

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The Makran Accretionary Wedge, a remarkable geological feature stretching over 900 kilometers across the northwestern Indian Ocean, has garnered significant attention due to its distinctive geological traits and the seismic threats it presents to the rapidly developing coastal region of Pakistan. This research provides an in-depth overview of the wedge's geological significance and the thorough evaluation of seismic hazards in Pakistan's coastal areas.

The seismic hazard assessment (SHA) for this region employs a dual methodology, integrating both deterministic and probabilistic approaches to fully evaluate earthquake risks. This comprehensive analysis has led to key findings with substantial implications for the region's preparedness and resilience. A detailed study of seismotectonics and geological features has revealed the presence of eleven fault zones across five seismic provinces. These fault zones are identified as potential sources of seismic activity. To assess the worst-case earthquake scenarios, the maximum credible earthquake magnitude for each fault source is calculated. A key component of the seismic hazard evaluation is determining the Peak Ground Acceleration (PGA) values for seven coastal cities. These values reflect the intensity of ground shaking and are derived from the maximum credible earthquakes associated with each fault source. The cities of Gwadar and Ormara are recognized as having high seismic risks, with PGA values of 0.25g and 0.30g, respectively, indicating their susceptibility to severe ground shaking. In contrast, Turbat and Karachi are categorized as low seismic risk areas, with PGA values below 0.15g, signifying their reduced vulnerability to earthquake-induced ground motion. The probabilistic analysis further produces PGA maps for return periods of 50 and 100 years, each representing a 90% probability of non-exceedance. These maps, which feature contour intervals of 0.07g, provide a probabilistic perspective on seismic hazards. In summary, this comprehensive seismic hazard assessment offers a detailed understanding of the earthquake risks facing Pakistan's coastal region.

POSTER 76

Probabilistic Seismic Hazard Analysis of the Shillong Plateau, Northeast India, Using Multiple Source Models and Logic Tree Approach

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In the present study, we have attempted to estimate the seismic hazard of the Shillong Plateau using Probabilistic Seismic Hazard Analysis (PSHA) by clubbing the up-to-date earthquake catalogue and seismotectonic of the region. An earthquake catalogue for the Shillong Plateau and adjoining region for the period of 825-2024 from various national and international data sources was compiled, homogenized, declustered, and checked for completeness. PSHA of the study region is computed using three distinct types of source models, namely, areal, linear, and gridded sources. The seismicity of the sources is evaluated by the modified Gutenberg-Richter model. Based on the efficacy test, three distinct GMPMs is selected. The logic tree approach is applied to minimize epistemic uncertainty. The probabilistic seismic hazard of the Shillong Plateau (SP) at the bedrock level has been computed in terms of Peak Ground Acceleration (PGA) and Spectral Acceleration (SA) for spectral periods 0.0-2.0 sec and 2%, 5%, 10%, 20%, and 50% probability of exceedance (PoE) in 50 years. Hazard curves and Uniform Hazard Response Spectrum (UHRS) for eleven district headquarters in the Meghalaya state of India are also prepared at bedrock level for 5% damping. PGA for 10% PoE in 50 years ranges from 0.66-1.04, whereas, for 2% PoE in 50 years, it ranges from 1.06-1.66. It can be observed that the seismic hazard is higher in eastern Meghalaya and gradually decreases towards western Meghalaya.

POSTER 77

The U.S. Geological Survey's 2025 National Seismic Hazard Model for Puerto Rico and the U.S. Virgin Islands

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The U.S. Geological Survey has completed a draft update of the National Seismic Hazard Model (NSHM) for Puerto Rico and the U.S. Virgin Islands (PRVI). The last update of the PRVI NSHM was completed in 2003, and therefore this update includes over 20 years of updated science and engineering data, methods, and models. Updates include (1) a seismicity catalog based on improved Puerto Rico Seismic Network data, (2) new declustering, smoothing, and seismicity rate models, (3) new magnitude scaling relationships, (4) an updated geologic fault and deformation model, (5) new modeling of subduction zone geometry and deformation, (6) improved fault source rupture models and a more complete representation of epistemic uncertainties, (7) updated ground motion models for both crustal and subduction sources, with adjustments made based on PRVI-specific data, and (8) development of epistemic and aleatory variability models specific to PRVI. These updates follow similar efforts performed in the recent 2023 50-state NSHM. Draft hazard results, including comparisons with the previous model, will be presented. NSHMs are community- and consensus-based models, with the goal to incorporate the latest data, models, and methods currently available. Public workshops throughout the update process, as well as an extensive review process, allow for community feedback and acceptance of the 2025 PRVI NSHM.

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Time-lapse Study of Earthquake Focus as an Additional Risk Control System

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There is no denying that the basic method of prevention of human and material losses is provision for adequate strength of constructions. At the same time, seismic load has stochastic character. So, at all times there is a little danger of earthquake forces to exceed selected design load. This risk is very low, but consequences of such events may be extremely serious.

Besides, it is known that temblors detrimentally affect environmental situation in regions, where they occur, resulting in panic and worsening various diseases courses. It may lead to mistakes of personnel of hazardous production facility like production and distribution of gas and oil, which may provoke severe accidents.

In such case, complex monitoring potential earthquake localities would be relevant. Even though number of successful real time forecasts of earthquakes is not great, it is well in excess such as may be under random guessing.

Experimental performed time-lapse study and analysis consist of searching seismic, biological, meteorological, and light earthquake precursors, processing such date with the help of fuzzy sets, collecting weather information, utilizing database of terrain, and computing risk of slope processes under the temblor in a given setting. Works were done in a real-time environment and broadly acceptable results took place.

Furthermore, look back study of precursors of known earthquakes is done. Situations before Ashkhabad, Tashkent, Haicheng seismic events are analyzed. Fairish findings are obtained.

It should be emphasized that such control does not required serious financial expenses and can be performed by small group of professionals.

Thus, complex monitoring potential earthquake localities including short-term earthquake forecast and analysis possible hazardous consequences of temblors, may be additional risk control system at seismic-prone areas.

Adventures in Social Seismology: Ethical Engagement, Earthquake Early Warnings, Operational Forecasts, and Beyond

Oral Session • Tuesday 15 April • 8:00 AM Local

Conveners: Lindsay Davis, U.S. Geological Survey (ldavis@usgs.gov); Roby Douilly, University of California, Riverside (robyd@ucr.edu); James D. Goltz, Disaster Prevention Research Institute, Kyoto University, (jamesgoltz@gmail.com); Susan E. Hough, U.S. Geological Survey (hough@usgs.gov); Maggie Ortiz-Millan, Earthquake Engineering Research Institute (maggie@eeri.org)

Geosciences in Dangerous Area: The Case of Haiti

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Over the past six years, Haiti has faced escalating challenges marked by political instability, including widespread civil unrest, the assassination of its last elected president, and the capital's incirclement by heavily armed gangs. These crisis are compounded by the country's vulnerability to significant natural hazards, such as large earthquakes and hurricanes. Amid these adversities, Haitian geoscientists supported by local citizens, have continued to advance scientific research and education. They have conducted field investigations under perilous conditions to collect critical seismic and geological data.

Since 2019, the S2RHAI project has fostered collaboration between Haitian citizens and local scientists to enhance seismic data collection. This initiative has successfully installed and maintained more than 30 seismic stations across the country, significantly improving regional seismic monitoring. During the August 14th earthquake, local scientists carried out multiple field missions to document and analyze this major seismic event. These efforts have laid the ground work for several upcoming scientific publications. Concurrently, the expansion and enhancement of Haiti's seismic network during these hard times have significantly improved the monitoring of seismic activity across the Northern Caribbean. Preliminary analyses of data collected from this network have begun to identify seismic gaps in northern Haiti, offering new insights into regional tectonic activity. Furthermore, the improved seismic network has enhanced the completeness of the seismic catalog, providing a more comprehensive understanding of the area's seismicity. This ongoing work highlights the resilience and uncommon but remarkable contributions of research scientists and local citizen to advancing earthquake science under extraordinary circumstances.

The Large-enrollment Seismology Skill Building Workshop Is an Inclusive and Effective Geoscience Recruiting Tool

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The Seismology Skill Building Workshop (SSBW) is a MOOC-style online training where students learn seismology-specific computer programming for ~12 weeks over the summer. It has enrolled at least 700 students annually since 2020 and grew to 1400 in 2024. It is designed for inclusivity by eliminating major barriers such as the cost of enrollment, computing requirements, access to a campus where seismology is offered, and costs associated with travel and class prerequisites. We have collected data via registrations, pre-/post-workshop surveys, and performance on assignments to evaluate whether this is an opportunity to increase interest and diversity in geoscience.

Annually, the workshop has enrolled ~30% of non-geoscience majors, indicating it offers an entrance to geoscience. Considering only US registrants, the participation of women (~60%) and marginalized racial and ethnic groups (~30%) was greater than that of undergraduate geoscience degrees (46% and 15%, respectively). Most demographic factors, including gender, race, and ethnicity did not show any association with initiation or completion of the workshop (Hubenthal and Brudzinski, 2024). When looking at interest in seismology/geophysics concepts, graduate school, and employment, we found a ~50% gain for students from marginalized groups compared to ~10% for other groups. We also found the "likelihood to pursue seismology and/or graduate school" was similar between the two groups after the SSBW. Using a comparison of pre- and post-test scores, we observed an overall ~40% gain in skill performance with students from marginalized groups showing gains greater than their non-marginalized peers. Collectively, the SSBW is an effective recruitment strategy when the playing field is leveled via an inclusive and effective pedagogy, as it allows participants from different backgrounds to discover, explore, and achieve in geophysics.

Navigating Earthquake News in the Age of AI

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Studies suggest that damaging earthquakes lead to abundant news content. Among questions journalists seek to answer are: What happened and what should we expect in the immediate future? Where and when was the earthquake? Who and what is impacted? Are there injuries? Why did this happen? When will it happen again? When is "THE BIG ONE?" Explanations are often crafted by well-meaning journalists with varying levels of knowledge and experience with earthquake science, but who seek to answer these vital questions for the public. Journalists covering an event use well-documented journalistic processes, such as consulting expert sources who are in the position to speak to the event and referencing evidence that both tells the story and validates the information provided by scientists.

However, in today's age of digital publishing, newsroom resources are scarce and journalistic work is evolving. Media outlets now combine traditional journalistic methods with novel content production tactics. For example, the Los Angeles Times uses Quakebot to pull USGS data on an earthquake's location, magnitude, and other critical information into an article draft that is reviewed by an editor and can be published within minutes. Other publications are experimenting with generative ai to create realistic, but fabricated, images showing scenes of future earthquake damage. While engaged scientists cooperate with journalists hoping their science will be fairly represented and informative, recent uses of these blended journalistic approaches begs the questions: What are impacts on readers who consume an article based on combinations of well-supported facts, expert sources, conjecture, pseudo science, and ai-generated information? Does the presence of expert sources lend credibility to potentially misleading information also found in an article? Is the reputation of the source unintentionally impacted when quoted in an article containing false or incomplete information? This case study seeks to unpack these questions and form recommendations for how scientists can navigate this increasingly complicated media environment in the age of AI.

Centering Users When Designing Earthquake and Aftershock Products

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After large earthquakes, probabilistic forecasts for aftershocks can be computed using statistical models and released by science agencies to support decisions on earthquake response and recovery. Visual design choices for forecast products can affect how the forecasts are used and understood by different users. We sought to understand how forecast visual products can serve multiple user groups by holding workshops with members of target user groups, including emergency managers, civil engineers, critical infrastructure operators, urban search and rescue, the media, public communicators and public health officials. In these workshops, users performed small-group activities to elicit their specific needs on the types and dimensions of aftershock forecast information (informational needs) and how this information would optimally be packaged (product needs). In these activities, users considered their informational and products needs relative to real decisions they must make at different time points following a damaging earthquake. Workshops were held with participants from the United States, Mexico, and El Salvador to identify cross-cultural components of effective forecast communication. While user needs varied by profession, country, and the type of decision users must make, there was also agreement about what mattered most for forecast product design. Maps showing forecasted shaking from aftershocks were widely requested and different shaking variables and forecast durations were preferred at different times following the mainshock. Needs for colors, file formats and other mapping decisions varied by profession, institution and other user-specific characteristics. Non-spatial products showing forecasted trends in magnitude levels or over time were requested for certain types of decisions and time points. Based on these workshop findings, we discuss solutions for user-centered design for aftershock and other earthquake information. These include products that have been optimized around three categories of use as well as an interactive map-based viewer that can meet diverse user needs.

Reflections on the Role of the International Community for the Promotion of Global Risk Reduction

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In the eyes of an earthquake professional, risk reduction is generally seen as a process that begins with science. As the international community seeks to support risk reduction in countries where resources are limited, efforts often focus on the science itself: characterizing active faults, determining ground motion models, updating hazard maps. It is perhaps illustrative, I suggest, to look back at how the State of California moved towards earthquake risk reduction. Starting in the early 20th century, leading earthquake professionals contributed effectively to the process of risk reduction only in part by seminal science. The scientific community in California also played a critical advocacy role, communicating with local officials, business leaders, stakeholders, and the public to advance risk reduction. The work of researchers set the stage for legislative actions after earthquakes revealed vulnerabilities in the built environment. Without local professionals (scientists and others) in an advocacy role, a hazard map by itself does nothing to reduce risk. When the community of international earthquake professionals strives now to promote risk reduction in resource-limited countries, it is important to remain mindful of the California experience. Without strong, sustained ties, and an understanding of local societies and cultures, international experts are unlikely to be able to effectively advocate in other countries. International experts can facilitate a consensus-building process in other countries, but any sustainable consensus-based system requires sustained engagement from local professionals, led by locally authoritative organizaitons. Well-intentioned efforts are advised to avoid undermining the authority, and ultimately the effectiveness and sustainability, of local earthquake professionals by implicitly emphasizing the qualifications, expertise, and products of the international community. Where projects in other countries involve coordination among international teams, they are unlikely to be effective unless locally authoritative agencies have a seat at the table.

The December 5, 2024 Offshore Cape Mendocino Earthquake: Response to Earthquake Early Warning in an Earthquake Experienced Region

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On Thursday, December 5, 2024 at 10:44 AM an earthquake of magnitude 7 occurred in the Pacific Ocean approximately 70 miles southwest of Ferndale California generating up to MMI VIII intensities in some locations onshore. The earthquake was in the Mendocino triple junction region, an area of frequent large earthquakes. This earthquake generated 16,825 felt reports in the US Geological Survey's 'Did You Feel It?' system and 1,808 validated responses to the earthquake early warning (EEW) supplemental questionnaire. This earthquake was the largest to occur in the United States for which EEW data has been generated and in an area in which many people have experienced significant earthquakes in the past. As data on human behavioral response has been collected over the past decade, the question arose as to whether behavioral response, assessments of the usefulness of EEW and perceptions regarding this briefest of all hazard warnings differed from previous data in the US and elsewhere.

Preliminary results suggest that on many dimensions, response and assessments of usefulness were similar to results from previous assessments of behavioral response to EEW alerts including, alert medium (mobile devices), locations where the alert was received (inside a building), general evaluations of usefulness (useful) and the preference for alerts only for events that disrupt ongoing activities. EEW response behavior was consistent with other alert situations in that those who received alerts before they experienced shaking were more likely to report mentally bracing for an earthquake, moving away from potential hazards and far less likely to have reported taking no action at all. Also consistent was that drop, cover and hold on was not particularly salient and characterized just 6.9% of those who received the alert before experiencing shaking. Neither alert nor earthquake experience had large impacts on behavioral response though those who reported having experienced previous earthquakes were more likely to respond actively or indicate an awareness of earthquake hazards than those who reported no previous earthquake experience.

Scientific Storytelling to Improve Earthquake Shaking and Impact Communication

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Communication remains essential to making society safer in the face of earthquakes. At the National Earthquake Information Center (NEIC), we have implemented five ongoing strategies to improve user engagement while focusing on storytelling-driven science communication. First, the Earthquake Hazards Program oversees the development of many deliverables across research areas, including earthquake shaking and impact products. However, it can be challenging to understand or coordinate how such products are used by various communities. To help address this, we developed flow charts to illustrate the workflow for producing specific products (e.g., ShakeMap) and how those products can be integrated with users' applications. Second, for user-driven technologies like ShakeCast that integrate user infrastructure fragility inventories with shaking intensity estimates from ShakeMap, we find newsletters to be an impactful communication device to update current users, answer frequently asked questions, or showcase a product's potential applications. As a third strategy, we use personas and user profiles to highlight how a specific technology can be utilized by organizations across various industries to demonstrate a technology's application to prospective users. Fourth, while fact sheets remain a key medium for communicating technical updates to users, we extend their reach by developing digital storyboards that translate fact sheets into engaging, interactive storytelling media tailored to various audiences. Finally, with the debut of NEIC's recording studio, we are producing videos that communicate science using engaging storytelling. For example, we filmed interviews about student interns' experiences to create an approachable format to convey science and illustrate the purpose-driven nature of this work, which remains one of the most influential factors for Gen Z when choosing career paths. Given storytelling's importance in human development, we see it as an underutilized strategy for communicating earthquake hazards science that can engage both existing and potential users through new digital media resources.

Deaf University Student Experiences With Earthquake Early Warning

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Earthquake Early Warning (EEW) alerts may give people valuable seconds to take protective action, such as drop, cover and hold on, before earthquake shaking starts. In order for individuals to take protective action, they need to receive the alert, understand the alert message, and have enough contextual knowledge to take appropriate protective action. DHH+ individuals often fail to receive proper alerts and disaster information, making them more vulnerable to severe impacts, such as twice the mortality of hearing indivisuals in large earthquakes (Takayama, 2017). Additionally, inadequate access to earthquake drills and preparedness resources leads to a lack of contextual knowledge needed for appropriate action. The existing gaps in effectiveness of the EEW alerts stem from language inequities for DHH+ persons in our schools, workplaces and families, which we analyze with linguistic anthropological and sociolinguistic frameworks to examine the nexus of DHH+ communities' languages and EEW messaging.

Conversations with DHH+ persons about their experiences with EEW reveal several gaps in the effectiveness of these alert messages. 1) Cascading risk - Being DHH+ does not ipso facto cause increased vulnerability during earthquakes or other disasters; however, DHH+ people having less access to emergency communication, preparedness information, and training over their lifetimes is compounded by barriers to receiving and understanding alerts not produced in their first language(s), contributing to increased hazard-risk, morbidity-risk, and mortality-risk. 2) Exclusion from disaster alerts - Disaster and EEW alerting systems continue to lag behind the technology-access needs of its users, particularly where DeafBlind persons and other persons with intersecting abilities are concerned. In some cases (as the findings we generated here), this results in complete exclusion from alerts. To advance language equity in EEW alerting, inclusion of DHH+ communities can improve messaging and reduce misunderstandings so that DHH+ persons can quickly take protective action when they receive an alert.

Public Feedback and Actions During EEW Alerts: Lessons From Central America

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After an eight-year effort through the ATTAC project, end-to-end public Earthquake Early Warning (EEW) systems, based on national seismic networks, are now operational across Central America. Public alerts were launched in the four countries between 2023 and 2024, today reaching approximately 300,000 users. The dissemination of alerts primarily occurs through mobile applications, developed for both Android and iOS devices. These apps deliver EEW alerts via critical push notifications based on Firebase Cloud Messaging, interrupting any ongoing activity or sleep mode on the device when shaking intensity reaches V on a Modified Mercalli Intensity scale at the user location. For the majority of users, app-related transmission delays are small, ranging from 1 to 4 seconds.

Understanding how users perceive and respond to EEW alerts is crucial for evaluating the system's effectiveness. To gain insights, we collect user feedback on app performance following significant events. So far, we have data from four recent seismic events: a M5.4 earthquake in Costa Rica (October 2023), a M5.2 earthquake and a M6.5 earthquake in Guatemala (May 2024), and a M6.3 earthquake in El Salvador (January 2025). This research aims to assess the app's ability to support protective actions and determine its efficacy as well as its acceptance among the public. The survey, based on a modified questionnaire based on Goltz (2022), explored alert timeliness, comparison between predicted and observed ground motions, public acceptance of alert thresholds, perceived usefulness of alerts, and the protective actions taken by users.

The findings show strong support for EEW systems among users in the region. While a small proportion of users took active measures (e.g., evacuation or moving to a safe area inside the building), the majority remained in a state of alert and situational awareness (e.g., mentally braced myself for shaking). The low uptake of active measures may reflect the absence of guidelines, often due to conflicting messages from multiple agencies.

Just Because We Can, Does That Mean We Should? An Ethical Discussion and Case Studies of International Aftershock Forecast by the U.S. Geological Survey

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Aftershock forecasting is an important tool that helps decision makers and various publics to understand what the future could look like in an earthquake sequence, after a large mainshock. The U.S. Geological Survey produces aftershock forecasts for various uses and audiences post-earthquake, assisting in decision making for those impacted. This information is available in several ways: domestically, an aftershock communication template is available to the public post Magnitude 5+ earthquakes; and, internationally, a product is shared with the Bureau for Humanitarian Assistance for events with PAGER alerts at the orange and red-level for fatalities. Given that the USGS already produces these, what is the ethical responsibility to make these international forecasts more available for public safety considerations? Further, by communicating these forecasts publicly beyond the United States borders, what are the considerations of scientific sovereignty of nations? What potential is there for miscommunication of forecasts in other nations, with diverse cultural and linguistic backgrounds? This presentation explores these ethical and social tensions, reporting on a group of listening sessions with scientific and response community members from around the world in 2022 and 2023. We also include case studies of aftershock forecasting from Vanuatu and El Salvador, in response to recent earthquakes in those nations. Further, we suggest some solutions to these ethical quandaries as well as future pathways

Adventures in Social Seismology: Ethical Engagement, Earthquake Early Warnings, Operational Forecasts, and Beyond [Poster]

Poster Session • Tuesday 15 April

Conveners: Lindsay Davis, U.S. Geological Survey (ldavis@usgs.gov); Roby Douilly, University of California, Riverside (robyd@ucr.edu); James D. Goltz, Disaster Prevention Research Institute, Kyoto University, (jamesgoltz@gmail.com); Susan E. Hough, U.S. Geological Survey (hough@usgs.gov); Maggie Ortiz-Millan, Earthquake Engineering Research Institute (maggie@eeri.org)

POSTER 120

Schoolshake: Inspiring the Next Generation, Increasing Community Resilience and Conducting Research Through a School-based Seismograph Network

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In 2021 the Geological Survey of Canada and University of Victoria launched SchoolShake, a program offering modern, hands-on earthquake science education to students on southern Vancouver Island, British Columbia. The goals of SchoolShake are to: 1) Engage youth in STEM, 2) Highlight geoscience-related fields as a career option, 3) Increase earthquake education, preparedness, and community resilience, and 4) Improve understanding of local seismic hazard by increasing seismic monitoring. The program deploys Raspberry Shake seismographs in schools, allowing students to explore real-time seismic data from their classroom. Since 2021, the SchoolShake network has grown to nineteen school and two community stations spanning Victoria to Haida Gwaii. In addition to setting up seismographs at no cost to schools, we have collaborated with a local educator to develop BC curriculum-aligned materials that leverage the Raspberry Shake seismograph and associated web tools. The program also offers educator workshops, classroom visits and school tours of NRCan research facilities.

SchoolShake stations are complimentary to the Canadian National Seismograph Network (CN) and the Geological Survey of Canda Research Network (PQ), effectively lowering earthquake detection capabilities, potentially resulting in increased knowledge of local crustal faults, and providing opportunities for seismic hazard research. In May 2023, a swarm of microseismicity near Victoria, which was not possible to locate using CN stations alone, was detected and many events were successfully located with the addition of the PQ and SchoolShake stations. The SchoolShake seismographs also allow for rudimentary ground motion studies following locally significant earthquakes, such as two widely felt earthquakes near Victoria in the fall of 2024. Students being able to access seismic data recorded at their school that is used for earthquake research has fostered enthusiasm for earthquake science in schools and contributed to the growth and success of SchoolShake in its first three years.

POSTER 121

Preliminary Multilingual Survey Results on Earthquake Early Warning and San Diego County's SD Emergency Multi-hazards App to Improve Equity in Disaster Risk Reduction

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ShakeAlert® earthquake early warning (EEW) aims to reach individuals' devices before strong shaking occurs, so they can take protective actions such as 'Drop, Cover, and Hold On' (DCHO, e.g., McBride et al., 2021). However, there have been few studies to best understand how people receive and respond to EEW alerts, and apps may be missing individuals who are not fluent in English (e.g., limited English proficiency (LEP)). California hosts the largest LEP population (>20% of residents) in the US. San Diego County's (SDC) *SD Emergency* app serves a diverse community of over 3.3 million people with ~34% having Hispanic/Latine ethnicity and a large immigrant and refugee population that speaks varied languages. We surveyed SDC residents to find out about their (1) earthquake experiences; (2) hazard warning experiences; (3) familiarity with the SD-Emergency app and how they use the app; (4) barriers to alert comprehension; (5) anticipated responses to EEW; and (6) suggested improvements to better fit their language needs. We offered the surveys in English, Spanish, Chinese, Tagalog, Arabic, and Vietnamese, but nearly all responses were to the survey in English, highlighting the challenge of engaging the LEP population. We did find ~30% of respondents had a member of their household with LEP, indicating some input from this community. In partnering with the National Opinion Research Center, we received approximately 900 vetted responses from SDC residents. Our preliminary findings indicate similar responses from LEP and non-LEP households. While most have felt earthquakes, only about a third have received an earthquake alert. Only 5% of respondents report DCHO as their first response to shaking, with Stopped/Stayed Put (65%), Stood in Doorway (14%), and Fled Building (10%) the most common answers. DCHO increases to 12% when asked about protective actions upon receiving an earthquake alert, with Stopped/Stayed Put (47%), Stood in Doorway (16%), and Fled Building (16%) still more common. The increase in DCHO with an alert demonstrates the importance of EEW for protective action, regardless of potential language barriers.

POSTER 122

The Propagation of Seismic Waves, Misinformation and Disinformation From the 2024-10-05 M 4.5 Iran Earthquake

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The 2024-10-05 Iran M 4.5 earthquake was a relatively unremarkable reverse-fault event, except that it took place at a time of heightened tensions in the Middle East. Its immediate aftermath saw widespread dissemination of misinformation, and potentially active disinformation, concluding that it was in fact a test of an Iranian nuclear weapon.

The 'evidence' for many of these claims was based on inaccurate interpretation of seismic data. In this paper, we analyse how geopolitically 'fake news' propagated through social media (mainly Twitter/X) following this event, eventually gaining traction in mainstream, earned media.

Although there were no significant geopolitical ramifications from the spread of this fake news, this event is nonetheless an illustrative warning of how seismic data can be misinterpreted and/or manipulated in public discourse.

POSTER 123

Self-developed Low-cost Shaking Table and Other Educational Tools as an Itinerant Laboratory for Seismic Engineering Educational Purposes: The Case of the LabIt

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Educational tools to encourage highschool and engineering students to study seismic engineering should be flexible, attractive and fun. This should not prevent the use of high-level knowledge and technology to develop such tools. However, a compromise between cost and quality must be faced because the financial resources are usually limited, especially in developing countries as Mexico.

As part of the activities in a sabbatical year in the Institute of Engineering (IINGEN) at the National Autonomous University of Mexico (UNAM), the corresponding author and presenter of this presentation is involved in helping to promote the LabIt (itinerant laboratory as its acronym in Spanish) developed by the LabIt members, which includes researchers from the IINGEN and undergraduate and graduate students. It includes the development of a low-cost shaking table test and other educational tools, such as physical models of structures built with a 3D printer, the use of social networks and traditional media and the fact that the laboratory can be easily moved directly to schools, universities and other entities to carry out educational presentations to promote seismic engineering as a potential future career for young highschool and engineering students. This project has proved to be very encouraging, effective for young audiences and fun. Moreover, it encourages interdisciplinary engineering tasks.

The main objective of this presentation is to describe the development of a low-cost shaking-test table and other tools through interdisciplinary engineering collaboration, and the implementation of an itinerant laboratory for seismic engineering educational purposes, as seen by an external invited researcher during a sabbatical year. It is concluded that the implementation of the LabIt as an educational seismic engineering strategy leads to encouraging results and should be supported and extensively promoted.

POSTER 124

Assessing the Usability of Near-Real-Time Earthquake Information for Supporting Impacted Communities

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Following an earthquake, near-real-time information provides valuable data on potential impacts like economic losses and fatalities to the public and decision-makers in the emergency management, humanitarian, finance, and other sectors. However, earthquake impact information is often designed without formal user input or a focus on impacted communities, resulting in information that is not necessarily suited for a variety of disaster management decisions. In this research, we investigated user needs for disaggregated risk metrics. Following initial focus groups with a broad set of users from various sectors, we developed a mockup showing additional metrics of exposure and loss that highlight impacted communities in a way that supports users' tasks. We then used an earthquake scenario with a targeted group of users to gain feedback on the mockup through a usability testing workshop. Workshop participants included nine emergency managers from the Federal Emergency Management Agency (FEMA), the California Governor's Office of Emergency Services (CalOES), the American Red Cross, and Innovative Emergency Management. Following qualitative analysis, workshop results revealed that disaggregated risk metrics could support emergency managers' tasks following an earthquake disaster. More broadly, this research highlights how a human-centered design process can create meaningful interactions with stakeholders who can ultimately use products to support impacted communities after future earthquakes.

POSTER 125

ShakeAlert's Contribution to Social and Behavioral Sciences: A Retrospective

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Since 2019, the U.S. Geological Survey has embarked on a comprehensive social science program to support the operation and communication of ShakeAlert, the earthquake early warning system of the West Coast of the United States. While earthquake early warning started publicly alerting fully on the West Coast of the United States in 2021, questions remain about what people understand and expect from ShakeAlert, including if they know what to do when they receive an alert. To evaluate whether the ShakeAlert System has been successful in increasing public understanding and protection actions when receiving a message from ShakeAlert system, the U.S. Geological Survey (USGS) developed the Social Science Working Group (SSWG) in 2019. The USGS collaborates with partners from universities, emergency management and other state agencies, the National Science Foundation, and USGS licensed alert distribution partners to implement a social science initiative focusing on three goals. First, to understand earthquake risk perception, protective action knowledge, and basic earthquake preparedness across Washington, Oregon, and California populations. While the research generated from the SSWG is now more than 53 articles, reports, book chapters, and other research publications, we argue that it is important to know how best to apply social science research to inform the ShakeAlert communication, education, outreach, and technical engagement (CEO&TE) programs. This presentation outlines the various publications that have been published or are in draft, future projects, and how social science and educational research has been integrated into the ShakeAlert System to improve the understanding and behavior taking for users of the system.

POSTER 126

Defining Aspects of the Seismology Learning Ecosystem by Exploring Introductory Seismology Courses and the Seismology Skill Building Workshop

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The Seismology Skill Building Workshop is a 12-week, Massive Open Online Course (MOOC) established in 2020. The course has three primary goals: to help students gain scientific computing skills, to increase interest in seismology, and to prepare students for graduate programs. Results from pre-/post-comparisons indicate that SSBW participants improved their scientific computation skills, interest in seismology and scientific computing, and readiness for graduate studies and/or careers in seismology by over 30%. To fully understand the relevance and impact of the SSBW and ensure the optimization of this course, we need to understand its position within the broader seismology learning ecosystem (SLE). This project aims to explore the scope and sequence of introductory seismology courses taught in the United States, the instructional methods used, and the scientific computing languages taught in these classes. This is accomplished through qualitative coding analysis of 7 introductory seismology course syllabi to build a survey for professors of introductory seismology courses. Surveys were sent to 64 potential faculty from the IRIS member representative list. Responses were analyzed using exploratory data analysis to examine trends in content, tools, and pedagogy. K-means clustering was used to examine potential different clusters of class types for comparison with the SSBW. Initial results indicate the 70-hour SSBW offers more in-depth instruction on computational and data access skills through class-based activities, while introductory courses provide more course content, primarily through lecture. Initial and future results will be used to benchmark and assess SSBW's ability to prepare students for success. Additionally, this SLE review aims to help current professors reflect, evaluate and improve their courses, and guide early-career seismology professors as they build their own curriculum. Finally, the SLE review will be used to build an open-source, non-workshop based online tools through EarthScope for students interested in seismology graduate programs, promoting diversity and equity in the field.

POSTER 127

Intercultural Praxis: A Tool for Engaging With Misinformation on Earthquake Risk

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Earthquakes remain one of the greatest natural hazards to society. Even so, the spread of misinformation and conspiracy theories is a common challenge to effective earthquake risk communication in the public sphere. Although scientists generally agree that misinformation must be addressed, the community appears uncertain on how to accomplish that. Intercultural Praxis, a technique developed in Intercultural Communication studies, is a tool that can be applied to help address this question. Using this strategy, several conflicting differences in value systems become apparent. First, scientists as a community inherently promote power distance between members which drives counter to high independent orientation cultures like in the US. Whereas expert authority is revered in the scientific community, such authority is often viewed distrustfully by the public, especially if funded by government entities. In such cases that scientists are funded by government entities, the public is likely to perceive scientists first as agents of the state before seeing them as members of the scientific community, which again promotes a perceived power distance that is viewed suspiciously by many individuals in Western cultures. Second, scientists must recognize that misinformation is not a 'bug' in the system but is instead a feature especially in the digital era. This is a challenge to the deficit model of communication, the most commonly used strategy for science communication that seeks to fill specific knowledge gaps in the public's understanding. However, with the public's aversion to power distance, this strategy commonly struggles to patch the knowledge gaps it intends to correct. In contrast, conspiracy theories are often successfully promoted using a strong emphasis on individualism and a person's ability to learn and reason for themselves with minimal expert guidance. As such, applying a dialogue-based model that promotes discussion and decreases power distance may help to bridge the gaps between scientists and the public in high-independent orientation cultures.

POSTER 128

What "Did You Feel It?" Data Can Tell Us About Earthquake Early Warning Performance

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We examine responses to the U.S. Geological Survey's "Did You Feel It?" (DYFI) survey and Earthquake Early Warning (EEW) companion questionnaire to assess the performance of the ShakeAlert EEW system for the West Coast of the United States. ShakeAlert rapidly detects and characterizes earthquakes and develops the EEW alert information, but it is up to official alert delivery partners to issue these alerts to people and other system users. As such, it is often unknown how many people were alerted and when. We examine the DYFI reports for several recent earthquakes with ShakeAlert-powered alerts that resulted in substantial responses to the DYFI EEW questionnaire, including the 2024 M7.0 offshore Cape Mendocino earthquake. We find that instances of magnitude overestimation by ShakeAlert relative to catalog source values do not necessarily indicate that there was significant over-alerting relative to the observed ground motions, and that comparisons to reported intensities from DYFI provide a better assessment of ShakeAlert's ground-motion prediction accuracy. Perceived warning times from the DYFI EEW questionnaire show that estimating maximum-expected warning times using the S-wave arrival is a reasonable assumption when discussing public EEW performance, except in higher-intensity areas where P-waves should be widely perceived. We also find many reports of shorter warning times, late alerts, and missed alerts in locations where longer warning times are expected based on the alert publication times from the ShakeAlert system; this suggests that alert delivery latencies may be substantial and highly variable. Overall, we find that the DYFI survey provides useful EEW efficacy information and can be used to inform our choices for how to convey the performance of the ShakeAlert system.

POSTER 129

Navigating Healthcare, Family Well-Being and Cultural Adaptation: The Experiences of South Asian Mothers on F1/F2 Visas in Urban U.S. Communities

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Abstract This study explores the intersecting challenges faced by South Asian mothers on F1/F2 visas as they navigate healthcare systems, maintain family well-being, and adapt culturally while balancing caregiving and academic demands in urban U.S. communities. Using a mixed-methods approach, the research combines surveys, GIS mapping semi-structured interviews, and focus groups to capture both macro-level trends and micro-level experiences. Key findings highlight systemic barriers in healthcare access, the absence of traditional familial support systems, and the compounded pressures of academic and caregiving responsibilities. The study also examines the role of social networks and cultural practices in mitigating these challenges, contributing to nuanced understanding of the dual burdens these mothers face. By linking theories of migration adaptation and intersectionality with empirical evidence, this research underscores the vulnerabilities of temporary visa holders in a sociopolitical landscape shaped by restrictive immigration policies and limited institutional support. Findings inform inclusive policies and culturally sensitive practices that address healthcare disparities, caregiving challenges, and the broader social dimensions of maternal health among temporary migrant families. This study advances sociological discourse on migration, medical sociology, and intersectionality while advocating for equitable healthcare and institutional policies that support immigrant families.

POSTER 131

Long-term Communication of Aftershock Forecasts: the Canterbury Earthquake Sequence in New Zealand

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During the 2010-16 Canterbury Earthquake Sequence in New Zealand, social and physical scientists collaborated on an exploration of aftershock forecast communication in the long-term (e.g., over six years). A 2013 study identified aftershock forecast information needs to be various formats (e.g., text, tables, graphics) and channels (e.g., website, media, in-person) for different decision-makers; simple and accessible messages that incorporate local/regional context; preparedness advice and empathetic messaging; coordinated messages between trusted agencies and other communicators; and access to progressively more technical information for those who seek it (Wein et al., 2015; Becker et al., 2019). We followed up in 2016, eight months after the M5.7 Valentine's Day aftershock. We held workshops with emergency managers, public health officials, and members of the public in Christchurch, New Zealand. We analyzed participant discussions for time dynamics of risk perceptions, earthquake preparedness, coping with uncertainty, trust in scientific sources, and information needs.

Key findings for long-term communications are: 1. divergent earthquake experiences revealed empathetic communication response needs for some new and re-traumatized residents and technical information (e.g., sequence behavior, earthquake sources) needs for others; 2. understanding aftershock sequence behavior is foundational to sense-making when large aftershocks occur; 3. strategic earthquake sequence updates from the trusted science agency and local agencies could serve as important reminders for earthquake preparedness; 4. communication of aftershock forecast uncertainty could aid with both the credibility of scientific information and living with uncertainty, and 5. inclusion of impact information and preparedness advice in aftershock scenarios could provide actionable information. Implications for research and practice of long-term communications of aftershock forecasts by science agencies pertain to behavioral dynamics, communication of uncertainty, communications tailored to experiences, impact-based forecasts, and coordinated messaging.

Building and Decoding High-resolution Earthquake Catalogs With Statistical and Machine-learning Tools

Oral Session • Tuesday 15 April • 4:30 PM Local

Conveners: Xu Si, Georgia Institute of Technology (xsi33@gatech.edu); Maximilian J. Werner, University of Bristol (max.werner@bristol.ac.uk); Shixiang Zhu, Carnegie Mellon University (shixianz@andrew.cmu.edu)

EarthquakeNPP: Benchmarking Neural Point Processes in California and China

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Recent advancements in point process models within the machine learning community have led to the development of Neural Point Processes (NPPs), which promise greater flexibility and improvements over classical models such as the Epidemic-Type Aftershock Sequence (ETAS) model. EarthquakeNPP is a benchmarking platform designed to direct the development of NPPs for earthquake forecasting. The platform hosts a suite of NPP models alongside a benchmark implementation of the ETAS model, enabling standardized forecasting experiments. The platform defines consistent training and testing partitions of earthquake catalogs and evaluates model performance using log-likelihood and CSEP generative evaluation metrics. We present initial results from benchmarking experiments on datasets from California, including high-resolution catalogs, and China using the China Earthquake Networks Center (CENC) catalog. While "off-the-shelf" NPP models currently do not surpass the ETAS model, we highlight ongoing efforts to adapt NPPs specifically for earthquake forecasting.

Denoising Score Matching for Online Change Point Detection

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We study the problem of online change-point detection, where the goal is to identify abrupt changes in the underlying data distribution from a continuous stream of observations. The change-point can occur unexpectedly and is often challenging to detect when the distributions before and after the change are unknown. Unlike classical methods that typically rely on estimating probability densities for detection tasks, we propose an approach that focuses on estimating the score functions of the underlying distributions. By leveraging the score representation to construct detection statistics, we avoid estimating the exact form of the density function, which can be intractable in real-world scenarios. We study the theoretical performance of the proposed detection method, and validate its performance on both synthetic and real-world sequential seismic data streams.

Fault Geometries of the 2024 Mw 7.5 Noto Peninsula Earthquake From Hypocenter Clustering

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Understanding intricate fault geometries is crucial for seismology. The New Year's Day 2024 earthquake at the Noto Peninsula in central Japan, with a Mw of 7.5, was one of Japan's largest reverse-fault crustal earthquakes. The aftershocks extended over 150 km from the western region to the north-eastern offshore. As hypocenter alignments typically reflect complex crustal fault structures, we developed a hypocenter clustering method to objectively extract intricate fault geometries of the Noto Peninsula earthquake, integrating point-cloud normal vectors (PCNVs) that reflect the local surface geometry of a point of interest.

For hypocenter clustering, we relocated 14,395 events in January 2024 using tomoDD under the fixed 3-D velocity model (Nakajima, 2022). PCNVs were estimated from the distribution of surrounding points, and HDBSCAN (Campello et al., 2013) was used for clustering hypocenter locations and PCNVs.

Our analysis extracted five planes beneath the peninsula, each 10–20 km in length. These included ENE-striking faults along the northern coast and a north-striking east-dipping fault in the southwestern area. Notably, the fault planes aligned with coastal lines from the western to northern coast. Additionally, we extracted an NE-striking plane in eastern Wajima between two ENE-striking planes in the northern coast, correlating with the gravity anomaly and surface geology, highlighting the complexity of fault ruptures.

Furthermore, the east-dipping fault in the western area was consistent with NS-trending aftershock focal mechanisms. NS-trending reverse-fault slip may be key to understanding seismotectonics of the Noto Peninsula.

[Acknowledgments]

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Exploring the Origin of Temporal b-Value Variation: Insights From the 2016/17 Central Italy Sequence

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As explored in various previous studies, the 2016/17 central Italy earthquake sequence exhibited notable spatiotemporal variations of the Gutenberg–Richter *b*-value. These variations have been linked to stress changes (Gulia and Wiemer 2019), fault rheology (Collettini *et al.* 2022), or the general complexity/heterogeneity of the fault system (Herrmann *et al.* 2022). Here, we reanalyse the sequence focusing on the spatio-temporal evolution of seismicity close to the Norcia mainshock (M_w 6.5). Specifically, we apply a combination of three algorithms: DBSCAN for performing event clustering, OPTICS for analyzing spatially nested dense zones within clusters, and PCA for inferring the planar geometry of those zones as fault surfaces. Before the Norcia event, we identified two clusters. One of them exhibited nested dense zones, and we could infer a near-vertical fault plane (dip of 63°) for the largest one; for the other cluster we inferred an overall horizontal fault plane orientation (dip of ~10°). After Norcia, we selected seismicity close to each of those structures associated with a fault plane. We analyze the magnitude-frequency distributions and *b*-values of the clusters and structures of interest. To reduce potential biases from short-term aftershock incompleteness, we excluded affected periods from the analyses.

We found that the MFD and *b*-value of in the structures of interest are temporally constant. In other words, the *b*-value depends on the structure. Our interpretation of this observation is that temporal *b*-value variations over the whole sequence might only be due to different structures being active (at various intensity) over time, i.e., spatial variations of seismicity. Our findings therefore highlight the role of distinct fault segments and structural heterogeneity in *b*-value analysis. Notably, higher *b*-values were associated with deeper, sub-horizontal seismicity, consistent with previous findings (Herrmann *et al.* 2022) This finding reiterates that spatially isolating seismically active clusters allows for a meaningful resolution of the fine-scaled variation of the *b*-value.

Insights Into the 2020 Monte Cristo Range Earthquake Sequence From a Near-source Aftershock Deployment

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High resolution, near-source data can provide crucial information about earthquake processes, including enhanced detection of small earthquakes and improved source characterization due to minimal path attenuation. The

Nevada National Security Site (NNSS) deployed 48 nodal geophones, referred to as LASSO (Large Array for Seismic Sensing and Observations) within hours (and meters) of the 2020 6.5, Monte Cristo Range earthquake (MCRE). With the data from this 3-month deployment, supplemented by regional seismic recordings from the Nevada Seismological Laboratory (NSL), we developed a machine learning workflow to generate a new, high resolution earthquake catalog for the MCRE aftershock sequence. Phase arrivals from the dense aftershock deployment improves detection capability several orders of magnitude beyond current published results while also providing improved constraints on earthquake locations, magnitudes, and seismic radiation patterns of small earthquakes. This unique dataset newly illuminates key characteristics of a highly active aftershock sequence and provides the foundation for future near-source analyses.

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Building and Decoding High-resolution Earthquake Catalogs With Statistical and Machine-learning Tools [Poster]

Poster Session • Tuesday 15 April

Conveners: Xu Si, Georgia Institute of Technology (xsi33@gatech.edu); Maximilian J. Werner, University of Bristol (max.werner@bristol.ac.uk); Shixiang Zhu, Carnegie Mellon University (shixianz@andrew.cmu.edu)

POSTER 33

Developing Machine-learning-based Seismic Data Processing Tools for a Carbon Storage Site

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Continuous seismic hazard monitoring is critical for ensuring the safety and security of carbon storage sites. However, the large volumes of data generated by passive seismic monitoring pose significant challenges for conventional processing techniques. Machine learning algorithms offer a promising alternative to streamline labor-intensive and time-consuming workflows. A key limitation in developing such algorithms is the limited labeled data. Transfer learning has proved effective in address this issue, successfully adapting machine learning models to smaller spatial scales, as demonstrated in geothermal applications. Building on this concept, we developed a machine learning-based tool, TL-Picker, to process passive seismic waveforms and accurately extract signal arrival times. Additionally, we created a complementary machine learning tool to locate seismic events by utilizing signal arrival times and seismic station information. Trained with synthetic arrival time data, this machine learning tool achieved performance comparable to a physics-based method. Finally, we implemented an unsupervised learning tool to infer fault planes from seismic event locations. Our suite of tools has the potential to advance the automation and accuracy of seismic monitoring, offering enhanced capabilities for ensuring the safety and operational efficiency of carbon storage sites.

POSTER 34

Improving Earthquake Detection and Localization in Hawaii With Deep Learning and High-performance Computation

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Earthquake and volcano monitoring depends on earthquake detections and locations. The accuracy of earthquake detection and localization is of great importance for understanding detailed structures and dynamics. With the continuous expansion of seismic networks and the surge in earthquake data volume, traditional methods are time-consuming, labor-intensive, and require continuous human involvement when processing large amounts of data. Thus, more and more deep-learning-based approaches have been developed and achieved better performance than traditional methods. ArrayConvNet, a convolutional neural network model trained by 1,843 analyst-reviewed earthquakes in Hawaii, can seamlessly detect and localize events and achieved 99.4% detection accuracy and predict hypocenter locations within a few kilometers of the U.S. Geological Survey catalog. Furthermore, application to continuous records results in more detection of earthquakes. Because of the enhanced detection sensitivity, localization granularity, and minimal computation costs, ArrayConvNet is a potentially valuable model, particularly for real-time earthquake monitoring.

To further enhance the deep learning model, we collected a comprehensive high-precision relocated earthquake catalog and compiled a large-scale seismic dataset, which includes 598,400 earthquake events in Hawaii after data augmentation. By using multiple GPU cards in High-Performance Computational Clusters, we are able to utilize such a huge amount of seismic data in model training and accelerate the process. The two-order of magnitude increase in the data leads to an improved deep learning model. The result shows that the new model outperforms the initial one in terms of localization accuracy on a test dataset, reducing the mean distance error by one order of magnitude and the standard deviation error by 18%~25.8% in horizontal (north-south/east-west) and vertical (depth) directions, as well as reducing the event origin time residuals by one order of magnitude.

POSTER 35

Towards a Deep Learning Approach for Short-term Data-driven Spatiotemporal Seismicity Rate Forecasting Using Standard and High-resolution Earthquake Catalogues

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Recent advances in earthquake monitoring from a combination of dense, low-cost, broadband networks and automated data processing methods, have enabled the generation of high-resolution catalogues with a lower magnitude detection threshold and greater precision in relative location. These catalogues, generated using techniques such as template matching and machine learning, are created much faster and contain far more seismic activity data than traditional catalogues compiled by human analysts. When such detailed catalogues are used, statistical and physics-based earthquake forecasting models have been shown to perform better in terms of forecasting power. Combining high-resolution catalogues with machine learning algorithms for earthquake forecasting, which themselves have significantly developed over the last few years due to increased data availability and computational power, offers a promising method for discovering hidden patterns and laws in earthquake sequences. This study aims to develop short-term, data-driven spatiotemporal seismicity forecasting models using deep learning, testing the hypothesis that deep neural networks can reveal previously uncovered relationships in earthquake data. In particular we compare between using standard and high-resolution catalogues to train the deep learning-based forecasting models and offer insights on the impact of high-resolution data on the forecasting power using metrics commonly used in both data science and earthquake forecasting. We test the performance of two different neural network architectures, a convolutional neural network and a transformer, and reach the conclusion that both architectures achieve similar forecasting skill. Overall, the findings indicate that deep learning algorithms are a promising tool for producing short-term seismicity forecasts, provided they are trained on a dataset that accurately reflects earthquake sequence properties.

POSTER 36

Earthquake Source Depth Determination Using Single Station Waveforms and Deep Learning

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Earthquake source depth plays a crucial role in characterizing earthquakes, assessing seismic hazards, and understanding subsurface structures. However, accurately determining source depths is often challenging. Traditional travel-time-based location methods struggle to constrain depths due to imperfect station distribution and the strong trade-off between source depth and origin time. Identifying depth phases at regional distances is further hindered by strong wave scattering, which is particularly challenging for low-magnitude events.

Deep learning techniques have great potential for deriving source depth information directly from continuous data streams based on waveform features. In this work, we propose a novel depth feature extraction network (named VGGDepth), which directly maps seismic waveforms to depth information using three-component single-station waveforms. The network structure is adapted from VGG16 in computer vision and is designed to take three-component single-station waveforms as inputs and depth labels as outputs, achieving a direct mapping from waveforms to depth.

We train the network by segmenting continuous waveform streams into time windows, which serve as inputs to the model. Two scenarios are considered: (1) training and testing on the same seismic station and (2) generalizing training and testing to multiple stations within a particular region. The results show that both VGGDepth models achieve high-depth prediction accuracy. We demonstrate the effectiveness of our methodology using seismic data from the 2016-2017 Central Apennines, Italy earthquake sequence and the 2019 Ridgecrest, USA earthquake sequence.

POSTER 37

Using Lossy Compression to Speed Up Seismic Event and Ambient Noise Analysis

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Many of our seismic event detection and ambient noise analysis algorithms are limited by file input/output (I/O). This is becoming a growing issue as we collect more long-term recordings of seismic data from many sensors, such as distributed acoustic sensing and lightweight nodes. Currently, our community data archives struggle to accept such data in their full form, but simple downsampling will lead to spatial or temporal aliasing. We consider lossy compression techniques that maintain an approximation of the broadband information in the data while achieving higher compression rates. A more compressed dataset isn't just cheaper to store on a data archive, but it also makes remote data quality checks possible during long-term studies and is faster/cheaper to read from the file system of any computer.

We have investigated several common lossy compression strategies for array data: wavelets, Zfp, and low-rank matrix factorizations (e.g. SVD and QR). One appealing quality of these compression techniques is the ability to carry out error propagation considering the representation of the data. In this way, we have calculated bounds on the errors that propagate through some workflows to help inform seismologists and engineers' compression choices as they collect data and transmit it back to their offices. We have released open-source software that allows users to easily test and compare the errors in template-matching event detection and pick times across compression levels and strategies. In addition to reducing the time to read files, we have created algorithms for template matching and related ambient noise cross-correlations to be carried out in some lossy-compressed domains much more rapidly without decompressing the data. We achieve a particularly large speed-up with cross-correlations of low-rank factorizations. We present results of ambient seismic noise analysis and template matching with continuous distributed acoustic sensing data. We compare the pros and cons in terms of errors, calculation speed and memory footprint.

POSTER 38

Seasonal Variations in the Magnitude-frequency Distribution of California Earthquakes

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Since 1812, California has hosted 45 earthquakes of magnitude $M \geq 6.5$. Of those events, 15 occurred during the months of April and December, while only 3 occurred during the months of July, August and September. Though a chi-squared test comparing the complete distribution of events per month to a uniform distribution produces a sampling probability p-value of greater than 10%, it is still interesting to analyze variations in the magnitude-frequency distributions (MFDs) of more recent California earthquakes for months with many $M \geq 6.5$ earthquakes compared to months with few $M \geq 6.5$ events. To do so, a catalog of M2+ earthquakes that occurred between 1980-2020 is declustered and separated by their month of occurrence into 12 subsets; a window sampling scheme is then used to combine three consecutive years of earthquakes that occurred during a particular month and organize them into a MFD. A Gutenberg-Richter (GR) relation is then fitted to the distribution and its a- and b-parameters are recorded. Time series plots of the a- and b-parameters demonstrate a sinusoidal oscillation through time with a period length of about one year that fluctuates beyond the 95% confidence interval bounds of neighboring points. Spectral analysis of these time series demonstrates strong peaks at integer multiples of one $year^{-1}$. Below 35.5°N, a-parameters (b-parameters), on average, increase (decrease) during the spring months and demonstrate the opposite pattern in the late summer. Above 35.5°N, the seasonal pattern is reversed. Roughly equal numbers of $M \geq 6.5$ events occurred on either side of 35.5°N, and so the distribution of months that hosted $M \geq 6.5$ earthquakes does not appear influenced by these annual variations. Seasonal variations in earthquake occurrence rates in other regions have been documented and attributed to climatic or astronomical processes; this study will further explore how the occurrence rates of earthquakes, represented by the GR a-parameter, as well as the ratio of large to small earthquakes, represented by the GR b-parameter, may be influenced by exogenous climatic or orbital effects.

POSTER 39

High-resolution Aftershock Catalog of the 2023 Kahramanmaraş Earthquake Sequence Reveals Detailed Fault Structures in Southeastern Türkiye

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On February 6^{th} 2023, two magnitude larger than 7.5 earthquakes struck Southeastern Türkiye, causing widespread casualties and heavy damages. They also triggered widespread aftershocks along the East Anatolian Fault and surrounding areas within the complex Maraş triple junction. To better understand the ongoing aftershock sequence, we deployed more than 200 SmartSolo nodal stations across and along both rupture zones, focusing on major clusters and high-risk areas throughout more than 100 days beginning in May 2023. In this study, we built a high-resolution earthquake catalog using machine-learning-based phase-picking and association techniques. Although the nodal stations were recorded at 500-Hz sampling rate, the absence of labeled datasets and pre-trained models for 500-Hz signals forced our previous studies to downsample the data to 100 Hz first, resulting in reduced accuracy and resolution. To overcome this challenge, we developed a deep learning-based 500-Hz phase-picking model capable of directly processing the high-sampling-rate waveforms. Firstly, we constructed a dataset derived from the Türkiye Disaster and Emergency Management Authority (AFAD) catalog, ensuring rigorous quality control. Using this dataset, we trained a 500-Hz phase-picking model based on a revised PhaseNet architecture. After retraining, the model was applied to 100 days of data, resulting in approximately 100 million picks corresponding to over 50,000 events. Compared to 100-Hz models, the 500-Hz model achieved higher accuracy and detected a greater number of seismic phases. Subsequently, we performed phase association, event location, and double-difference relocation to produce a high-resolution aftershock catalog. Based on the new high-resolution catalog, we constructed a detailed fault structure map from a 3D fault attribute volume, revealing the main and subsidiary splay faults along the East Anatolian Fault and adjacent regions. This enhanced structural resolution can help improve our understanding of the relationship between structural properties and earthquake behaviors, and overall seismic hazards in this region.

POSTER 40

Automatic Phase Picking Model for Ocean Bottom Seismic Data: Phasenet Model Trained Using Japanese S-net Data

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With the recent enhancement of seismic networks, a vast amount of seismic waveform data has been obtained. Advanced information technologies, such as deep learning, are being utilized for processing this data, with seismic phase picking being a prime example. This has significantly simplified the process of deriving earthquake catalogs from seismic waveform data. Numerous automatic picking models, including PhaseNet (Zhu and Beroza, 2019) and EQTransformer (Mousavi et al., 2020), have been proposed. The performance of machine learning models depends not only on the model architecture but also on the training data. Naoi et al. (2024) successfully improved the performance of the PhaseNet model by training it with data from Japan's permanent seismic network. In this study, I focus on the application to ocean bottom seismic data and conducted transfer learning using PhaseNet from Naoi et al. (2024) with data from Japan's ocean bottom cable seismic observation network, S-net (NIED, 2019). During this process, I corrected the axis orientation of the data based on components related to gravity recorded in S-net's acceleration data, ensuring one of the three components was aligned vertically. We also compared the performance with OBSTransformer (Niksejel and Zhang, 2024) and PickBlue (Bornstein et al., 2024), both trained with ocean bottom seismic data. Currently, our model shows higher accuracy measured based on arrival time differences between the manual and automatic pick, while OBSTransformer and PickBlue show higher detection rates.

Acknowledgements: I used seismic data from S-net maintained by NIED (NIED, 2019), and SeisBench, a platform for machine learning in seismology (Woollam et al., 2022). This study was supported by MEXT Project for Seismology toward Research Innovation with Data of Earthquake (STAR-E) Grant Number JPJ010217.

POSTER 41

Investigating Complex Seismogenic Structures in the Northern Longitudinal Valley, Eastern Taiwan Through an AI-based Catalog of the April 3, 2024 Mw 7.3 Hualien Earthquake

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The Mw 7.3 Hualien earthquake struck the northern Longitudinal Valley in eastern Taiwan on 3 April 2024, causing considerable damage in Hualien City and widespread strong shaking across Taiwan. Over the following month, intense and prolonged aftershock activity occurred and reveal complex spatial geometry, indicating complicated tectonic structures in the northern Longitudinal Valley. The high frequency of the aftershocks poses serious challenges to manual picking routines and may delay further analyses. To address these challenges, we developed an automated workflow, AutoQuake, capable of handling the large volume of continuous waveform data using fine-tuned AI algorithms. AutoQuake pipelines phase picking, phase association, 3-D double-difference relocation, local magnitude estimation, and focal mechanism determination in one seamless process to generate a high-quality, more complete event catalog. This AI-based catalog demonstrates exceptional performance in detecting small earthquakes and is more than four times larger than the routine catalog from the local agency. The new catalog reveals two west-dipping and two east-dipping fault planes, shedding light on the intricate fault structures and interactions between the Central Range Fault (CRF) and the Longitudinal Valley Fault (LVF) systems in the northern Longitudinal Valley. This study demonstrates the potential of AI-based workflows in managing large datasets and providing a more timely response to major earthquake sequences, facilitating the investigation of complex seismogenic structures and further seismic hazard assessment in the region.

POSTER 42

Denoising Score Matching for Online Change Point Detection

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Earthquake prediction is a major scientific challenge and controversial topic in earthquake science. It relies on identifying precursory signals occurring only before large damaging earthquakes. However, despite decades of research, no reliable precursory signals were found, and the current view is that individual earthquakes cannot be accurately predicted. Recently, there has been a renewed interest in studying earthquake precursory phenomenon, largely driven by improved ultra-dense near-field observations by seismic and geodetic recordings, availability of big data and related products such as high-resolution earthquake catalogs, and new developments in machine learning methods in earthquake science. These precursors often appear as change points in sequential data streams, posing challenges for detection due to the complexity of the data.

In this study, we propose offline and online versions of a denoising score-matching change-point detection algorithm, where the pre- and post-change data distributions are unknown and can be arbitrarily complex. Our key novelties are: (i) We estimate the score function of the data distribution as a component of the detection statistic, ensuring computational scalability and enabling strong modeling capacity through deep neural networks; (ii) We introduce a diffusion process to the data stream by injecting noise at appropriate scales, which helps increase the detection power of the statistics by enhancing score estimation in regions where pre- and post-change distributions overlap. We illustrate the advantages of our methods by theoretically deriving the upper bounds on the detection delays and empirically validating our methods' efficacy on both synthetic and real geophysical monitoring signals right before the 2014 M6.6 Jinggu earthquake in Yunnan, China. Our preliminary results show that the precursory signals exist, and our method can effectively extract them compared to traditional methods.

Challenges and Opportunities in Constraining Ground-motion Models from Physics-based Ground-motion Simulations

Oral Session • Thursday 17 April • 8:00 AM Local

Conveners: Sanjay Singh Bora, GNS Science (s.bora@gns.cri.nz); Asako Iwaki, National Research Institute for Earth Science and Disaster Resilience (iwaki@bosai.go.jp); Duo Li, GNS Science (d.li@gns.cri.nz); Chih-Hsuan Sung, University of California Berkeley (karensung@berkeley.edu); Graeme Weatherill, GFZ Potsdam (gweather@gfz-potsdam.de); Shihao Yuan, Colorado School of Mines (syuan@mines.edu)

Incorporating Results From Numerical Simulations Into Ground-motion Models

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Large data sets of simulated ground motions are being generated. These simulation data sets supplement the sparse sampling of ground motions from large-magnitude events in empirical data sets. Often, the simulations are conducted for just a few key scenarios in a region. An issue is how to use these two data sets to develop improved ground-motion models (GMMs). One approach is to combine the empirical data and the simulation data into one large data set and conduct a regression analysis in the traditional manner. The simulation data set will typically have many ground motions at many more locations than empirical data sets, leading to the question of how to weight these two data sets in the regression. An alternative approach is to compute the residuals of the simulated data relative to an ergodic empirical GMM and develop adjustments to the GMM to reflect the behaviors in the simulated data set. This approach allows inclusion of the features of the simulations that are considered reliable and exclusion of features that are less reliable. In particular, the simulations may include systematic path effects in the due to the 3-D velocity structure that are more reliable than the source effects which are based on limited validation exercises for the same sparse set of large-magnitude earthquakes used in the empirical GMMs. This represents an extension of the approach of using the scaling in the simulations rather than the absolute ground-motion amplitudes. The simulated data set can be used to adjust the ergodic scaling of median path effects (average path effects for a region) and to constrain the median non-ergodic path effects for a specific source-site pair. The variability of the ground motion from simulations has not been adequately validated and is currently not directly used in practice, but the relative scaling of the variability for different sites can be used to adjust the regional average standard deviation to site-specific standard deviations. Currently, simulations have not been adequately validated to replace GMMs, but they can be used to adjust GMMs is an interim step.

Toward Utilization of Physics-based Simulations in Seismic Hazard Assessment: Insights From Japan Experiences

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Ground-motion simulations that incorporate the fault and 3D velocity models, often referred to as "physics-based" simulations (PBS), predict ground motion for a specific earthquake scenario by numerically modelling fault rupture and wave propagation processes in time and space. In this presentation, we discuss the benefits and challenges in two primary ways to utilize PBS in seismic hazard assessment from the experiences of the National Seismic Hazard Maps for Japan. One way is to use PBS data as a supplement to ground-motion observation data in the framework of probabilistic seismic hazard assessment (PSHA). While comprehensive and well-maintained databases of ground-motion observation data have contributed to the development of GMMs in the world, GMMs exhibit large uncertainties due to lack of data for large-magnitude earthquakes and distinctive strong-motion recordings that reflect specific conditions such as near fault effects and basin effects. The other way is to use a set of PBS time-series waveform data for detailed seismic risk assessment at specific sites/area and for specific structures for an anticipated earthquake. In both ways, PBS provides ground-motion prediction given the simulation method and input parameters for future scenarios. In order to utilize PBS data in seismic hazard assessment, the limitations and uncertainties of PBS must be investigated in terms of i) simulation method of fault rupture and wave propagation, ii) 3D velocity model, and iii) input parameter ranges.

The National Seismic Hazard Maps for Japan contains simulation data for scenario shaking maps for > 1000 scenarios for major inland active faults. The rupture model follows the kinematic rupture characterization method based on Irikura and Miyake (2011). Broadband ground-motion time-histories are computed by 3D finite-difference simulations at long periods (> 1 s) and 1D stochastic synthesis at short periods (< 1 s) based on the 3D velocity model (J-SHIS model). We review the validation studies of the methods and the models, and discuss the challenges in identifying the uncertainties associated with the simulations.

Epistemic Uncertainties in Seismic Source Modeling for Finite-fault Ground-motion Simulations

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Modern Probabilistic Seismic Hazard Assessment (PSHA) increasingly requires finite-fault ground-motion simulations, in particular for critical facilities, to either augment existing databases of recorded ground-motions (in magnitude-distance ranges of limited or missing data) or to generate ground-motion time-series for specific scenarios of interest and importance. To capture the epistemic uncertainties in seismic source modeling for finite-fault ground-motion simulations, three key components have to be considered: (1) modeling and parameterizing seismic-wave propagation; (2) modeling and parameterizing fault geometry and fault segmentation; (3) modeling and parameterizing the spatio-temporal earthquake rupture process. I refer to these components as Step 1-3, as they are typically considered in this sequence. A fourth component, local site effects, is not subject of this contribution.

In this presentation, I first briefly summarize the key ingredients (geological and physical parameters) to be defined. Next, I succinctly review the most common computational methods in use for conducting finite-fault ground-motions simulations for PSHA purposes. The goal is to identify corresponding epistemic uncertainties and to aggregate these into a general logic-tree structure to be used in PSHA for critical facilities. Given the resulting and rather complicated logic-tree, admissible simplifications in the logic-tree structure need to be developed, i.e. acceptable short-cuts given the geological and seismotectonic boundary conditions and knowledge for a given site. My talk concludes with discussing the question of how many finite-fault ground-motion simulations may be needed to adequately quantify epistemic ground-motion uncertainty.

Implications of the SCEC/USGS Community Stress Drop Validation Study for Physics-based and Empirical Ground Motion Modelling

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The problem of decomposing recorded waveforms into source, path, and site effects is fundamental to both earthquake source analysis and ground motion modeling (GMM). For this reason, the Statewide California Earthquake Center (SCEC)/U. S. Geological Survey (USGS) Community Stress Drop Validation study is relevant to, and dependent on, GMM. We present the findings of the Community Study, focusing on what we have learned about the statistical distribution as well as spatial and temporal variability of earthquake stress drop, a key input variable in non-ergodic empirical GMMs. Through the Community Study, we distributed a common dataset of earthquake records for the 2019 Ridgecrest Earthquake Sequence and to date have received 56 unique submissions of spectral corner frequencies, moment magnitudes, and spectral stress drops. While overall results reveal significant scatter of spectral stress drops among the different methods, we use this variability to quantify the epistemic uncertainty of stress drop for any one earthquake. We average over all the submitted results for a distribution of stress drops with magnitude, depth, time, location and other parameters. We demonstrate how stress drop parameters, and their variability can be used as inputs to physics-based ground motion simulations and to constrain non-ergodic terms in empirical GMMs, both as analogs to the event term and as direct modeling inputs in Fourier models. We highlight the tradeoffs in assumptions and constraints inherent in estimating any single parameter from recorded waveforms. In this case, the estimates of corner frequency and moment are highly dependent on the assumed attenuation and path models, a problem common to both source and ground-motion modeling. The full data set, including a ground-motion flat file, is now available to the broader community for continued study and use in GMM. The next stage of the community endeavor will likely involve synthetic data and we welcome new members to participate in any aspect. Visit https://www.scec.org/research/stress-drop-validation for more information.

Ground Motion Simulations Based on Source Slip Distribution, Fourier Amplitude and Phase Models for the Chilean Subduction Zone

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Relatively small earthquakes can be modeled using Fourier amplitude spectra to simulate surface strong motions using a point source assumption; however, large megathrust earthquakes require accounting for their finite fault modeling and the rupture's rise-time to constrain strong ground motions. To model ground motions for earthquakes up to Mw 7.0, we developed Fourier amplitude and phase empirical models, which, coupled with a duration estimate, can accurately reproduce observed subduction interface ground motions. To model higher magnitude events (e.g., 2010 Mw 8.8 Maule, 2014 Mw 8.2 Iquique, and 2015 Mw 8.4 Illapel earthquakes), we divided the rupture surface into smaller areas that have an estimated slip and therefore a seismic moment (M_0) can be computed for each subfault. Also, using Molina et al.'s (2023) rise-time scaling relations for subduction interface earthquakes, we simulated the rupture process to add the contribution of each subfault to the strong motion simulation at each seismic station. The observed versus predicted comparison of seismic intensities for three major earthquakes in Chile (2010, 2014, and 2015) includes Fourier amplitudes, Arias intensity, bracketed duration, pseudo-spectral acceleration ordinates, PGA, and PGV. Despite the simplicity of the procedure, the simulated ground motions capture all the essential characteristics of the measured ground motions for engineering applications.

Characterizing Ground Motion Through Multi-fault Dynamic Rupture Simulations in Central New Zealand

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New Zealand lies at the boundary between the Pacific and Australian plates and is highly vulnerable to multi-fault ruptures involving both subduction and crustal faults. Such a tectonic setting highlights the imperative need to understand how multi-fault ruptures, particularly across different seismogenic regimes, contribute to seismic hazards. The current nationwide probabilistic seismic hazard model largely relies on empirical ground motion models, with significant uncertainties due to the paucity of devastating earthquakes (e.g. Mw8.0+) and limited seismic records at near-source distances.

To address this research gap, we will use physics-based ground motion modeling to investigate fundamental characteristics of regional seismic response to complex multi-fault ruptures, leveraging advances in numerical methods to improve seismic hazard analysis. In this study, we simulate a series of multi-fault rupture scenarios and associated ground motions that account for long-term tectonics, regional rheology, high-resolution topography, shallow basin structures, and fault networks in central New Zealand. We will focus on: (1) establishing a unified numerical workflow for dynamic rupture and modelling ground motions, (2) numerical validation using local intermediate seismic sources and strong motion records in the Wellington basin, 3) evaluation of the impacts of multi-fault ruptures, regional topography, seismic attenuation, and basin non-linearity on the ground motion levels. Our simulated rupture scenarios will advance our knowledge of earthquake physics and fault kinematic source characterization, while also providing theoretical references to improve empirical ground motion models and, consequently, seismic hazard analysis.

Evaluation of Uncertainties Using Simulations of Small Earthquakes for the Northern California Velocity Model Adopted for the Cybershake Study 24.8

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Seismic community velocity models (CVMs) are foundational for many basic and applied topics ranging from derivations of earthquake source properties to simulations of ground motions. The CVM quality directly impacts the accuracy and epistemic uncertainty of simulated wave fields generated by scenario earthquakes or 3D physics-based simulations. We present an innovative methodology to evaluate the effect of epistemic uncertainty of the CVM on key ground motion intensity measures related to seismic hazard analysis. This methodology involves using point sources to simulate wave fields from small earthquakes located in different parts of the crustal volume of interest and comparing the results to observations. Using small events and the point source approximation facilitates a focus on properties of the CVM rather than finite source ruptures. Evaluating differences between recorded and simulated data in spectral amplitude, phase matching, and signal duration allows us to estimate epistemic uncertainties and identify features and subregions of the CVM to improve. Here, we apply this framework to evaluate the performance of the Northern California CVM developed for the CS24.8 CyberShake study. The evaluation employs three-dimensional ground motion simulations of sets of local small-to-moderate earthquakes with magnitudes ranging from 3.5 to 4.5. Because of the relatively low ground-motion amplitude induced by these earthquakes, the near-surface materials are expected to be well-represented by a linear-elastic stress-strain relationship at all recording sites. Therefore, the misfit between recorded and simulated waveforms can be mainly attributed to structural complexities not fully represented in the used CVM and, to a lesser extent, the source parameterization (location, depth, focal mechanism, source time function). We will present the spatial distribution of residuals in the spectral domain, identify areas where the CVM performs best, describe the impacts of the results on the CyberShake simulations, and provide important guidance for future refinements of CVMs.

Aleatory Variability and Epistemic Uncertainty from Physics-based Ground-motion Simulations as part of Probabilistic Seismic Hazard Analysis

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Modern seismic hazard studies require quantifying aleatory variability and epistemic uncertainty of ground-motion estimates. For numerical simulations of ground motions, the six-component framework of Liou and Abrahamson (2024) is used to identify all parts of the aleatory variability and epistemic uncertainty. The six components are grouped into the method category and the parametric category. The method category refers to the algorithm and basic formulation of the simulations, and the parametric component refers to the inputs to the simulation. Each category has three parts: aleatory variability, epistemic uncertainty in the median, and epistemic uncertainty in the aleatory variability. All six components are needed for probabilistic seismic hazard analysis (PSHA) applications. For current sets of ground-motion simulations, some of the six components of the epistemic uncertainty and aleatory variability are missing, limiting the applicability of physics-based PSHA to research studies. The missing components need to be addressed before physics-based simulations are widely used in PSHA. For 3-D simulations, the key missing component is the parametric epistemic uncertainty of the median due to the uncertainty in the 3-D velocity models. Ideally, multiple 3-D velocity models would be used; however, this involves a significant effort. As an alternative, the standard deviation of the misfit between observations and predictions for past earthquakes can be partitioned into the method aleatory variability due to limitations and simplifications in the simulation method and parametric epistemic uncertainty due to the errors in the 3-D velocity model. Though the partitioning for a specific simulation set is unknown, generic percentages can be used to split the standard deviation from the validation into the method aleatory and parametric epistemic components. We provide an example of estimating the six components of aleatory variability and epistemic uncertainty using some assumed values and identify what is needed from 3-D simulations to move physics-based PSHA from research to engineering practice.

Site Response High-frequency Frontiers and the Added-value of Site-Specific Earthquake Record-based Measurements of Velocity and Attenuation

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One-dimensional ground response analyses based on 1D velocity profiles and generic relationships between damping and velocity are frequently employed with the assumption that they can provide a reliable assessment of site effects. According to this hypothesis, epistemic uncertainty in site response primarily stems from unconstrained soil properties, and this uncertainty rises sharply with increasing frequency in all Fourier-based ground-motion models. Our results show that the inversion of the spectral ratio of the horizontal-to-vertical components of strong motions based on the diffuse field concept accounting for the site-specific damping profile allows to capture significantly more site-specific features in site response, especially at high frequencies where both the deep sedimentary structure and the damping profile above the seismological bedrock have a strong influence on the disparity between observed and predicted ground motion. While the use of refined velocity and generic damping profiles for testing sites of the Japanese KiK-net already provides a reduction in the high-frequency residual and corrected site-to-site variability (and then the accuracy of predictions), the inclusion of site-specific damping allows this value almost to be halved. These results show that many sites are indeed too complex to be modelled by classical 1D ground-response analysis relying on generic damping relationships, while only site-specific record-based models allow a significant reduction in the bias with respect to coarse and generic site models.

Assessing the Applicability of the Use of Simulation Results in Non- Ergodic GMMs for Areas Without Empirical Data

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This study examines ground-motion simulations from the Southern California, Pacific Northwest, Utah, and Japan regions to evaluate the spatial correlation and variance of nonergodic path and site terms associated with ground motions from crustal and subduction events. The spatial distribution of the nonergodic site and path terms derived from the simulations was estimated using the varying coefficient model (VCM) within the geographical region of the simulations. The nonergodic terms obtained from these simulations demonstrate larger variations in the path and site terms compared to those derived from empirical data, and notable discrepancies exist between the median nonergodic terms for simulation and empirical data sets. Part of the discrepancy is due to the different spatial sampling for the simulation and empirical data sets, with much finer spatial coverage in the simulation data sets. The nonergodic terms from the simulations fall within the epistemic uncertainties range of the empirical results, indicating that the simulations are not rejected by the empirical data and that the integration of simulation results into the ground motion model has the potential to enhance predictive accuracy in regions where empirical data is limited. Furthermore, the nonergodic terms derived from simulations exhibit significantly higher spatial resolution than those obtained from empirical data, highlighting a key advantage of utilizing simulation-based nonergodic terms. The subsequent phase of this research will involve further investigations that evaluate the three-dimensional velocity structures and geological data to assess the appropriateness of including simulation results in seismic hazard applications, particularly in regions with insufficient empirical data.

Development of a Non-ergodic Ground Motion Model for the Groningen, Netherlands Region Based on a Hybrid Empirical and Simulation Dataset

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We present a new non-ergodic ground motion model (GMM) for the Groningen natural gas field in the Netherlands, aimed at improving the region's seismic hazard characterization. Non-ergodic GMMs offer the ability to reduce aleatory variability, which often controls the seismic hazard, especially at longer return periods. This reduction, however, is accompanied by epistemic uncertainty in areas with sparse observations, while it shifts the median ground motion in regions with available recordings. To further constrain epistemic uncertainties, we conduct a series of 3D wave propagation simulations using a detailed 3D velocity model for Groningen. These simulations employ point sources to illuminate seismic wave paths absent in the empirical datasets.

We propagate ground motions up to a maximum usable frequency of 5 Hz by using a dense spectral element mesh and a modified Burne source time function to mitigate spatial aliasing. The non-ergodic GMM is based on a Gaussian Process Regression framework. We represent systematic source and site effects using isotropic kernels, while a new vector-integral kernel function is proposed to capture the systematic path effects. This kernel accounts for correlations along entire seismic rays, incorporating source and site locations, azimuthal dependence, while honoring reciprocity.

To handle large empirical and simulated datasets efficiently, we implement a sparse approximation of the precision matrix through a Kullback-Leibler (KL) divergence minimization. We estimate hyperparameters through a cross-correlation Kernel Flow scheme, which enhances model predictability for previously unobserved scenarios. Our formulation achieves a 40% reduction in aleatory variability, significantly improving the accuracy of seismic hazard assessments for Groningen.

Estimating Systematic Source, Site, and Path Effects in Non-ergodic Ground Motion Models: Insights From the Turkish Ground Motion Database

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The development of ground motion models (GMMs) is transitioning from ergodic to non-ergodic approaches, which account for spatially varying and systematic source, site, and path effects. This study utilizes a robust ground motion dataset and different strategies for estimating non-ergodic terms, assessing their interactions in the context of the formulation of non-ergodic GMMs. The study results show that different strategies, specifically the sequence for estimating systematic effects, can significantly impact the trade-off between non-ergodic terms, leading to different mean and correlation length estimates, but without significantly impacting the final non-ergodic standard deviation after removing systematic effects. In this context, a strategy for treating the interaction and trade-off of systematic non-ergodic terms is recommended. Specifically, the proposed approach includes an iterative identification of the distance threshold below which path effects are not expected to contribute significantly to other systematic effects, allowing a more robust estimation of site and source effects. The insights gained in this study highlight that developing GMMs extends beyond a mere exercise of statistical inference or statistical fitting, particularly for non-ergodic ground motion modeling.

Non-ergodic Site Model for Ground Motion Analysis: Incorporating Regionalization, Kappa and Basin Effects

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In this work, we present a linear site model developed using the NGA-West 3 database for Western United States including California, Nevada, and Utah. The site model is derived from the site-to-site residuals of the Fourier Amplitude Spectrum (FAS), calculated using an updated ground motion models (GMM) developed for the NGA-West 3 database. Our site model consists of four main components: (1) Kappa Model: This model is based on site-specific kappa values derived within the ground motion model. We developed a map-based kappa model by combining a kriging model and a geology-informed model, weighted inversely by variance. The map gives more weight to station data in areas close to stations and relies more on the mean model from the geology-based approach in areas farther from stations. (2) Regionalization: We implemented a multi-scale regionalization approach, with each sub-region applying its own correction factor. For areas with dense data coverage, such as the coastal range of California, the regionalization is based on detailed surficial geological units. For less densely sampled areas, physiographic divisions are utilized, providing a refined model where data is abundant while extending coverage across the entire U.S. (3) Basin Model: Basin stations are identified using high-resolution topographic data, and additional corrections are applied to account for basin size. (4) Geotechnical Approach: We incorporated geotechnical parameters using mixed-effect regression, including V_{s30}, $Z_{1.0}$ and $Z_{2.5}$, where measurements are available, to further refine the model.

This non-ergodic site model combines traditional geotechnical approaches with geospatial and geological information, such as topography, physiography, and surficial geology. These additional datasets are highly reliable, well-distributed, and readily accessible resulting in a spatially continuous site term for ground motion models in the Western United States. The resulting model significantly reduces site-to-site variability and will be published as a component of the NGA-West 3 project.

Research, Development and Implementation Priorities for Ground-motion Characterization in USGS Earthquake Hazards Program Hazard, Risk Assessment and Forecast Products

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We present a 10-year roadmap for research, development, and implementation of ground-motion characterization in hazard, risk assessment, and forecast products of the U.S. Geological Survey's Earthquake Hazards Program. Key goals include (1) prioritizing research to increase accuracy and precision, (2) using a consistent framework across geographic and tectonic regions, (3) identifying necessary data and software, and (4) identifying mechanisms for leveraging expertise from within the Earthquake Hazards Program and external partners. We focus on synergies across Earthquake Hazards Program products, such as the National Seismic Hazard Model, ShakeMap, and ShakeAlert.

Our roadmap is guided by two central questions: (1) How do we most effectively use ground motions recorded primarily from small to moderate-magnitude earthquakes to improve ground-motion characterization for damaging earthquakes? (2) How might ground motions from future damaging earthquakes differ from previously recorded ground motions? We seek a unified approach to ground-motion characterization across the National Seismic Hazard Model footprint that also incorporates multi-scale spatial variations in ground-motion model components. Priorities that we have identified include (1) expanding the suite of intensity measures to support a broader range of applications (for example, ground failure), (2) incorporating non-ergodic event terms, (3) implementing descriptions of multi-fault ruptures that capture variations in strike and dip, (4) improving one-dimensional and three-dimensional models of linear and nonlinear site response, (5) developing a

unified approach for computing a mean model and epistemic uncertainties from multiple ground-motion models, and (6) leveraging simulations to fill in gaps in instrumental recordings. Furthermore, we recognize that to address these priorities, we will need comprehensive, up-to-date, well-managed databases of earthquake source parameters, ground-motion records, ground-motion intensity observations, and site characteristics.

Uncertainty in Ground-motion Forecast: A Perspective From New Zealand National Seismic Hazard Model Revision

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Recent revision of New Zealand National Seismic Hazard Model (NZ NSHM 2022) represents a major change in hazard results as well as in the methodology and processes to capture the plausible range of uncertainty in ground-shaking forecast. The change in ground-motion characterization modelling (GMCM) scheme also represents as a major change in comparison to the approach adopted in the penultimate version of NZ NSHM. In the GMCM scheme, four typically used NGAWest2 GMMs along with three NZ specific GMMs were used for crustal earthquake sources. For subduction sources, recently developed three NGA-Sub GMMs along with a NZ-specific GMM were used. The changes in GMCM for NZ NSHM 2022 dominate changes in hazard across majority of the regions in the country. Particularly in high hazard regions such as along the eastern coast of the North Island proximal to Hikurangi subduction zone. The change in hazard due to the change in GMCM is 1.5-2 times than that from the previous nation-wide hazard model.

Clearly, the GMMs and the GMCM scheme adopted in the NZ NSHM 2022 represent state-of-the art nevertheless, the changes caused by the change in GMCM alone are significantly large. This requires further scrutiny for better understanding and future planning. One major challenge in the context of NZ is that dominant contribution in hazard comes from the potential earthquake magnitudes and distances that are beyond (or at the limit of) the calibration range of the typically used GMMs resulting in weak empirical constraints on both median and sigma models. Thus, it results in significant uncertainty in the ground-shaking forecast which ultimately affects hazard. Additionally, the efficacy of nonlinear soil response models used in the GMMs is also considered a major source of uncertainty. The non-ergodic GMMs are expected to provide reduction in sigma estimate however, challenges persist in constraining such GMMs for data-scarce regions. In this presentation, we discuss our perspective and plans to address some of these challenges in the context of NZ.

Challenges and Opportunities in Constraining Ground-motion Models from Physics-based Ground-motion Simulations [Poster]

Poster Session • Thursday 17 April

Conveners: Sanjay Singh Bora, GNS Science (s.bora@gns.cri.nz); Asako Iwaki, National Research Institute for Earth Science and Disaster Resilience (iwaki@bosai.go.jp); Duo Li, GNS Science (d.li@gns.cri.nz); Chih-Hsuan Sung, University of California Berkeley (karensung@berkeley.edu); Graeme Weatherill, GFZ Potsdam (gweather@gfz-potsdam.de); Shihao Yuan, Colorado School of Mines (syuan@mines.edu)

POSTER 39

Simulation of Physics-based 0-10 Hz Ground Motion Using High-performance Computing Supporting Refinements to Regional Ground Motion Models for the Central Eastern U.S.

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One of the main challenges in developing Ground Motion Models (GMMs) for Central Eastern US (CESUS) is dealing with the scarcity of recorded ground motion for large magnitude earthquakes and short distances. One way to reduce the impact of lack of recorded data on the quality of the GMMs is to apply new constrains in their development that are derived from physics-based ground motion simulations. Recent improvements of regional-scale ground motion simulations resulting from physics-based rupture models and accessible high-performance computing have demonstrated their potential use in engineering applications, including refinements to GMMs in regions with available wave propagation models. Such simulations can make a significant contribution to the reduction of uncertainty in GMMs at near-fault distances where ground motion variability is not fully captured by current sparse recorded data.

We performed fully deterministic ground motion simulations for a suite of rupture realizations for hypothetical M6.5 and M7.0 earthquakes on planar crustal faults using a regional 3D model constrained by a 1D velocity model validated against recorded data. The high-frequency wave scattering was emulated by correlated stochastic perturbations to the 3D velocity model. We used SW4, a highly efficient anelastic finite difference code with an excellent performance on CPU and GPU clusters. The kinematic rupture models for strike-slip and thrust faulting were generated using the Graves and Pitarka method. To capture unknown source effects, we used band-limited variations of selected kinematic rupture parameters. We show simulation results to demonstrate the performance of our simulation platform in comparisons of broad-band synthetics (0-10Hz) with CEUS GMMs. The simulations indicate that there is a settled oversaturation of the SA at short periods (<1s) and at short distances. The overall favorable comparison between the synthetic ground motion and GMMs is a significant step toward building confidence on the use of synthetic ground motion in developing physics based constrains on GMMs.

POSTER 40

Estimation of the Horizontal Site Amplification Factors at Sites in the Noto-hanto Area in Japan based on the Microtremor Horizontal-to-vertical Spectral Ratios: A Special Case for the Vertical Amplification Correction Function

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We have been studying the relationship between the Horizontal-to-Vertical Spectral Ratios of microtremors (mHVSRs) and the Horizontal-to-Vertical Spectral Ratios of earthquakes (eHVSRs), as well as the relationship between eHVSRs and the Horizontal Site Amplification Factors (HSAFs) of earthquakes delineated by the Generalized Inversion Technique (GIT, Nakano et al. BSSA2015). We proposed that we can transform mHVSR into pseudo eHVSR based on the empirically-obtained Earthquake-to-Microtremor Ratio (EMR). We also proposed the Vertical Amplification Correction Function (VACF) that can transform eHVSR or pseudo eHVSR into HSAF as the average of the Vertical Site Amplification Factor (VSAF*). We have proven that these double-correction method of EMR*VACF can successfully reproduce pseudo HSAF from mHVSR (Kawase et al., SDEE2018, Ito et al., BSSA2020).

Immediately after the Noto-Hanto earthquake of Mw7.4 that occurred on January 1, 2024, on a thrust fault of 150 km long extending in the northern part of the Noto Peninsula in Japan, we visited the heavily damaged cities and towns in the epicentral area to measure microtremors in order to delineate the site amplification factors and subsequent underground structures. We deployed our instruments at about 20 sites in Suzu City, Wajima City, Anamizu Town, and Nanao City. We collocated at least one site in each city and town with the strong-motion observation sites by NIED or JMA in order to verify the HSAF evaluation method by referencing HSAFs separated by GIT. At several sites with ordinary HSAFs we have successfully reproduced them by using the double correction method of EMR and VACF from mHVSRs. However, at three sites, namely ISK002, E10, and ISK005 with extraordinarily large (80~100 times) HSAFs in the frequency range equal to or less than 1 Hz, we found that we cannot reproduce observed HSAFs from pseudo eHVSRs unless we use VSAF* specific at these sites. This strongly suggests that the extraordinarily large HSAF and VSAF* at these sites could be the result of the 2D/3D deep basin resonances.

POSTER 41

Advancing Seismic Site Response Predictions: Integrating Vs Gradients and Vs Contrasts

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Current practices for seismic site response estimation rely on (1) ground motion models (GMMs) that use the time-averaged shear-wave velocity (V_S) in the top 30 m (V_{S30}) as a predictor, and (2) one-dimensional site response analyses (1D SRAs) that employ the entire V_S profile available at a given site. While 1D SRAs are generally considered more accurate, recent studies showed that 1D SRAs could carry significant model errors. This finding led us to investigate the ability of innovative site-specific parameters to advance GMM predictions of site response.

In a previous study, we demonstrated that V_S gradients, g_{10} and g_{30} (gradients over the upper 10m and 30 m depth, respectively), can be used as parameters to improve site response predictions at different vibration modes. In this presentation, we investigate (1) the role of velocity contrasts (VCs), including bedrock-to-soil VCs and inter-layer VCs, and (2) the consistency between the trends observed in real-world and simulation-based data. We use ground motion records collected by the California Strong Motion Instrumentation Program (CSMIP) and V_S profiles from the Shear-wave Velocity Profile Database (VSPDB). A dataset of 84 stations has been collected, representing a wide range of V_S characteristics. Ground motion records sourced from the Center for Engineering Strong Motion Data (CESMD) were processed using the *gmprocess* application and reviewed following state-of-the-art protocols. The ground motion processing workflow and challenges in computing V_S gradients using measured profiles will also be discussed.

POSTER 42

Tamp1.5: Estimating the Effect of Site-specific Kappa on High-frequency Ground Motion Utilizing Elastic Response Spectral Shapes

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Kappa is a parameter that can significantly affect high-frequency ground-motion estimation but is often elusive in its quantification. Commonly, the zero-distance kappa is assumed to be associated with damping effects; however, kappa encompasses more than just damping. If kappa is interpreted as only due to damping, the result can be large scale factors (2-3) being applied to high-frequency ground motions for site-specific applications. The site-specific kappa includes the effects of deviations between the simplified model and the observations. As a result, kappa includes effects of errors in the source, path, and site amplification models at high frequencies and not just damping. Along with the uncertainty of what contributes to a site-specific kappa, accurate estimation of kappa can be highly subjective, often depending on the usable frequency band of the availability site-specific data. We present an alternative methodology for estimating the effects of site-specific deviations in kappa (delta kappa) that are related to damping. The short-period spectral shape is characterized by the shortest period at which the amplitude of the 5%-damped response spectrum (PSA) reaches 1.5 times peak ground acceleration, called Tamp1.5. A ground-motion model (GMM) is developed for Tamp1.5. The Tamp1.5 site term is treated as a proxy for the site-specific delta kappa due to damping only. The relation between the Tamp1.5 site term and the T=0.05 sec site terms from a PSA GMM is developed. The site-specific delta kappa is estimated using the relation between delta kappa and the change in the T=0.05 sec PSA. With these two steps, the Tamp1.5 site term is converted to a delta kappa site term. The Fourier amplitude spectrum (FAS) from a GMM is then scaled by exp(-pi * delta_kappa * freq) to estimate the site-specific FAS including kappa effects. This methodology provides a more objective approach for estimating the site-specific delta kappa due to damping, facilitating more accurate ground-motion modeling and improving site-specific seismic hazard assessments for the short-period ground motion.

POSTER 44

Validation of Two New CyberShake Studies in California

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The SCEC CyberShake platform is a 3D physics-based ground motion simulation platform developed for seismic hazard analysis. Previous CyberShake studies predict higher median ground motions relative to NGA-West2 Ground Motion Models (GMMs). Since 2022, two new CyberShake studies have been completed: CS22.12 in Southern California and CS24.8 in Northern California. Compared to previous CyberShake studies, there are several changes in the two new studies aimed at producing more realistic ground motions: 1) the rupture generator is updated to reduce the level of coherency in rupture propagation; 2) a taper is applied to the top of the 3D velocity models to replicate firm-rock conditions; 3) the minimum V_S value in the simulation is reduced from 500 m/s to 400 m/s; and 4) V_{S30} are now obtained from Thompson (2022).

To evaluate the effects of the implemented changes, we develop non-ergodic GMMs based on the two new CyberShake studies and compare them to NGA-West2 GMMs. The median predictions of CS22.12 show good agreement with the NGA-West2 GMMs at 2, 5 and 10s, supporting the implemented changes. However, the median predictions of CS24.8 are significantly larger than the NGA-West2 GMMs at 2s, and slightly larger at 5s. Our analysis finds that very strong directivity effects in CS24.8 are likely the primary cause for these large ground motions. Several factors contribute to the strong directivity in CS24.8: 1) All the major faults in CS24.8 rupture toward the sites, which are concentrated in the San Francisco Bay area; 2) the ruptures in CS24.8 tend to be narrower and longer, which is likely more effective in producing directivity effects; 3) many ruptures channel directivity toward the Santa Clara Valley in CS24.8, however only a fraction of events rupture toward the Los Angeles Basin in CS22.12. Moreover, differences in attenuation, crustal reflections and surface wave generation between the two 3D velocity models used in simulations may also play a role in affecting the ground motion level. These regional differences between the two CyberShake studies highlight the importance of non-ergodic GMM development.

POSTER 45

Incorporating Stress Drop into Non-ergodic Ground Motion Models

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The ground motion of an earthquake is determined by three components: the source, the path, and the site. While path and site effects have been extensively studied and modeled, source effects are often simplified in ground motion models (GMMs). Stress drop, a critical source parameter that reflects the energy release during fault rupture, significantly influences ground motion but is oversimplified or overlooked in GMMs. In this study, we utilize stress drop datasets derived from small earthquakes to provide consistent non-ergodic source effects in ground motion models. Using a Bayesian Gaussian Process framework, we extract robust spatial variations in stress drop from highly variable data. We analyze more than 5,000 small-magnitude earthquakes in the San Francisco Bay area and compare processed stress drop values with non-ergodic source terms derived from peak ground acceleration (PGA). Our results reveal consistent patterns between stress drop and PGA, emphasizing the key role of stress drop in capturing source effects in ground motion. Additionally, we show that incorporating processed non-ergodic stress drop reduces uncertainties in ground motion predictions, as shown using the DesignSafe dataset (Ji et al., 2022). This study highlights the potential of using stress drop datasets from small earthquakes to enhance seismic hazard assessments and improve non-ergodic ground motion models for seismic hazard predictions.

POSTER 46

Basin Identification Using the Continuous Wavelet Transform on Digital Elevation Models for Seismic Hazard Analysis

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Accurately identifying sedimentary basins and modeling their associated amplification effects are critical for seismic hazard analysis, especially in regions like California, where seismic hazards are significantly influenced by sedimentary basins. Traditional methods for basin identification depend on manual efforts, which are time-consuming, labor-intensive, and prone to uncertainties from subjective judgment. Current ground motion models use depth parameters such as $Z_{1.0}$and $Z_{2.5}$ that derived from tomographic velocity models to model basin effects. This approach introduces additional uncertainties that vary spatially across the velocity models as velocity models have variable accuracy and are only available in a few regions worldwide. In this study, we present an automated method for identifying sedimentary basins using 90 m Digital Elevation Models (DEMs). Topographic features often reveal underlying geological structures, with basins typically appearing as low, flat terrains resulting from sediment deposition in natural depressions. By applying the Continuous Wavelet Transform (CWT), we decompose the topography into different length scales. Sedimentary basins exhibit distinct characteristics: minimal coefficients at small scales due to the lack of local roughness and negative coefficients at scales corresponding to basin extents. By identifying these features automatically, our approach detects basins in the western U.S., producing results consistent with traditional manual methods while also identifying additional basins that manual approaches may have overlooked. Furthermore, the wavelet function at ground motion station locations, represented as wavelet coefficients across length scales, is utilized to develop site models for the NGA-West 3 project. This method offers a high-resolution and accurate identification of basins and their characteristics and can be used to predict basin amplification effects. This method can be easily extended to other regions globally, leveraging the widespread availability of high-quality DEMs.

POSTER 47

Evaluating the Relationship Between Slip and Slip-velocity on Large-magnitude Ruptures Based on Surface Displacement

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Defining proper relationships between the dynamic parameters that govern the spatiotemporal evolution of a seismic rupture is a foundational step to constraining earthquake source modeling. The energy flux in the process zone balances how much energy is spent in the rupture growth and how much energy is radiated, among other physical processes involved in the rupture, such as the breaking and damage evolution of the source volume and diabatic processes. Thus, building baselines of the actual scaling of these parameters is a fundamental step to constrain rheology models for dynamic rupture simulations. In this study, we evaluate the relationship between the main outputs of dynamic rupture processes: slip, slip velocity and rupture velocity. We start by performing a set of dynamic simulations which shows that the total slip and maximum slip velocity are conceptually uncorrelated: the total slip is mainly related to global features of fault systems' geometry, whereas the slip velocity depends on the environmental stress and the dynamic process occurring in the process zone. We then use empirical data to explore these features by evaluating the correlation between surface fault displacement, a measured proxy for slip, and the Fourier amplitude of the wave field recorded at near-fault stations of four large-magnitude earthquakes that occurred in the past 25 years. Additionally, we estimated the arrival time of the rupture front from near-fault ground motion recordings with significant permanent fault displacement, allowing us to evaluate the relationship between the rupture velocity, slip and slip velocity. Surprisingly, our analysis shows that the fault displacement is not only non-correlated with the Fourier amplitude, but they exhibit an anti-correlation for frequencies above 0.3 Hz: regions of the rupture developing larger displacements radiate energy with weaker high-frequency content. Based on our findings, we proposed a model to constrain frequency-dependent near-fault ground-motion amplitudes for historical earthquakes based on paleoseismic displacement data for seismic hazard analysis applications.

Compiling Active Faults for Improved Hazard Modeling from Cascadia to Alaska

Oral Session • Thursday 17 April • 4:30 PM Local

Conveners: Tiegan E. Hobbs, Natural Resources Canada (thobbs@eoas.ubc.ca); Richard Styron, The Global Earthquake Model Foundation (richard.styron@globalquakemodel.org); Martin Zaleski, BGC Engineering (mzaleski@bgcengineering.ca)

Crustal Stress in Alaska and NW Canada: New Insights Into Intraplate Deformation and Fault Slip Potential

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The crustal stress field represents the summed effects of plate-boundary and basal tractions, gravitational body forces, and surface loads. In turn, local stress controls the seismogenic potential and coseismic slip behavior of crustal faults. Here, we leverage the quadrupling of focal mechanisms from intraplate Alaska and NW Canada over the past 15 years to produce an inversion-based crustal stress model that constrains the causes and kinematics of deformation. Edge tractions alone produce smoothly varying intraplate stress fields marked by horizontal stresses that decay with distance inland, and this characterizes first-order stress patterns: Maximum horizontal compression (σ_H) is broadly margin-perpendicular (e.g., N40E in British Columbia, N25W in the eastern Brooks Range, N80W in the Bering block) and reverse-oblique faulting near the plate boundary grades to strike-slip ~500 km inland. Deviations from these trends must result from other processes. In the arcuate Mackenzie Mountains $\sigma_H$is range-perpendicular, rotating from N65E to N5E along the range while regional $\sigma_H$trends N30E. Collision of the translating crust with the craton edge or a divergent mantle flow at the keel could create this stress perturbation. Western Alaska (from the Iditarod-Nixon Fork Fault across the Bering Sea) is extending southward. Dynamic return flow northwest of the Pacific slab may increase gravitational potential energy, causing the switch in deformation style, while minor far-field compression guides margin-parallel stretching. In this heterogeneous stress field, the seismogenic potential of intraplate faults cannot be assessed with a single model. We build stress models for 1803 segments on 84 crustal faults from the USGS National Seismic Hazard Model to quantify fault slip potential, predict coseismic behavior (e.g., rake), and identify along-strike stress variations that could influence rupture segmentation. This modeling underscores the importance stress heterogeneity in fault kinematics and ultimately seismic hazard.

Current State of Paleoearthquake Data for the Alaska Range

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Extending over 600 km in a broad arc across southern Alaska, the Alaska Range is an active orogen containing numerous Quaternary-active faults - but only a limited paleoseismic record. Furthermore, a majority of the paleoseismic data from the Alaska Range is currently either unpublished or only found in graduate theses and in project reports. We compile the accessible paleoseismic results from the active faults of the Alaska Range to accomplish the following goals: 1) formally publish paleoseismic information that is currently in 'gray' literature sources, 2) attempt to access and publish previously unpublished paleoseismic information, 3) consolidate paleoearthquake dates into a single source with a consistent format to facilitate potential analysis of along-fault and fault system earthquake behavior, 4) solicit community input on additional data sources and, 5) identify high-priority targets for future research. We also identify new constraints on fault location, geometry, and slip sense for several faults derived from fieldwork and remote observations using the continually-expanding coverage of high-resolution satellite imagery and topographic data. Formal publication of this paleoearthquake information will permit inclusion of this data in USGS hazard products and support regional paleoseismic and tectonic studies.

Active Faulting in Western Canada: Definition and Review of Current Knowledge

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Despite several active crustal faults being identified within the North America plate in neighbouring Washington State and Alaska, there are relatively few mapped in western Canada. There are myriad reasons, including thick vegetation, recent glaciation, and low strain rate, that make it difficult to identify active faults, and there is a lack of clarity on how the term 'active fault' is best applied in these conditions. Even among the faults with recently-documented Holocene activity, few have been incorporated into the national seismic hazard model yet. To this end, we propose a definition for active faults in western Canada based on (1) evidence of Holocene or Quaternary displacement, (2) potential to host earthquakes with magnitude greater than or equal to five, (3) geomorphic expression consistent with faulting, and (4) orientation compatible with failure in the neotectonic stress field. We then apply this definition to previously-studied faults in the region to present, for the first time, a summary of active faults across western Canada. We consider the potential impact of these faults in terms of seismic hazard and risk modelling. This work will be of interest to researchers and practitioners in Canada and neighbouring regions, as well as those in analogous locations around the world.

CRESCENT CFM: Building a Community Fault Model for the Cascadia Subduction Zone

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Earthquakes on faults within the upper (North America) and lower (Juan de Fuca) plates of the Cascadia subduction zone are the least constrained earthquake sources in Cascadia. Many of these faults are located beneath or near population centers and have the potential for significant seismic and cascading hazards. A community fault model (CFM) for the Cascadia region will enable group evaluation of these earthquake sources. The Cascadia Region Earthquake Science Center (CRESCENT) CFM working group is developing a comprehensive topological and activity model of active faults in the upper plate of the Cascadia subduction zone. The topological model combines both on and off-shore fault systems, and models of the plate interface. An initial simplified CFM has been built based on the USGS National Seismic Hazard Model 2023 fault sections database. Off-shore wedge faults and upper plate faults constrained by new data are being reviewed and prioritized for incorporation into the CFM. By providing well-constrained fault geometries and geologic slip rates, the CFM can benefit several use-cases, including seismic hazard analyses, stress modeling and multi-cycle rupture modeling, providing boundaries and constraints in the CRESCENT Community Velocity Model, and potentially in probabilistic tsunami hazard analyses. We seek feedback from the community to continue to improve the inventory and representation of active faults in the CRESCENT CFM.

Seismicity Relocations Between 2016 and 2019 Near the 1872 Entiat Earthquake in Central Washington

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The 14 December 1872 Entiat earthquake of estimated M 6.8 is the largest known crustal earthquake to have occurred in the Pacific Northwest. The event has been an enigma for decades and has motivated numerous investigations to identify its source as part of siting studies for critical facilities in Washington. The Entiat area has been a persistent area of concentrated seismicity and it has long been suspected to be the epicentral area of the 1872 earthquake. Based on LiDar data, Sherrod et al. (2015) was the first to suggest that the Spencer Canyon fault (SCF) was the source of 1872 and this was confirmed by Sherrod et al. (2021) based on a paleoseismologic investigation of the fault. Brocher et al. (2017) analyzed the Entiat seismicity and concluded that the events were aftershocks of the 1872 earthquake. To better characterize the seismicity, the Washington Geological Survey (WGS) deployed a dense local portable PASSCAL array of 13 three-component short-period seismometers around the Entiat seismicity from 2016 to 2019. The array provided an ideal dataset to calculate accurate locations and improve depth estimates with the intent of characterizing the relationship with and geometry of the SCF and/or other possible structures in this area. In this analysis, we combined data from the WGS array with regional observations from the Pacific Northwest Seismic Network (PNSN) to develop an enhanced earthquake catalog with high-precision hypocenter locations. Using a refined velocity model and a combination of PhaseNet-derived automatic picks and cross-correlation differential travel times, we relocated 203 events out of the 266 events with magnitudes ranging from M_L -0.4 to 3.4 from the PNSN catalog using the double-difference algorithm. Our results reveal several distinct, near-vertical clusters in the upper crust (<10 km depth), with no clear association with the northwest-dipping SCF. This suggests that these small earthquakes may be occurring on secondary structures within the broader deformation field of the 1872 rupture, potentially representing triggered aftershocks accommodating ongoing strain release.

Compiling Active Faults for Improved Hazard Modeling from Cascadia to Alaska [Poster]

Poster Session • Thursday 17 April

Conveners: Tiegan E. Hobbs, Natural Resources Canada (thobbs@eoas.ubc.ca); Richard Styron, The Global Earthquake Model Foundation (richard.styron@globalquakemodel.org); Martin Zaleski, BGC Engineering (mzaleski@bgcengineering.ca)

POSTER 76

Mapping New Subsurface Faults in the Butte Valley, Northern California

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Butte Valley, in Siskiyou County, California, lies between the Western Cascade Range and the Mahogany Mountain Ridge, a prominent northwestward-trending fault block bounding the valley to the east. The region is dominated by block faulting structures, with normal faults characterized by almost vertical displacement ranging between few to several hundred meters along minor and major faults, respectively. The valley is a downfaulted basin, surrounded by well-preserved scarps of late Pleistocene to recent age. While structural elements are exposed on scarps and rocks surrounding the valley, their continuations are partly or fully concealed beneath the alluvium and lake deposits. No detailed investigations into the faults beneath the valley alluvium have been carried out, and their characteristics remain unknown.

In August 2024, we conduct a high-resolution seismic reflection survey in Butte valley, northern California, to investigate its subsurface structure. The survey acquired three profiles for a total of 9 km using 100 kg accelerated weight drop recorded by a 1.2 km-long linear array of 240 4.5 Hz vertical geophones, and achieving a nominal fold of 40. Across the surveyed area, the data image horizontally stratified reflectors above a ubiquitous high-amplitude reflector, traceable at a depth ranging between 120-150 meters. Based on correlation with the outcropping Butte Valley basalt, we interpret the high amplitude marker as a basalt sill of Pliocene age. Notably, this significant regional marker is displaced by ~40 and 25 m with a down to the northeast sense of motion at two locations along one of the profiles, revealing the presence of two northeast dipping normal faults. The data resolve no deformation in the overlying deposits. However, the surface projection of these faults is marked by northwest striking geomorphic features such as ponded alluvium and closed depressions indicative of latest Pleistocene and Holocene activity. We interpret these faults as part of the Cedar Mountain fault system resulting from the east-west extension at the boundary between the Cascade Ranges and the Modoc Plateau.

POSTER 77

Origins of the Purcell Mountains Swarm

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Seismicity in Alaska's Purcell Mountains remains largely absent from published literature, yet the region exhibits vigorous, swarmlike activity. The most recent swarm onset began in February of 2019, producing over 9,600 cataloged events to date. Five events are magnitude 5 or greater and were reportedly felt throughout the region. Broadscale tectonic studies propose this northwestern region of Alaska is predominantly strike-slip faulting with normal faulting constrained farther west. However, available focal mechanisms for this sequence report both strike-slip and normal faulting with temporal variation. This suggests the Purcell Mountains region is structurally more complex than currently represented. We leverage the region's exceptional data quality and pursue a detailed moment tensor-derived focal mechanism study paired with event relocations. Using the Alaska Earthquake Center's published hypocenters from the 2019 swarm onset, we first invert moment tensor solutions for the largest events and compare with published solutions as a control. We then invert moment tensor solutions for events without published solutions and with decreasing magnitudes. We aim to characterize the seismic origins of the Purcell Mountains swarm and identify fault structures in this remote region of Alaska.

POSTER 78

Deep Learning-driven Seismicity Catalog of the Cascadia Region

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The Cascadia region, particularly the Cascadia subduction zone, is well known for its potential to generate destructive megathrust earthquakes. A comprehensive and complete seismicity catalog is crucial for enhancing our understanding of regional tectonics and assessing seismic hazards over both short- and long-term timescales.

Using advanced deep-learning pickers, we construct a detailed catalog of offshore seismicity based on seismic data from the four-year Cascadia Initiative amphibious array and three additional temporary Ocean Bottom Seismometer (OBS) deployments. Continuous OBS and land-based seismic data were analyzed using deep-learning phase pickers, OBSTransformer and EqTransformer, respectively. Preliminary earthquake locations were determined through three association methods—REAL, Gamma, and PyOcto—considering only events identified by all three. These locations were further refined using absolute location methods and double-difference relative relocation techniques. To enhance seismicity completeness, template matching was applied, particularly in regions with low seismic activity, such as the Juan de Fuca Plate and the Cascadia margin.

Our catalog consists of approximately 24,000 earthquakes, with magnitudes ranging from -2.81 to 5.21 and a completeness magnitude of 1.5. This includes ~19,000 events in the Blanco Transform Fault System, ~3,400 in the Gorda Plate, ~650 in the Juan de Fuca Plate, and ~700 along the Cascadia margin. This comprehensive and complete earthquake catalog enhances our understanding of regional tectonics. The characteristics and implications of these newly detected earthquakes will be discussed, with a focus on their underlying mechanisms.

Data-driven and Computational Characterization of Non-earthquake Seismoacoustic Sources

Oral Session • Wednesday 16 April • 2:00 PM Local

Conveners: Souheil M. Ezzedine, Lawrence Livermore National Laboratory (ezzedine1@llnl.gov); Benjamin L Moyer, University of Maryland, College Park (blmoyer@umd.edu)

Catching the Sonic Boom From the NASA's OSIRIS-REx Capsule Re-entry

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In collaboration with Sandia National Laboratory, we deployed a seismoacoustic array at the Eureka Country airport, Nevada, to record the sonic boom generated by the capsule re-entry of NASA's OSIRIS-REx mission on September 24, 2023. We fielded a 1 km aper- ture array, consisting of a 3 × 6 Golay array and two acoustic subarrays. All the seismic and acoustic instruments successfully recorded the double sonic booms. We also per- formed a 94 m long refraction survey including 48 geophones with a corner frequency at 28 Hz to map the near-surface P- and S-wave velocity structure near each infrasound ar- ray. According to the seismic data frequency-wavenumber analysis, the incident acoustic wave (an amplitude of less than 1 Pa) impinged on our array with a horizontal slowness of 0.35 s/km, corresponding to a velocity of about 2.85 km/s with an azimuth of nearly N2°E and an incidence angle of around 6.5°. The FK analysis also illustrates additional energy at different azimuth and slowness values. The denoised radial components of the Golay array demonstrate the incident acoustic wave with horizontal slowness of 0.30 s/km (3.33 km/s) and an azimuth of less than 6°. This discrepancy in slowness and az- imuth of vertical and radial components could be evidence of scattering. Moreover, array site earth model is inferred from a near-surface refraction and surface wave dispersion techniques. The resulting first-order layered P-and S-wave velocity models derived from the refraction data show five layers of unconsolidated sediments up to 33 m, including two low-velocity zones. Using the velocity models, we generated ground motion syn- thetic seismograms and surface pressure to investigate the observed Golay array ground motion and acoustic data. This study aims to investigate the mechanisms governing the conversion of acoustic wave energy into seismic waves and explore the wave propagation in the near surface.

Coupled Seismic and Acoustic Waves Generated by Satellite Starlink-2382's Reentry

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On August 27th, 2024, at approximately 19:30 UTC, the Starlink-2382 satellite entered the Earth's atmosphere following a controlled de-orbit maneuver over Central Europe. This resulted in a relatively shallow entry of the satellite into the atmosphere, which was intended to provide sufficient time for the satellite to fully burn up before reaching the Earth's surface. This study employs seismo-acoustic data to analyze the trajectory of Starlink-2382's de-orbit, utilizing 3D atmosphere models including wind and acoustic ray tracing methods. To identify signals produced by the falling satellite, we utilize seismo-acoustic recordings of Austrian, French, German, and Swiss regional networks that are provided in an openly accessible format. Utilizing these identified signals, we have preliminarily characterized the satellite's trajectory, determining an azimuth of 53.5° from north and an initial zenith angle of 89.9°, with an entry velocity of approximately 28 km/s from the satellite's telemetry data. This study demonstrates the effectiveness of the seismo-acoustic method for determining the trajectories of supersonic objects traversing the Earth's atmosphere, and their deceleration within it. Our findings indicate that this approach offers greater accuracy than optical trajectory derivation methods in this specific context. Utilizing these parameters, we calculate the ablation coefficient to be 3.5e-8 s^2m^{-2}, which is necessary for the 260 kg satellite to fully burn up in the Earth's atmosphere during its descent. We compare these results to data from previous meteoroid falls and discuss the implications of our findings. Furthermore, we analyze the acoustic-to-seismic ground coupling efficiency for this event and characterize the measured amplitudes at the seismo-acoustic recording stations used to derive preliminary ground coupling coefficients. Knowledge about the acoustic-to-seismic ground coupling coefficients allows the estimation of future satellite or meteoroid fall masses using seismo-acoustic data alone.

Seismoacoustic Source Characterization and Uncertainty Quantification

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We present an innovative approach to integrate seismic and acoustic waveform signatures to enhance the estimation of source parameters, including depth, size, and source type, while quantifying associated uncertainties. Initially, we analyze seismic data to derive fundamental source parameters through the Moment Tensor Uncertainty Quantification tool, which also provides estimates of uncertainties. Building on these estimated source mechanisms, we predict acoustic characteristics, including frequency content and duration, and compare to observed acoustic data. Combining the acoustic and seismic datasets increases understanding of the source and increases understanding of uncertainties. However, accurately predicting acoustic signatures is highly computationally expensive. To address this burden, we explore the potential role of machine learning to more accurately predict acoustic signatures given source-receiver geometries, complex terrain, and atmospheric modeling that accounts for seasonal atmospheric variation. We evaluate seismoacoustic datasets at the local scale of 5-200 km from the Dry Alluvium Geology 4 chemical explosion experiment and the Utah Test and Training Range rocket motor burns tests. The integration of seismic and acoustic data offers new insights into and potential for more accurate source characterization and uncertainty quantification. This work not only contributes to the understanding of explosive sources but also enhances the methodologies employed in monitoring for these sources.

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Inversion of Helicopter Characteristics Using Infrasound Data

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Helicopters produce sound across both the audible and infrasonic frequency bands. We are analyzing data from a three-station infrasound network to study the acoustic signals generated by a helicopter during maneuvering within a confined area of approximately 6 km^2. The helicopter, part of a prescribed burn experiment, operated within this area for almost 2.5 hours, executing multiple closed paths while maintaining two main elevations. The network included 2 two/three-sensor stations and a small aperture six-sensor array. The recorded waveforms show clear tonal noise, with fundamental frequencies slowly drifting between 11 and 15 Hz. The amplitude of the fundamental frequency seemed to increase with decreasing frequency. We are modeling this variability as a Doppler effect, while the amplitude increase is hypothesized to result from a highly anisotropic noise pattern. We are integrating back-azimuth estimations from the sensor array with the temporal evolution of the fundamental frequency recorded across the network to extract details of the helicopter's operations, such as rotor angular velocity, location, and speed. To validate these inversion results, we are using GPS-based onboard location data from the helicopter. The initial results highlight the potential of acoustic measurements to track and characterize the dynamics of helicopter operations, particularly during complex maneuvering.

Estimating an Airborne Dipole Source Using 3D Wavefield Simulations and Seismic Stations on the Ground

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Acoustic signals can couple to the ground, and give an opportunity to use seismic stations to investigate airborne sources. The study of Bishop et al. (2022) used wavefield simulations in a fluid-solid medium to quantify the role of topography on the seismic (ground) recordings of a monopole source in the air. We build upon this study by linking the wavefield modeling with the source estimation code MTUQ, which can accommodate point forces (e.g., dipole in the air) or moment tensors (e.g, monopole in the air), as well as 1D or 3D Green's functions. We perform a series of synthetic numerical experiments to demonstrate that a dipole airborne source can be estimated using ground-based stations, including within the presence of realistic topography. We explore the influence of station coverage, topography, and assumed source location on the estimated results. The established capabilities raise the prospects for future efforts to estimate moving dipole sources in 3D models that include 3D heterogeneity (in the air and solid) in addition to topography.

Data-driven and Computational Characterization of Non-earthquake Seismoacoustic Sources [Poster]

Poster Session • Wednesday 16 April

Conveners: Souheil M. Ezzedine, Lawrence Livermore National Laboratory (ezzedine1@llnl.gov); Benjamin L Moyer, University of Maryland, College Park (blmoyer@umd.edu)

POSTER 66

Probabilistic Tsunami Hazard Assessment in the Southern Atlantic

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For sites far from subduction zones, infrequent and less studied sources can contribute significantly to the tsunami hazard. The southern Atlantic Ocean contains one subduction zone, the Scotia, and many volcanic edifices in different phases of activity. This tsunami hazard study implemented an initial deterministic hazard assessment to evaluate sources including earthquakes on subduction zones and local faults, local continental slope landslides, and volcanic flank collapse. In the site region, local faults on the continental shelf were reviewed for evidence of Quaternary activity and sense of slip, and landslide scars along the continental slope were mapped and categorized to determine potential source characteristics. Subduction zone sources were developed using global source databases for both the Sumatra and Scotia subduction zones. Of the deterministic sources, only tsunamis generated by volcanic flank collapse were determined to generate significant waves at the site. Due to many of the potential volcanic sources in the Southern Atlantic not having previous assessments of past or potential flank collapses, an analog database was developed for volumes, source and deposit shape from the well-studied volcanic systems of the Canary Islands and Reunion Island. These data were combined with island-specific characterization that was used to determine the similarity and thus relevance, of that analog data to potential source sites determining the uncertainty of potential tsunami source parameters and weights. In total, seven volcanic edifices were characterized for the deterministic study and subsequently eight were characterized for the probabilistic study.

POSTER 67

Evaluating Synthetic Acoustic Waveforms From Fire Sources Using 3D Finite Difference Method

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Wildfire poses an increasing risk to forested and urban areas. Combustion related to fire has been shown to generate low frequency acoustic waves and infrasound (sound below 20 Hz). *infraFDTD* is a 3-D numerical solver for the acoustic wave equation using Finite-Difference Time-Domain (FDTD) method and second-order approximations, and has previously been used to model the acoustic source of volcanoes with an assumed gaussian source time function (Kim and Lees, GRL 2011). Adapting *infraFDTD* demonstrates that synthetic acoustic wavefields from experimentally derived fire source time functions produce signals with frequencies constrained from 0-25 Hz, and dominant frequencies in the 0.1-1 Hz range. This is consistent with acoustic observations from a prescribed burn at Eglin Air Force Base in March 2023.

Comparative analysis with literature also confirms that fires with extensive flame fronts produce stronger infrasound signals at 0.1 Hz. By utilizing models to give constraints on source properties, fires can be better identified from acoustic observations in the field. Additionally, inverse modeling using the Reverse Time Migration (RTM) (Kim and Lees, GJI 2015) technique demonstrates the potential for imaging the acoustic source of fires from observation stations below 15 Hz.

POSTER 68

A Novel Physics-guided Contrastive Learning Strategy for Seismic Signal Analysis

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A moving seismic source generates signatures that change both temporally and spectrally. When combined with the seismic propagation due to the laterally varying structure of the shallow crust, we can expect significant variations in the received seismic signal. We present a contrastive learning strategy that uses temporal similarity, derived from time-frequency coherence, to estimate and aggregate consistent seismic signal patterns for complex anthropogenic sources. By leveraging physics-guided frequency-based temporal analysis, our approach captures the non-stationary characteristics of seismic data more effectively than standard methods, and under multiple propagation conditions.

To evaluate our approach under varying noise levels and signal complexities, we use three seismic and acoustic datasets for a variety of ground vehicles: (1) MOD, a self-collected set of seven vehicles plus a dismounted human; (2) ACIDS, containing nine ground vehicles traveling at speeds from 5-40 km/h; and (3) NSIN, featuring eleven commercially available vehicles in three different environments under varying speeds, distances, and directions. Using our physics-augmented embeddings in a lightweight downstream classification model (using just a few neural network layers), we create classifiers that are robust to the inherent non-stationarity in seismic signals. Experimental results show that time-frequency coherence yields more accurate inter-sample similarity assignments and improves downstream tasks with up to 7% higher target classification accuracy while requiring fewer labeled samples than conventional contrastive learning frameworks. These findings demonstrate the strong potential of the Foundation Models for advanced seismic signal understanding under varying noise and propagation conditions.

POSTER 69

Advancing Geophysical Data Training With MsPASS and GeoLab

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Cloud computing is revolutionizing the accessibility and scalability of geophysical research and education. As part of EarthScope's commitment to advancing the community's technical capabilities as operators of the NSF SAGE and GAGE facilities, the GeoLab JupyterHub environment has proven to be a key platform for hosting and facilitating short courses. A standout example is the use of MsPASS (Massive Parallel Analysis System for Seismologists) within GeoLab to provide a new hands-on training workshop in seismology data processing. MsPASS software utilizes modern container technology, an integrated data management system (MongoDB), and a parallel framework (Dask) to provide users with a workspace where they can quickly prototype and test parallelizable workflows that scale with the availability of cloud-based infrastructure. By using Python as the job control language, MsPASS provides seamless interaction with the cloud through Jupyter Notebooks. GeoLab's built-in Dask Gateway enables MsPASS to take full advantage of the scalable framework it is built on and orchestrate massively parallelized workflows.

By leveraging GeoLab's pre-configured computational environment, the MsPASS short course eliminates technical barriers and enables participants to focus on skill development, with no requirement for individual students to have advanced local computing resources, install software packages, or configure their individual environment. With EarthScope instructional design support, participants gained practical experience in tackling real-world data challenges, leveraging cloud-computing resources, and developing reproducible workflows. The success of MsPASS in GeoLab highlights the scalability and potential of the platform as a model for delivering inclusive, high-impact geophysical training.

POSTER 70

Deep Clustering of Ambient Volcanic Seismicity: An Example at Erebus Volcano, Antarctica

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We present a novel approach for unsupervised deep clustering of different families of ambient seismic behaviors at Erebus volcano, Antarctica. As part of an NSF-CAIG initiative, we explore several multimodal and array flexible architectures with the goal of utilizing continuous multi-station seismic datasets to sort transient behaviors on multiple time scales into families in a clustering space. Variational autoencoder based architectures, in particular, show promise in terms of clustering robustness and family reproducibility when paired with convolutional layers and spectrogram inputs. For Erebus volcano, where multiple cataloged datasets exist including icequakes, Strombolian eruptions, teleseisms, iceberg tremor, and various flavors of ambient noise, such deep learning setups have already shown for example the ability to cleanly separate Strombolian eruptions from icequake activity, a task that typically requires a multi-step process involving STA/LTA detectors and multi-station matched filtering. We further show that inter-family separability, such as in the case of repeating icequake activity, can be seen in the subspace of clustered families, showcasing the flexibility and depth of these approaches. We anticipate eventual training and implementation of real-time networks with the goal of adding to a pool of next generation tools aiming to improve monitoring efforts of dynamic media.

POSTER 71

Seismic Reflection Imaging of Fluid-filled Sills in the West Eifel Volcanic Field, Germany

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We applied state-of-the-art seismic processing and imaging techniques to crustal-scale seismic reflection data from the BELCORP/DEKORP87 lines 1A and 1B. The aim of the presented work was to identify structural evidence in the Earth's crust and upper mantle related to the ongoing magmatic activity in the Quaternary West Eifel Volcanic Field (WEVF) in Central Europe where ca. 70 eruptions happened since 65 ka. Following careful signal-processing, Fresnel volume migration was applied and yielded images with exceptionally strong lithospheric reflectors in the SE of the WEVF. Sparse signal representation revealed numerous reversed polarities. Using petrophysical relations, the corresponding reflections can be interpreted as reflections from melt and/or volatile-bearing (supercritical CO_2) zones which appear as horizontally elongated lens-shaped sills. Furthermore, we observed reflections with similarly inverted polarities from structural features located around the Moho at of 31 km depth, indicating fluids or melts from the uppermost mantle and supporting magmatic underplating models.

POSTER 72

Dense Seismic Noise Measurements for the Assessment of Site Response Variabilities: Application to a Liquefiable Site in the Po Plain

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The seismic response of a site depends mainly on local soil characteristics; however, a strong seismic motion can induce nonlinear soil behavior, which in turn can modify the site response. The nonlinear soil behavior may lead in some cases to soil liquefaction. In northern Italy, following the two Emilia earthquakes of May 2012 (Mw of 6.1 and 5.9), widespread surface liquefaction of silty sands was observed in the Po Plain. A temporary accelerometric station, SAN0, was installed in San Felice sul Panaro and recorded potential nonlinear soil behavior during the second earthquake. Moreover, slight evidence of soil liquefaction was observed a few meters from the station and more signs were noted several hundred meters to the south of the station. Despite various geotechnical investigations conducted around the station, a significant gap remains in the comprehensive characterization of site response variability and shear wave velocity (Vs) profiles at the city scale, which are essential for understanding local seismic responses.

To address this gap, we carried out an extensive seismic campaign at the site thanks to the Transnational Access of the Italian Project "MEET - Monitoring Earth's Evolution and Tectonics" (*https://meet.ingv.it/bandi/transnational-access*). It involved deploying 43 of individual stations across the city, including in areas with dense evidence of liquefaction. Moreover, five arrays of ambient vibration recordings with radii of 50, 100, 200, 300, and 400 meters were deployed, each consisting of five stations centered around the seismic station SAN0. Initial analysis was conducted using the Horizontal-to-Vertical Spectral Ratio (H/V) and the Ambient Vibration Array (AVA) methods. These techniques are well-established for identifying site response variability and characterizing the shear wave velocity profile of the subsurface. Additionally, this study explored day-night variations in seismic noise, highlighting the influence of environmental and anthropogenic factors.

POSTER 73

Scaling Implications of Terrestrial Impact of Meteors: Cratering, Ejecta and Cloud Formation, Induced Ground Motions

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Meteorite terrestrial impacts are established as the causes of large circular geological structures, major crustal deformations, large volumes of displaced rocks, extensive ejecta, and ultimately non-ideal debris cloud formation. Statistically, these are rare events, and the physical processes involved in terrestrial impacts and their subsequent induced effects, such as cratering, ejecta formation, airborne debris cloud formation, seismic ground motions, and eventual tsunami generation if impacts are shallow water seas, are very complex, and a physics-based approach is essential to differentiate between the different physical and mechanical processes and to address the key parameters that drive their behaviors and their implication on scaling laws. In the present study, we rely not only on HPC numerical simulations but also on the expertise acquired from of high energy near-surface explosions. Results presented in this paper indicate a slightly shallower or, depending on the geology, greater depth of analogue burst explosions is required to mimic scaling laws of crater diameter, displaced mass, ejecta blanket formation, and the characteristic times for crater-induced ground motions such as peak-particle velocities and accelerations. Crater debris depth and ejecta-travel distances are also numerically investigated because they play the key source parameters of cloud formation and global circulation. Numerical results show with confirmed confidence using existing observation data that the variations within the ejecta velocities are more consistent with half shallow buried yield-dependent high-explosive cratering events which is counter-intuitive to the common-wisdom assumptions. We supplement the results with meteorite impact movies on different crustal emplacements & geologies.

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POSTER 74

Seismoacoustic Tracking and Characterisation of Space Debris Re-entries

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Space debris and uncontrolled re-entries of orbiting spacecraft into the Earth's atmosphere are problems of growing international concern. Debris poses a hazard both on the ground and in the air, and poses environmental risks as well. Radar and visible light cameras are most commonly used to track re-entry events, but come with many challenges including limited coverage and restrictions on data releases.

In this work, I will demonstrate that existing seismic networks are able to track and characterise the shockwaves and acoustic signals produced by re-entering debris. These waveforms can be used to determine the re-entering object's speed, trajectory, size, and potentially whether any fragments may have reached the ground. Case studies will include recent re-entries over California and Louisiana.

I will also discuss the potential for near-real-time 'rapid response' trajectory reconstruction and possible synergies with visible light observations where these are recorded.

POSTER 75

Fast Probabilistic Seismic Hazard Analysis Through Adaptive Importance Sampling

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Probabilistic Seismic Hazard Analysis (PSHA) traditionally relies on two computationally intensive approaches: (a) Riemann Sum and (b) conventional Monte Carlo (MC) integration. The former requires fine slices across magnitude, distance, and ground motion, and the latter demands extensive synthetic earthquake catalogs. Both approaches become notably resource-intensive for low-probability seismic hazards. We introduce Adaptive Importance Sampling (AIS) PSHA, a novel framework to approximate optimal importance sampling (IS) distributions and dramatically reduce the number of MC samples to estimate hazards. We evaluate the efficiency and accuracy of our proposed framework using various seismic sources, including areal, vertical, and dipping faults, as well as combined types. Our approach computes seismic hazard up to 3.7×10^4 and 7.1×10^3 times faster than Riemann Sum and traditional MC methods, respectively, maintaining COVs below 1%. We also propose an enhanced approach with a "smart" AIS PSHA variant that leverages the sampling densities from similar ground motion intensities. This variant outperforms even "smart" implementations of Riemann Sum with enhanced grid discretizations by a factor of up to 130. Moreover, we demonstrate theoretically that optimal IS distributions are equivalent to hazard disaggregation distributions. Empirically, we show the approximated optimal IS and the disaggregation distributions are closely alike, e.g., with a Kolmogorov Smirnov statistic between 0.017 and 0.113. This novel approach also demonstrates extensibility to PSHA with multiple scenarios, i.e., accounting for epistemic uncertainty. We illustrate how to estimate the mean and fractile curves under this framework and highlight its potential to incorporate the distribution of epistemic uncertainty random variables in PSHA.

POSTER 76

Data-informed Polarization Analysis to Improve Seismic Discrimination and Source Characterization

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We investigate techniques for identifying and isolating polarized seismic signals to enhance source identification and explore shallow earth structure. Short period (≥1 Hz) seismic surface wave signals are commonly observed at local distances (<200 km) from near-surface events like explosions and human activities and pose a challenge in local-distance seismic discrimination. These signals can interfere with or bias common discriminants, such as P-to-S phase amplitude ratios, which are commonly used to distinguish earthquakes from explosions. Here we explore methods to remove polarized surface wave signals from locally recorded seismograms to improve phase amplitude discriminants. Furthermore, surface waves provide valuable insight into shallow subsurface velocity structure due to their sensitivity to shallow geologic heterogeneities. We highlight the dual nature of polarized surface wave signals, emphasizing the need to carefully consider their removal or exploitation based on research objectives. Our results demonstrate the value of polarization analysis of seismic signals to enhance both seismic source identification and our understanding of shallow earth structure.

POSTER 77

A Moment-based Correction for Non-stationarity in Random Vibration Theory

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Random vibration theory (RVT) is a robust probabilistic tool for the bidirectional conversion between Fourier amplitude spectra (FAS) and expected pseudo-spectral acceleration (PSA) without explicit time domain information. In practice, RVT allows for the development of ground-motion models in the FAS domain and the computation of associated time domain peak values (e.g., PSA) for engineering analyses. This approach offers several advantages over traditional methods due to the inherent limitations of PSA, such as oscillator frequency interdependence, which presents challenges in ground motion development, limits adaptability, and restricts the utilization of small-magnitude motion data. However, earthquake ground motions do not meet the assumption of stationarity (i.e., time-invariant statistics), a fundamental assumption of RVT. Various authors have proposed adjustments to RVT to address this deficiency. These adjustments, which are typically developed using simulated time series, rely on additional parameters and often fail to capture the effects of spectral shape due to site response or regional differences. We present a new correction for RVT based on the moments of the FAS of the oscillator response. This approach is based on the theory of transient random vibrations and is calibrated to recorded earthquake ground motions. By using the moments of the FAS in the calculation of the correction factor, the factor changes as the shape of the FAS changes. The calibration is performed using records from the NGA-West2 database at multiple damping levels (0.5 to 30 %), and then tested against the NGA-East and a preliminary NGA-West3 databases. The results show that the proposed correction is robust.

POSTER 78

Waveform Modeling of Acoustic-seismic Interactions Using a Hybrid Wavenumber Integration Method

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High Mach number atmospheric projectiles such as incoming bolides or spacecraft create elongate conical shock wavefronts that decay into propagating acoustic waves that may be recorded by atmospheric and ground level infrasonic instruments as well as near-surface seismic instruments. The resulting seismic wavefield is interesting from at least two points of view. The conversion from atmospheric acoustic waves to seismic waves in the solid earth creates seismic data that can be used to understand the size and intensity of the acoustic source where local infrasound data are not available and, codependently, the response of the earth to the acoustic source is a function of earth structure which opens up this dataset for probing physical characteristics of the near-surface. A hybrid wavenumber integration method is developed for an acoustic line source, as an approximation to highly elongate Mach cone wavefronts, in a smooth, vertically continuous atmosphere over a layered elastic halfspace. Atmospheric wave propagation is treated using the WKBJ approximation with a Thompson-Haskell propagator matrix formulation for the layered halfspace. Regional waveform data from Space Shuttle return missions in 2007 and 2010 for the Central United States show a variety of responses that include the interaction of the ballistic acoustic wave with near-station structure at high phase velocity for Oxford, Mississippi, and creation of long duration surface waves at other stations with the Mississippi embayment at larger distance from the vehicle trajectory.

POSTER 79

Thermo-mechanical Modeling of Deformation Sources Driving Seismicity at Campi Flegrei Caldera

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The ground deformation unrest at Campi Flegrei caldera has been going on for about two decades and has been paired with increased seismic magnitudes and rates since 2015. Recent geodetic and seismic measurements indicate a significant increase in uplift rates, providing insights into the spatial and temporal patterns of deformation. Magma transport effects on the measured deformation have been discussed as well as the presence of gas and fluid accumulation that builds the pressure up beneath the caprock. Geodynamic modeling allows gaining insight into the subsurface processes yielding the observed deformation and seismic activity. Geodynamic stress predictions can then be used to model the seismic response, thus coupling geodynamic and seismic models.

Joining the interpretations from seismic imaging, geodetic observations, and rock physics, we perform thermo-mechanical modeling of magma reservoirs using the Lithosphere and Mantle Evolution Model (LaMEM) code, which takes into account visco-elasto-plastic rheologies. Employing the existing structural information on the caldera, like a caprock layer and a hydrothermal system, the 3D thermo-mechanical numerical simulations of the magmatic system account for deep crustal magma migration from an ~8 km-deep magma sill to a magma reservoir up to 5 km depth and suggest that this, combined with the effect of overlying rheologies and structure, may be the source of the deformation. The stress response of seismically active caldera rim faults has also been implemented. The simulations aim to understand the changes in the deformation pattern and amplitude as well as the stress field for future modeling of the seismic responses, thus contributing to the source and structure characterization.

POSTER 81

Urban Acoustics and Infrasonic Detection of Crowd Noise

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The efficacy of a 10 meter, six-node hexagonal infrasonic array for detecting crowd-sourced infrasound signals from a football stadium was demonstrated using directional analysis. Data were collected over two three-hour periods: during a football game and a non-event day for comparison. Beamforming techniques analyzed angle of arrival, power, and speed. Results show directional clustering toward the stadium on game days in mid-frequency ranges (4–16 Hz). Similar clustering on non-event days prompted a Watson-Williams test, with a p-value of 0.009, suggesting a significant statistical difference. Rose diagrams and mean direction plots demonstrate tighter clustering toward the stadium direction on game days compared to broader distributions on non-event days. Signal power analysis revealed mid-frequency ranges on event days had elevated stadium-aligned power ratios (e.g., 8–12 Hz ratio of 0.225 versus 0.142 on non-event days), supporting the hypothesis of crowd-induced signals. Low (0–4 Hz) and high (16–20 Hz) frequency ranges showed consistent directional behavior across both days, suggesting influence from ambient noise sources. These findings underscore the array's ability to detect anthropogenic infrasound amidst urban noise, illustrating potential for geophysical applications in event monitoring and crowd dynamics analysis. We surmise that multiple array stations distributed spatially would improve detection over single station deployment.

POSTER 82

Exploring Sensitivity of Infrasound Signal Predictions to Atmospheric Inputs

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Accurately predicting infrasound propagation and interpreting signal detections rely on robust atmospheric specifications. Disparities between observed signals and model predictions often manifest as unexpected detections, undetected signals, or mismatches in travel times and source directions. These challenges emphasize the importance of understanding the sensitivity of propagation models to variations in atmospheric inputs. The current de facto source of atmospheric data (G2S) provides geographically and temporally averaged specifications. However, radiosondes collect data at specific times and locations that may be more accurate. This study investigates how incorporating atmospheric data collected by radiosondes influences the accuracy of model predictions. Seasonal and diurnal variations, along with other atmospheric factors, are considered in evaluating the sensitivity of model outputs. The results will be discussed to assess how such detailed measurements influence predictive accuracy and what implications this has for the broader field of infrasound monitoring. We will also discuss the potential value of integrating radiosonde measurements into modeling efforts. This work aims to provide a foundation for improving infrasound propagation predictions, thereby advancing the reliability of infrasound applications in diverse applications.

POSTER 83

Classification of Aircraft Type Using Seismic Data in Alaska

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Recent work has shown that seismic data, particularly at frequencies above 10 Hz, often contain abundant acoustic-seismic coupled signals from aircraft. These signals have characteristic time-frequency signatures due primarily to the aircraft's sound doppler effect and engine features. We use a set of 306 seismic nodal sensors deployed in central Alaska in February and March 2019 to estimate the closest time, closest distance, and speed for a set of 1770 known flights passing within 2 km of a seismic sensor. By estimating these three parameters, we are able to determine the base frequencies (up to 250 Hz) that characterize the aircraft. Our uncertainties can be reduced by taking into account temperature and wind conditions, which affect the sound speed between the aircraft and seismic sensor. The Alaska data set of diverse aircrafts—propeller planes, helicopters, 1940s Curtiss C-46 Commandos, 747 Boeing jets—provides an excellent opportunity to establish and refine procedures for characterizing aircraft from passively recording seismic and acoustic sensors. Our final catalog provides a frequency classification of 141 unique aircraft types that were recorded by our seismic sensors, and our method could be applied in a straightforward manner to other datasets.

POSTER 84

Tsunami Warning Cancellation Using Data Assimilation Approach

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Tsunami warning cancellation refers to the act of rescinding issued tsunami alerts when it is confirmed that the threat of a tsunami has diminished. This plays a crucial role in mitigating tsunami hazards, avoiding unnecessary economic constraints and the burden of sustained emergency responses. For example, after the Noto Earthquake occurred on January 1, 2024, the tsunami warning was not fully cancelled until 10 a.m. (JST) the next day, approximately 18 hours after the earthquake. Rescue personnel from outside can only enter the disaster area after the tsunami warning has been cancelled.

We investigated the predictability of tsunami warning cancellation using a novel approach based on data assimilation (Maeda et al., 2015). This approach has the potential to predict tsunamis independently of seismic source information and was applied to tsunami warning issuance (e.g., 2012 Haida Gwaii earthquake; Gusman et al., 2016). We adopted this approach to tsunami warning cancellation with the aim of developing a comprehensive warning process. The originality of our research is that we integrated tsunami data assimilation with a nonlinear wave model to accurately predict the characteristics of the later phase of tsunami waves.

We focused on the coastal areas of the Kii Peninsula, Japan, using the 2011 Tohoku earthquake as a case study. We assimilated tsunami data from 10 offshore stations (DONET) and predicted the tsunami waveforms at five coastal tide gauges. The results demonstrated significant consistency (over 80%) between the predicted and observed maximum height in the tsunami later phases, suggesting that data assimilation could provide valuable insights as a guideline for tsunami warning cancellations. In the future, we will extend our research to far-field tsunamis across the Pacific Ocean. Considering the topography of different regions including Japan, Alaska, and Hawaii, we will propose corresponding countermeasures for tsunami warning cancellation in each region.

POSTER 85

Making the Cloud Accessible for Geophysical Research: EarthScope's Path for Cloud Adoption and Workflow Migration

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The EarthScope Consortium manages NSF's SAGE and GAGE facilities and makes all of its geophysical data available through a commercial cloud system. This enables EarthScope and the communities it supports to leverage the abundant computational resources and cost-effective benefits of adopting data-proximate workflows with direct access to large, analysis-ready geophysical data sets. As part of a broad effort to support communities with intuitive resources to quickly migrate their workflows to the cloud, EarthScope has partnered with the International Interactive Computing Collaboration (2i2c, https://2i2c.org/) to launch GeoLab, a scalable JupyterHub environment in AWS. This platform will provide equitable access to cloud compute resources for researchers, educators, and the general public. GeoLab is data-proximal and integrated with the rapidly expanding capabilities of EarthScope's Application Programming Interfaces (APIs) and python Software Development Kit (SDK). In the coming year, we anticipate fully integrating the API and SDK with our authentication system, which will enable direct access to our cloud object storage – a crucial feature to migrate analysis workflows away from the typical download-intensive model and towards a data-proximate model that allows for high-throughput analysis to be done at a massive scale.

In the last year, GeoLab has been an instrumental tool for EarthScope to host data analysis workshops. This has streamlined the educational experience for users by eliminating installation and environmental configuration steps that commonly complicate the start of courses. GeoLab provides students and researchers with equitable access to advanced training in modern cloud-computing practices and open-source domain-specific software, regardless of their location or available computing resources. We continue to expand access to these resources, and invite all members of the geophysics community to follow our progress.

Earth's Structure from the Crust to the Core

Oral Session • Wednesday 16 April • 8:00 AM Local

Conveners: Ebru Bozdag, Colorado School of Mines (bozdag@mines.edu); Gatut Daniarsyad, Agency for Meteorology, Climatology and Geophysics (gatut.daniarsyad@bmkg.go.id); Daryono Daryono, Agency for Meteorology, Climatology and Geophysics (daryonobmkg@gmail.com); Jan Dettmer, University of Calgary (jan.dettmer@ucalgary.ca); Theron Finley, University of Victoria (tfinley@uvic.ca); Jeremy M. Gosselin, Natural Resources Canada, Sidney (jeremy.gosselin@nrcan-rncan.gc.ca); Indra Gunawan, Agency for Meteorology, Climatology and Geophysics (indra.gunawan@bmkg.go.id); Nicolas Harrichhausen, University of Alaska, Anchorage (njharrichhausen@alaska.edu); Hao Hu, University of Oklahoma, (huhaoletitbe@gmail.com); Lorraine J. Hwang, University of California, Davis (ljhwang@ucdavis.edu); Keith Koper, University of Utah (kkoper@gmail.com); Andrew Lloyd, Lamont-Doherty Earth Observatory, Columbia University (andrewl@ldeo.columbia.edu); Walter D. Mooney, U.S. Geological Survey (mooney@usgs.gov); Nelly F. Riama, Agency for Meterology, Climatology and Geophysics (nelly.florida@bmkg.go.id); Jeroen Ritsema, University of Michigan (jritsema@umich.edu); Vera Schulte-Pelkum, University of Colorado (vera.schulte-pelkum@colorado.edu); Derek

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Investigating Along-strike Differences in Crust and Upper Mantle Structure of the Central Andes Through High-resolution Receiver Functions

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To obtain a comprehensive image of the Andean Cordilleran structure, we embarked on a joint broadband-nodal passive seismic deployment between Summer 2022 – April 2024 constructing two profile lines perpendicular to the orogen strike. Line 1 (~23-24°S) was deployed from the Chilean coast, across the volcanic arc, Puna plateau, and into the Chaco Plain where the high Andes (greater than 2000 *m* elevation) are ~500 km wide. Line 2 (~35.5-36°S) was deployed from the Chilean coast across the volcanic arc to the backarc Payun Matru Volcanic Field in the northern Neuquén basin where the high Andes are ~250 km wide. Both lines allow a juxtaposition of the differing deformational styles and volcanic arc magma storage systems that we can use to compare the state of the crust and upper most mantle. We use receiver functions to image the discontinuities that relate to seismic velocity changes with depth and migrate the data using composite velocity models aggregated from the literature.

Our results show shallow low velocity zones (LVZ) associated with arc and backarc magmatism in each region. The northern LVZ is associated with the large Altiplano-Puna Volcanic Complex and is more voluminous and laterally covers a region from the arc across the Puna plateau. The southern profile shows a smaller LVZ below and presumably associated with the Laguna del Maule volcanic complex. Along the northern profile we see clear dipping interfaces consistent with the slab Moho and top of the subducting Nazca oceanic crust that disappears at depths between ~120-140 km suggesting eclogitization of the Nazca crust. In contrast, the southern profile lacks a clear seismic signal of the subducting slab that may be related to its younger age and warmer temperature. In the northern profile we image a west-dipping discontinuity with an increase in velocity with depth that may be related to the to the Main Andean Decollement. These two transects reflect different mountain building and magmatic processes that we will discuss including volumetric models of melt distribution of the Laguna Maule volcano and along strike models of crustal thickness.

Seismic Imaging of the Ecuadorian Margin Lithosphere Using Teleseismic Receiver Functions Analysis and Ambient Noise Tomography

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The Ecuadorian margin represent the northern extension of the South America subduction zone, shaped by the accretion of mafic oceanic terranes and the ongoing subduction of the Carnegie Ridge. This region offers an ideal setting to investigate the interactions between subducted ridges and overriding plates, as well as the associated tectonism, magmatism, and seismogenesis. In this study, we present high-resolution imaging of crustal and upper mantle structures beneath the Ecuadorian forearc and Western Cordillera volcanic arc combining teleseismic receiver function analysis and ambient noise tomography. Our dataset includes seismic records from 11 permanent broadband stations from Instituto Geofisico-EPN, 20 temporary broadband stations from IRIS operating between 2016 and 2017, 65 temporary broadband stations operating between 2021 and 2022, and 783 nodal geophones deployed in November 2020 and March 2022.

Our receiver function analysis reveals the slab interface dipping from at ~20–25 km depth near the coastline to ~100 km depth beneath the volcanic arc, with an estimated oceanic crustal thickness of ~15–20 km and a dip angle of ~20–25°. Within the overriding crust, we identify an intra-crustal layer at ~25-35 km and a variable upper plate Moho increasing from ~30 km beneath the forearc to ~50 km beneath the arc. A shallower velocity discontinuity at ~5-8 km depth is observed beneath the Manabí Basin that we interpret as the mafic basement beneath the basin. Our 3-D velocity model from ambient noise highlights significant velocity variations within the Ecuadorian forearc crust. Specifically, we observe two lower-than-surrounding velocity anomalies at depths shallower than 10 km beneath the western Manabí basin and Coastal Cordillera, and Borbon basin. In addition, we see a high velocity anomaly striking north-south along the boundary between accreted forearc terranes and volcanic arc at depths of 20-40 km that likely represents the mafic oceanic accreted terrains at depth. These observations provide important insights into the tectonic, magmatic, and seismogenic evolution of the Ecuadorian subduction zone.

Upper Mantle Structure Beneath the Mongolian Region From Multimode Surface Waves: Implications for the Western Margin of Amurian Plate

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Multimode phase speeds of surface waves are used to build a new radially anisotropic S wave model in the eastern Eurasian and Mongolian regions. Our dataset includes seismic waveforms of over 1655 teleseismic events ($Mw \geq 5.8$) from 2009 to 2021, recorded at permanent and temporary stations in and around Mongolia. The multimode dispersion curves of Love and Rayleigh waves were extracted using the nonlinear waveform fitting method for individual seismograms. Then, we retrieved phase speed maps for each mode and frequency, incorporating finite-frequency effects. Finally, localized multimode dispersion curves extracted from the phase speed maps were inverted for local 1-D SV and SH wave profiles, which are combined into a radially anisotropic 3-D shear wave model. Our new model exhibits significant lateral variations of S wave speeds at 70–100 km depth beneath Mongolia, i.e., slow anomalies in the tectonically active western Mongolia in contrast to fast anomalies in stable eastern Mongolia. In the radial anisotropy model, SH waves are faster than SV waves in most areas of the Mongolian lithosphere above 100 km depth, except for the northeast of the Altay Mountains. The Hangay Dome region is characterized by significantly slower velocities that may relate to its uplifting. A large-scale low velocity beneath the northeast of the Hangay Dome with a slower SV wave speed than SH may indicate the existence of partially molten layers. This study also reveals distinct lateral variations of S wave speeds across the boundary between the Amurian and Eurasian plates, characterized by the fast anomaly in eastern Mongolia, corresponding to the lithosphere in the western Amurian plate.

The Wave Gradiometry Method: Theory and Applications for Imaging 3D Velocity, Anisotropy and Attenuation

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The Wave Gradiometry Method (WGM) has emerged as a powerful multi-purpose tool for extracting strain and rotation tensors, identifying phases, and, most importantly, imaging the near-surface or deep structure (Langston, 2007). The WGM measures the spatial gradients of the wavefield within a subarray to extract four major attributes: phase velocity, wave directionality, amplitude perturbation, and radiation pattern.

An azimuth-dependent dispersion curve inversion (ADDCI, Liang et al., 2020) is applied in conjunction with the WGM method to extract 3D shear wave velocity and 3D azimuthal anisotropy. Amplitude perturbation accounts for geometrical spreading relative to propagation distance, intrinsic attenuation, and wave scattering within the medium. By eliminating the effects of scattering and geometrical spreading, the dispersion curve of attenuation is obtained, allowing for the determination of the medium's 3D attenuation properties.

In this study, we review the theoretical foundations, technical developments, and major applications of the WGM, and compare it with other major array-based imaging methods. Although the WGM can be applied to arrays of various scales, our focus is on its applications to large-scale arrays, such as the USARRAY (with an average spacing of 70 km) and CHINARRAY (with an average spacing of 35 km). We will compare our results with those from other techniques to highlight the advantages and disadvantages of the WGM.

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Unraveling Serpentinite Distribution in the Subduction Zone of NW South America

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Serpentine bodies, primarily formed through the hydration of mafic and ultramafic rocks, exhibit distinctive geophysical properties in the convergent margin of NW South America. This region features a complex subduction zone that includes a suture zone and a lithospheric tear, which control serpentinite outcrops' distribution and depth geometry. By analyzing gravity and magnetic anomalies, geothermal data, Vp/Vs ratio tomography, and magnetotelluric and gas measurements, we investigated the subsurface connections of serpentinite bodies, particularly within the Romeral Suture Zone (RSZ) and the Eastern Cordillera of Colombia. The main findings indicate that serpentinite occurrences are associated with specific geophysical anomalies and seismicity patterns, highlighting their role in subduction dynamics. Vp/Vs ratio tomography and space-time variations of apparent resistivity reveal deeper serpentinite diapirism on both sides of the volcanic arc, likely linked to buoyant advection from the subducted plates, affecting magmatism and earthquake distribution. The Caldas Tear could respond to the subduction geometry and the distribution of serpentinites, suggesting an interaction between tectonic processes and serpentinization. These insights enhance the understanding of subduction zone mechanics and the natural hydrogen occurrences linked to serpentinized rocks, contributing to the broader knowledge of geotectonic evolution in subduction environments.

chinalgq_v1.0: Seismic Lg-wave Attenuation Model in China

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Continental China is characterized by complicated tectonics, incorporating ancient cratons and orogenies from different geological periods, resulting in considerable large continental earthquakes. However, the tectonic interplay among geological blocks and the mechanisms of intra-continent earthquakes remains to be further explored. The amplitude attenuation of seismic Lg-wave during its propagation is closely related to the crust's temperature, fluid content, and strength. Thus, Lg attenuation helps investigate crustal deformation and evolution. However, the lack of a nationwide, high-resolution, and broadband Lg-wave attenuation model has impeded the application of amplitude measurements under a consistent attenuation framework. This study obtained a new Lg-wave attenuation model for China based on waveforms from 2,318 earthquakes at 1,041 permanent stations. Using an established tomographic scheme, Lg attenuation was solved independently at individual frequencies between 0.05 and 10.0 Hz. To accelerate the convergence and improve the robustness of the solution, we started with an initial Lg attenuation model compiled from a series of previous studies. The checkerboard test demonstrated that the resolution reached 1.0°, and bootstrap resampling estimated the relative uncertainty in Q to be less than 5%. The lateral variations in the resultant Lg-wave Q model corresponded to regional tectonics. High Q values were observed in stable geological blocks in south China and Tarim, whereas active regions, including the Tibetan Plateau, were characterized by significant low-Q anomalies. The average Q over 0.2 to 2.0 Hz appeared uncorrelated with crustal thickness but showed a linear correlation with the strain rate and heat flow, suggesting that crustal deformation and temperature were the primary factors influencing the Lg attenuation. Therefore, the Lg Q could indicate the crust's mechanical strength, revealing the collage pattern of new and old geological blocks in China. This research was supported by the National Natural Science Foundation of China (42104055, U2139206).

Surface Wave Constraints on Crustal Structure Beneath Elysium Planitia

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The properties of the Martian crust, including its thickness, composition, and porosity, provide invaluable constraints on the origin and geological evolution of Mars. Surface wave observations from marsquakes recorded by InSight's seismometer SEIS (Seismic Experiment for Internal Structure) have provided the best direct constraints on Martian crustal structure to date. However, surface wave signals have only been unequivocally identified in three events, limiting our understanding of crustal heterogeneity. In this study, we identify fundamental mode Rayleigh wave signals in two Cerberus Fossae marsquakes (S0235b and S1133c) and invert group velocity dispersion measurements for shear wave speed structure along two corridors in Elysium Planitia. Surface wave signals are isolated using frequency-dependent polarization analysis, which allows us to filter seismic energy based on particle motion. Rayleigh wave signals from S0235b and S1133c exhibit retrograde elliptical motion and yield back azimuths broadly consistent with body wave polarization analysis. We find that the average shear wave speed structure along the S0235b path is 8% slower than along the S1133c path, although much of the discrepancy could be due to uncertainty in marsquake source locations. Our results provide new insights into lateral variations in the crustal velocity structure on Mars and offer clues about the source depths of Cerberus Fossae marsquakes.

An Overview of the Crustal and Uppermost Mantle Structure and Tectonics of Asia

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The structure of the crust and uppermost mantle of Asia is considered in the context of the Earth Crustal Model 1 (ECM1), a 1° × 1° global crustal model. ECM1 describes the thickness of the crust, including the overlying sediments, and the corresponding seismic velocities of P-waves, S-waves, and density. The crust is described by tiles with eight layers of variable thickness for ice, water, sediments, and the crystalline crust. ECM1 differs from previous crustal models in several aspects: (1) the sediment model incorporates newly published oceanic and continental compilations of sediment thickness; (2) the application of a vastly expanded database of 19,200 seismic measurements which sample seismic velocities within the sedimentary cover, crystalline crust and uppermost mantle; (3) the continental S-wave velocity is based on field measurements, unlike other models which estimate the S-wave velocity using the measured P-wave velocity and an assumed Vp/Vs ratio; (4) a new digital map of crustal types is used to interpolate seismic velocities for unmeasured areas. We use field measurements of crustal structure to calculate the Vp, Vs, Vp/Vs and density at 5 km intervals for continents and 2 km intervals for oceans down to Moho depth for each crustal type. In comparison with the global average properties of the crust, we find that the crust and uppermost mantle of many regions of Asia are anomalous, including Tibet, the north China craton and the continental magmatic arc of Indonesia. We interpret these anomalies in terms of the processes that have formed and modified the crust.

Imaging the Crustal Structure of Fiji and Its Surrounding Regions From Seismic Receiver Functions

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Fiji and its surrounding regions in the Southwest Pacific lie within the greater back-arc domain of the Tonga trench, an area formed by subduction and back-arc rifting. The region has been shaped by active tectonic processes which have prompted extensive research interest. We present new results regarding the crustal structure of Fiji and its surrounding areas using receiver function analysis. Our goal is to image the regional crustal structure and enhance the assessment of seismic hazards in this region. We have calculated P-wave receiver functions from 114 seismic stations from both permanent and temporary regional networks that are accessible from the IRIS DMC. We used earthquakes (M5.5 - M7.0) that occurred between January 1990 and September 2024. After applying stringent data quality criteria, we have reliably determined crustal thickness and Vp/Vs ratios for 33 stations. The crustal thickness in the study varies from 18 to 26 km, values that are thicker than normal oceanic crust (7 km) and thinner than average continental crust (40 km). The thickest crust (26 km) is located beneath central Fiji and eastern Samoa, indicating a prolonged history of arc crust formation and subsequent crustal thickening. Vp/Vs values average 1.7 in central Fiji and all of Samoa, suggesting a felsic crustal composition. This implies that this crust is composed of lighter, silica-rich material. In contrast, the thinnest crust, associated with a high Vp/Vs ratio (> 1.85), is observed beneath the eastern margin of Fiji, the Lau Ridge, and the Lau Basin. These high Vp/Vs ratios suggest a denser, mafic crust, and point to the influence of back-arc rifting. High (> 1.85) Vp/Vs ratios may also indicate the presence of hydrated rocks or partial melt within the crust, conditions that would lower S-wave velocities and therefore increase the Vp/Vs ratio.

Three-dimensional Least-squares Migration of Teleseismic Receiver Functions and Its Application to the Qaidam Basin

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The receiver function (RF) method has been widely applied to resolve seismic discontinuities in the Earth's crust and mantle. The advent of dense seismic arrays enables wavefield sampling at unprecedented spatial resolution, providing new opportunities to develop advanced RF imaging techniques for improved subsurface characterization. In this study, we develop a high-resolution RF imaging technique based on three-dimensional least-square migration (LSM). The Split-step Fourier algorithm is employed to construct the forward and adjoint operators, reformulating the migration process as a least-squares optimization problem. This approach facilitates the easy incorporation of model constraints to suppress strong acquisition footprints and compensate for inadequate illumination.

The application of the LSM method to a dense linear array deployed in the Qaidam basin, northeastern Tibetan Plateau, reveals high-resolution crustal structures. Pronounced sedimentary layer-generated conversions and reverberations enable us to conduct waveform modeling that accurately constrains the basin structure and refines the migration velocity model. The modeling results indicate that a 12-km thick sedimentary sequence can adequately explain the converted phase near 3 seconds, which aligns well with the sedimentary base identified in high-resolution seismic reflection data for hydrocarbon exploration. The final migration image reveals that the Moho is relatively shallow (~50 km) beneath the basin margins adjacent to the Eastern Kunlun and Qilian orogenic belts, but deepens to ~55 km towards the basin center. These improved seismic constraints from LSM provide new insights into the deep structure and evolution of the Qaidam basin, contributing to a better understanding of intracontinental tectonics in Central Asia.

Full-waveform Modeling Explains Surface-wave Diffraction Patterns Observed on Large Dense Seismic Networks

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Stripe-like patterns of amplitude and wavefront deviations of surface waves have been observed at large dense networks of broadband seismic stations such as USArray and, recently, AlpArray and AdriaArray. We have previously shown that the patterns are not caused by the structure beneath the observation location, but rather imported with the wavefield from outside the network footprint. We have confirmed the hypothesis that these patterns are caused by diffraction and interference after the wavefield has passed a strong scatterer. The wavefield carries the diffraction imprint for thousands of kilometers and allows for localizing the position of the scatterer, its size and strength. This previous explanation was based on modeling of the travel-time delays caused by the interference after passing a single scatterer.

The next step is confirming the viability of this explanation using full-waveform modeling in 3-D Earth structure. We utilize AxiSEM3D to simulate global wavefield propagation through 1) a simple case of a single scatterer, and 2) a more complex structure with several scatterers to compute teleseismic seismograms for hundreds of stations. We process the synthetics with the same methods as the real data, showing that the full-waveform modeling is capable of reproducing the interference patterns observed in real data. We demonstrate how the stripes emerge in synthetic amplitudes, group velocity deviations, wavefront distortion and arrival angle deviations, and how it affects the dispersion curve measurement. In addition, we also observe deviations elongated transversely to the direction of propagation in our model predictions. Such regions of apparently faster and slower velocities have also been observed in real data, but had no explanation until now. Our full-waveform modeling thus not only confirms our previous hypotheses but allows for new interpretations of the observed interference phenomena. Our findings have implications for surface-wave tomographic imaging of structure beneath the network and allow us to image distant anomalies that are causing diffraction far outside of the network footprint.

Ambient Noise Tomography Along the Mexican Volcanic Belt

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The Mexican Subduction Zone is a geologically intriguing segment of the Cocos plate due to its drastic variations in slab geometry. Previous studies utilizing dense seismic arrays, such as the MASE and VEOX arrays, have provided detailed insights into the slab's dip angle changes in the central flat-subduction segment and the eastern steep-dipping region, respectively. These arrays featured high spatial resolution, with an inter-station distance of 5 km.

In this study, we present results from an ambient noise tomography analysis using a new and complementary array located along the west flank of the subduction zone. This array consists of 10 seismic stations arranged in a linear profile perpendicular to the trench, with a spacing of 30 km. The west flank is notable for its Holocene large monogenetic volcanic field and recent episodes of pulsing seismic swarms. To investigate this region's subsurface characteristics, we performed a joint multimodal inversion of dispersion curves and H/V ratios, revealing lateral variations in shear wave velocity across the profile, where the slab angle changes abruptly.

Our findings highlight the presence of low-velocity zones, which we interpret as regions of hot, partially molten material rising from the mantle. These results provide new insights into the geodynamic processes occurring along the western segment of the Mexican Subduction Zone.

Upper Mantle Anisotropy in North America and the Pacific From Global Adjoint Tomography

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The Earth's upper mantle exhibits significant anisotropy due to its composition and deformation throughout its evolution and dynamics. Despite its importance, there is no consensus on current anisotropic tomographic models. Additionally, discrepancies persist between results derived from different data sets, such as surface waves and shear-wave splitting observations. Using the transversely isotropic global adjoint model GLAD-M25 as the starting model, we developed GLAD-M28-AZI—a global azimuthally & radially anisotropic model constructed through 3D spectral-element simulations. GLAD-M28-AZI incorporates the full complexity of wave propagation and data sensitivities within an iterative adjoint tomography framework. We used minor- and major-arc Rayleigh and Love waves from 300 earthquakes during iterations. Despite our limited data, GLAD-M28-AZI achieves a continental-scale resolution in areas with sufficient data coverage. The model reveals azimuthal anisotropy in subduction zones perpendicular to the trench at depths of 50–100 km, which transitions to a trench-parallel orientation at 200–300 km in regions such as South America, New Zealand, and the Western Pacific where deeper anisotropy patterns are consistent with SKS splitting observations. As an example of continental scale observations, in North America, in addition to common features with continental-scale tomographic models, we observe distinct trench-perpendicular azimuthal anisotropy in Alaska where the north-south fast direction on the east of Alaska is interrupted by the Rockies in the south and the cratonic border along the McKenzie River at around 200 km. Azimuthal anisotropy depicts the east-west extension in the Basin and Range and consistency with plate motions, showing depth-dependent correlation with SKS splitting measurements. We will discuss the implications of our observations on GLAD-M28-AZI compared to other models and data sets for understanding continental to global scale mantle dynamics.

AK112: Full Waveform Inversion Tomography of Alaska Improves Waveform Fits While Imaging Crustal, Mantle and Slab Structure

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We present a new full waveform inversion (FWI) tomography model of Alaska and the surrounding regions. FWI tomography resolves seismic wavespeeds by minimizing the misfit between observed and simulated seismograms including the full volumetric finite frequency sensitivity of waveforms to Earth's structure. For Alaska we solve for the radially anisotropic shear and isotropic compressional wavespeeds on a ~2000 km domain by fitting regional distance complete waveforms (body- and surface waves) from 120 M_W 5.0 – 6.5 earthquakes from the Global Centroid Moment Tensor catalog. We inverted time-frequency (TF) phase misfits in 7 multiscale inversion stages and 112 total iterations starting with minimum period of 40 seconds and reducing to 20 seconds. The model was evaluated by computing the misfits for 40 independent validation events. We find that TF misfit reductions were about 55% for both the inversion and validation data sets providing confidence in the model. The model provides improved fits to complete waveforms compared to the starting model and other models of the region especially at far-regional distances. The resulting model images known crustal, upper mantle and slab structure but with new detail of radially anisotropic shear wavespeeds: sedimentary basins in the Gulf of Alaska, Cook Inlet, Northslope Foreland Basin ; discontinuous crustal structure across major terranes boundaries; subducting slab geometry and back arc volcanics; and crustal and mantle signatures including anisotropy of the Yakutat Terrane. The new model has the advantage of specifying all parameters needed to simulate waveforms (anisotropic shear and isotropic compressional wavespeeds, attenuation and density) across a large domain spanning the coastlines, plate boundary and major terranes from the surface through the crust to the upper mantle. In addition to tectonic interpretations, the model could be used for full waveform simulations for long-period earthquake ground motions or source characterizations (e.g. moment tensor and finite fault inversions).

Constraints on Mantle Dynamics From a Massive Seismic Dataset

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Shear wave speeds in Earth's mantle that vary with wave propagation and polarization direction -- a property called seismic anisotropy -- offer insights into mantle convection. Investigations of mantle dynamics through analyses of seismic anisotropy are often conducted with data limited to regional investigations; however, seismic data are available on a tera- or petabyte scale, and data availability is exponentially growing.

I have analyzed shear-wave splitting, which is indicative of seismic anisotropy, using a massive seismic dataset. This dataset contains seismograms for earthquakes with magnitudes ≥5.9 from the year 2000 to the present, retrieved from 24 data centers worldwide (~5,000 events). My measurements allow the inference of seismic anisotropy in two poorly sampled parts of the mantle, the lowermost mantle and the upper mantle beneath ocean basins: 1. I present lowermost mantle anisotropy results inferred from core-refracted phases from the massive dataset, which cover 75% of the lowermost mantle, mostly in the Earth's faster mantle volumes. In these regions, seismic anisotropy is widespread, and my observations suggest a close link between the subduction of tectonic plates and convective flow in the deepest mantle. 2. By utilizing specific combinations of seismic phases, I infer body wave constraints on upper mantle seismic anisotropy beneath ocean basins using land-based seismic stations. One intriguing observation is that, where the seafloor beneath the Pacific Plate is oldest, shear wave fast polarization directions are oriented 60–90 degrees away from the absolute plate motion. This likely reflects fossil anisotropy in the lithosphere, offering valuable insights into ancient deformation events.

Global Mantle Imaging With the Multi-mode Body Wavefield

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Seismological imaging has revealed a global mantle transition zone discontinuity, primarily driven by phase transformations in mantle minerals. However, the origins and extent of other recently observed discontinuities—such as the mid-lithosphere discontinuity, low-velocity zones above and below the mantle transition zone, and mid-mantle discontinuities—remain uncertain. Resolving the causes of these features requires joint analysis of multimodal body waves (P and S waves). By combining S and P reflections with conversions, we can potentially mitigate the trade-offs between compositional, thermal, and volatile influences, translating seismic data into detailed rock property profiles. This study outlines a framework for multimodal seismic analysis, integrating SS precursors and P-to-S receiver functions to better characterize the velocity and density gradients that contribute to mantle stratification. We highlight recent technical advancements enhancing Ps-RF and SS-precursor imaging. These include FADER (Fast and Automated Detection and Elimination of Reverberations) and CRISP-RF (Clean Receiver Function Imaging with Sparse Radon Filters) for Ps-RFs, as well as SHARP-SS (Sparse and High-resolution Algorithm for Reflection Profiling using SS waves) for SS-precursors. We demonstrate the effectiveness of this joint imaging approach with case studies from Africa's ancient lithosphere, global oceans, and North America.

Sequencing Postcursors of P and S Core-diffracted Waves: Implications for the Hawaiian Mega-ULVZ Properties

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Mantle plumes beneath major oceanic hotspots appear to be rooted in unusually large structures near the core-mantle boundary, which have dramatically reduced seismic wavespeeds. The origin of these large ultralow velocity zones, referred to as mega-ULVZs, remains controversial partly due to lack of constraints on the relative reduction in shear vs. compressional wavespeeds (i.e. the δlnVs/δlnVp ratio). This ratio can give clues into the compositional makeup of the mega-ULVZs. Here, we conduct a joint analysis of core-diffracted P- and S-waves (Pdiff and Sdiff) to infer the δlnVs/δlnVp ratio necessary to explain new seismic observations of Pdiff and Sdiff postcursors produced by wavefield interactions with the Hawaiian mega-ULVZ. Using three-dimensional wavefield simulations of various mega-ULVZ models, we model delay times and amplitudes of postscursor signals for both Pdiff and Sdiff. We find that the amplitude of Pdiff postcursors is dramatically lower relative to Sdiff postcursors due to wavefront healing and differences in wavelength. We constrain δlnVs/δlnVp ratios for the Hawaiian mega-ULVZ to be in the 1:1.3-2 range, corroborating previously reported values based on analysis of higher frequency waves. This inferred range is best explained by the enrichment of solid iron-rich (Mg,Fe)O, with no requirement for partial melting based on our accompanying mineral physics modeling. However, we also show that inferred δlnVs/δlnVp ratios depend strongly on the assumed volume of the mega-ULVZ, which needs to be better constrained by complementary seismic datasets.

Global Observations of Melt-induced Low Velocity Zones Surrounding the Mantle Transition Zone

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The mantle transition zone (MTZ) is an important part of global volatile circulation because its primary minerals, wadsleyite and ringwoodite, have an affinity for H, and therefore water, compared to the rest of the mantle. Mineral phase changes from olivine to wadsleyite and from ringwoodite to bridgmanite define MTZ at ~ 410 and ~660 km depth, respectively. Deeply subducting slabs can transport water to the MTZ, a process which buffers the Earth's oceans and atmosphere. In the presence of flowing material or a local instability, hydrous MTZ rock can be displaced and generate dehydration-induced partial melting. These partial melts are seismically detectable as seismic low velocity zones (LVZs). The presence or absence of these signals can be used to infer MTZ water content and mantle flow. Here, I apply global seismic imaging, primarily SS and PP precursors, to search for LVZs that may be induced by water. These waveforms are ideal for a global study because they image the mid-point between an earthquake and a seismic station; they do not require a seismic station to be located directly above the imaging target. However, detection of LVZs is complicated by signal-processing artifacts such as side-lobes. In this work, I first define the nature of all signal-processing artifacts prior to any interpretation. My data set has SS and PP precursors recorded on over 9,000 permanent and temporary seismic stations. Preliminary results indicate that there are detectable reductions in seismic velocity between ~300-400 km depths.

A New Constraint on Vp and Vs in the Uppermost Mantle From Late Coda

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The Preliminary Reference Earth Model (PREM) is a widely used seismic reference model in seismology. However, global SS-S and PP-P differential travel times have bimodal ocean/continent distributions with mean values of +3 s of both PP-P and SS-S. This suggests that PREM represents the seismic structure of the continental upper mantle better than the oceanic upper mantle and that, on average, PREM overpredicts the P-wave (v_p) and S-wave (v_s) velocities in the upper mantle.

PP-P and SS-S can be influenced by deep mantle structure, especially when P and S waves propagate through D". It is therefore important to find independent constraints on v_p and v_s in the upper mantle. We explore P-wave reverberations in the mantle contained in the six-hour long segment of a vertical-component seismogram following the major-arc Rayleigh wave. We detect top-side reflections (i.e., p410s and p410p) off the 410-km discontinuity in stacks of cross-correlated "late coda" from 83 large earthquakes recorded by the Southern California Seismic Network. The lag time between p410s and p410p is about 39 s for an inter-station distance of 100 km. Together with PP-P and SS-S, we estimate that v_s and v_p in the uppermost 200 km of the mantle are 1% and 5% lower than in PREM, respectively. This is an important constraint for tomographic studies of Earth's upper mantle, especially studies focused on horizontal v_p variations and radial anisotropy.

Investigating the Intrinsic Attenuation of Large Low Velocity Provinces

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At the base of the mantle, two massive anomalously seismically slow regions (LLVPs) have been discovered; their nature, origin, and role in global mantle dynamics are still debated. Seismic waves exhibit a notable velocity drop when traversing these structures, previously explained by elevated temperature and iron enrichment. However, inferences of temperature and composition from velocity constraints are inherently nonunique. The attenuation experienced by seismic waves as they travel through LLVPs can provide additional information on their temperature, because attenuation is expected to have an exponential dependence on temperature. While the elevated temperatures expected for LLVPs would imply higher attenuation, estimates of attenuation of the LLVPs remains debated. Indeed, recent studies based on normal modes argue that attenuation is lower in LLSVPs than in the surrounding mantle (Talavera-Soza et al., unpublished), suggesting that grain size, rather than temperature, perhaps plays a dominant role in controlling attenuation variations in the lower mantle. Here, we analyze previously published databases of body wave attenuation measurements (Lai and Garnero, 2019, 2020), specifically t* of S, SS, ScS and other phases sensitive to the lowermost mantle structure. We account for the effects of upper mantle attenuation variations using differential t* of reference phases and corrections based on published attenuation models in order to constrain the attenuation in LLVPs. LLVP areas appear to be characterized by multimodal differential t* values that have a higher attenuation on average compared to regions outside the LLVPs. We discuss our results in the context of previously published models of lower mantle attenuation.

Earth's Structure from the Crust to the Core [Poster]

Poster Session • Wednesday 16 April

Conveners: Ebru Bozdag, Colorado School of Mines (bozdag@mines.edu); Gatut Daniarsyad, Agency for Meteorology, Climatology and Geophysics (gatut.daniarsyad@bmkg.go.id); Daryono Daryono, Agency for Meteorology, Climatology and Geophysics (daryonobmkg@gmail.com); Jan Dettmer, University of Calgary (jan.dettmer@ucalgary.ca); Theron Finley, University of Victoria (tfinley@uvic.ca); Jeremy M. Gosselin, Natural Resources Canada, Sidney (jeremy.gosselin@nrcan-rncan.gc.ca); Indra Gunawan, Agency for Meteorology, Climatology and Geophysics (indra.gunawan@bmkg.go.id); Nicolas Harrichhausen, University of Alaska, Anchorage (njharrichhausen@alaska.edu); Hao Hu, University of Oklahoma, (huhaoletitbe@gmail.com); Lorraine J. Hwang, University of California, Davis (ljhwang@ucdavis.edu); Keith Koper, University of Utah (kkoper@gmail.com); Andrew Lloyd, Lamont-Doherty Earth Observatory, Columbia University (andrewl@ldeo.columbia.edu); Walter D. Mooney, U.S. Geological Survey (mooney@usgs.gov); Nelly F. Riama, Agency for Meterology, Climatology and Geophysics (nelly.florida@bmkg.go.id); Jeroen Ritsema, University of Michigan (jritsema@umich.edu); Vera Schulte-Pelkum, University of Colorado (vera.schulte-pelkum@colorado.edu); Derek Schutt, Colorado State University (derek.schutt@colostate.edu); Ying Zhang, University of Oklahoma, (yingzhang3.geo@gmail.com)

POSTER 86

Toward an Accessible Framework for Synthesizing Solid Earth Models Across Multiple Scales

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Solid Earth models describing the spatiotemporal variations of the subsurface material properties, including but not limited to the distribution of elastic parameters, density, porosity, temperature, viscosity, resistivity, and magnetic susceptibility, from the surface to the core represent the most fundamental product for studying the structure, composition, and evolution of our planet and for informing natural hazard assessment. These models are developed at various scales ranging from local to global. However, the lack of infrastructure to synthesize multiple multiscale Earth models restricts research investigations to single models with limited spatial resolution, thus hindering scientific discoveries in the broader Solid Earth community. Here, we introduce a flexible, user-friendly program for multiscale model synthesis. New technologies and techniques in seismology, such as the application of machine learning, nodal or dense seismic arrays, and fiber-optic sensing, have enabled the rapid development of local Earth models in fault zones and sedimentary basins that have structural details lacking in the more regional and global models. Therefore, incorporating such detailed local models into existing regional or global models will enhance structural and source studies, including Earth model inversion, development of high-resolution earthquake catalogs, physics-based ground motion modeling, dynamic earthquake rupture modeling, and earthquake hazard assessment. We illustrate an application to the West Coast of the U.S. (California and Cascadia) using publicly available local-to-regional seismic wave speed models to develop seamless composite state-wide multiscale Earth models.

POSTER 87

Exploring the Mackenzie Mountains Lithosphere: 3D P Wave Velocity Tomography and Thermal Structure

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The Mackenzie Mountains of northwestern Canada are distinguished by their complex tectonic history. Despite the distance from the nearest plate boundary (~700 km), the Mackenzie Mountains are experiencing active crustal deformation making it an intriguing feature for study as the mechanism leading to uplift is not well understood. In our research, we aim to enhance the existing tomography on the lithosphere below the Mackenzie Mountains by incorporating traveltime tomography of direct P, Pn, and teleseismic phases. The P wave velocities will be converted to temperature and the variations in lithospheric temperature will be assessed. The initial model utilized in this study is from ambient noise tomography by Schutt et al. (2023). A total of 65976 arrival times are utilized for this study, which were recorded from 5451 events using 294 well distributed seismic stations in the study area. In this study, comprehensive imaging was obtained through the use of the FMTOMO software package, which uses the fast-marching method to predict travel times and a subspace inversion method to adjust model parameters to fit the data observations. Our results reveal a low velocity feature beneath the Mackenzie Mountains that extends from the crust to the asthenosphere. The velocity structure will be used to estimate temperature, thereby giving an improved understanding of the tectonic processes and mantle dynamics at play in the uplift.

POSTER 89

Imaging Lateral Boundaries in the San Bernardino and San Gabriel Basins With Scattered Phases in Ambient Noise Data

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The Northern Los Angeles Basin Seismic Experiments were a series of nodal seismic deployments performed between 2017 and 2019. The deployments included nine linear subarrays which collectively spanned the San Gabriel and San Bernardino basins. We consider ambient noise cross-correlations along these linear subarrays, with the aim of imaging sharp lateral structures, such as basin boundaries and faults. We stack raw data from each subarray along lines of constant slowness and correlate the output with each individual node. For any given frequency band, these cross-correlations distinguish how surface waves approaching the subarray at a particular azimuth are expected to propagate across each sensor, including any phases scattered off nearby faults. The moveout and polarity of these scattered phases across the lines provides insights into the azimuth of the faults and material contrast across the boundaries, respectively. This approach may prove especially powerful in locating hidden faults which do not show a clear surface expression and cannot be easily imaged through their seismicity. Improved resolution of fault structures near these arrays can aid our understanding of the seismic hazard and geologic history within the San Gabriel and San Bernardino basins.

POSTER 90

Toward a Radially and Azimuthally Anisotropic Adjoint Model for the Middle East

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After our transversely isotropic adjoint model of the Middle East, MEAD-M20, which is a result of 20 conjugate-gradient iterations and shows promising results to improve moment tensor solutions in the region, we continue our iterations by including azimuthal anisotropy in parameterization. Similar to MEAD-M20 we use publicly available seismic data from EarthScope and local networks, such as Kandilli Observatory, and proprietary data from Saudi Geological Survey, Iraqi Seismic Observatory, Iranian Seismological Center through our collaborations. We have made our multitaper traveltime measurements in two period bands within the range of 30-100 s using Rayleigh and Love waves where we will gradually decrease the shorter period to better constrain the crustal structure. Moreover, we will include double-difference multitaper traveltime measurements to achieve higher-resolution underneath densely covered regions combined with multi-scale smoothing of the gradient. At this stage, we use Rayleigh and Love waves for transversely isotropy by updating vertically (βv) and horizontally (βh) polarized shear waves and the anisotropic parameter (η), while we only use Rayleigh waves for azimuthal anisotropy (2θ term) by updating normalized anisotropic parameters Gc' and Gs'. We have performed 3 iterations so far where the initial results of azimuthal anisotropy is consistent with plate motions. At the second stage, our goal is to include the 4θ term in our inversions as well. We will present our new model and discuss our observations in the context of the region's tectonics, geodynamics and its contribution to improving source parameters.

POSTER 91

Seismic Imaging of Kilauea East Rift Zone Magma Reservoirs Using Receiver Functions

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Shield volcanoes, such as Kilauea in Hawaii, are the largest volcanoes on Earth and form as eruptions of basaltic lava flows build up into broad, gentle slopes over time. A common characteristic of shield volcanoes are well developed rift zone systems, which weaken the volcano's structure and facilitate the expansion of volcanic systems by enabling magma to flow horizontally and erupt in areas away from the summit. With two active rift zones, Kilauea poses significant risks to nearby neighborhoods and infrastructure. Though magma reservoirs beneath these rift zones have been identified, recent activity suggests changes in magma movement along the rift zone. To investigate these possible changes, about 130 nodal seismometers were temporarily deployed in two dense linear arrays across the Kilauea East Rift Zone (ERZ) in September 2024, one near Pu'u 'Ō'ō and the other along Highway 130 across the Lower East Rift Zone. Upon retrieving the instruments in November 2024, the data were processed for analysis. We will select relevant earthquake arrivals and implement receiver function (RF) techniques – including H-k stacking to estimate crustal thickness and common conversion point (CCP) stacking to visualize crustal discontinuities. Preliminary analysis of ERZ data collected along Highway 130 in 2018 and 2019 shows that higher Gaussian frequencies generate the clearest arrivals of RFs on CCP profiles. These arrivals begin at about 15 km depth, representing the Moho discontinuity. Surrounding regions of low and high seismic velocity contrast likely correspond to areas of solidified lava rock and zones of magma storage. The H-k and CCP stacking methods will allow us to produce a crustal structure profile using current data, highlighting velocity discontinuities in the crust that could provide new insights into the rift zone history and magma behavior beneath Kilauea, with significant ramifications for both comprehending magma storage and movement within the volcano, and improving hazard assessments for communities settled in close proximity to these active rift zones.

POSTER 93

High-resolution 3D Seismic Imaging and Aftershock Catalog for the 2021 Mw 7.2, Nippes, Haiti Earthquake

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Less than twelve years after the devastating 2010 Mw 7.0 earthquake, on August 14, 2021, a Mw 7.2 earthquake struck the southern peninsula of Haiti. Following this event, 12 temporary broadband stations were deployed near the rupture area to complement the Raspberry Shake stations that were already installed in the framework of a citizen seismology initiative. Geodetic analysis from previous studies showed that the rupture mechanisms is composed of a combination of thrust motion on the eastern part of the rupture and left-lateral strike-slip motion on the western region. Furthermore, several secondary fault structures were revealed by InSAR phase gradient techniques. Aftershock location from August to December 2021 outlined the main rupture as three north-dipping structures with slightly different strike and dip in the north of the Enriquillo-Plaintain Garden fault (EPGF) and two small clusters on the EPGF near the hypocenter area. However, the secondary fault features were not visible in this initial catalog. Therefore, it is imperative to enhance the aftershock catalog to properly delineate all the active structures that have participated in this event. In this study, we first use a STA/LTA and a Kurtosis algorithm to detect and pick all the arrivals for all the aftershocks that have occurred between the period of August 2021 to January 2023. We then use those detected events as template waveforms and apply a matched filtering analysis that cross-correlate those templates with the continuous data to increase the number of aftershock detection. Furthermore, we then selected 9740 of the well detected events to invert for a 3D Vp and Vs velocity structures which we then use to relocate the entire catalog. Preliminary results show that we are able to significantly increase the number of aftershock detection and better delineate the active structures. Additionally, our 3D velocity model reveals a clear horizontal polarity velocity contrast or bimaterial interface across EPGF fault near the hypocenter area which could have affected the rupture propagation.

POSTER 94

Enhancing the Observability of Precritical PKiKP Phases with Polarization Filters and Incoherent Array Processing

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The inner core plays a key role in Earth's dynamo, which generates and maintains the magnetic field throughout Earth's history. Seismically observable properties of the inner core, such as the impedance change and topography at the inner core boundary, provide insight into its composition and evolution. In this study, we focus on documenting and enhancing the observability of steep angle reflections (PKiKP) from the inner core boundary (ICB). At precritical distances (< ~90 degrees), PKiKP waves are uniquely sensitive to the change in density and shear wave velocity across the ICB. The coda waves following precritical PKiKP are sensitive to scatterers and other complex structure within the inner core. PKiKP has very small amplitude at precritical distances and has mostly been observed at high frequencies (1–3 Hz) using small-to-medium aperture arrays (< 50–100 km) of short-period seismometers. Occasionally, PKiKP has been observed at individual three-component broadband stations. Here we search for precritical PKiKP waves recorded at broadband seismometers deployed across North America from earthquakes in Central America. We examine how its frequency-dependent amplitude varies with focal mechanism, background noise level, and local site conditions. We experiment with frequency dependent polarization filters and incoherent array processing as means of enhancing the observability of PKiKP and its coda waves. Polarization filters can extract clear seismic phases which are strongly polarized relative to the noise, for instance by comparing horizontally rectilinear motion (HRM) and vertically rectilinear motion (VRM). This approach has recently been used to detect a solid inner core on Mars with data from a single seismometer.

POSTER 95

Full Waveform Inversion for Homogeneous 21-parameter Anisotropic Materials

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The elastic properties of a material, including rocks and minerals in the Earth, are described in terms of a 6 x 6 symmetric matrix containing 21 parameters. Materials having isotropic elasticity are described in terms of two parameters (bulk modulus and shear modulus), while some materials, such as feldspar, require all 21 parameters. These elastic properties can be estimated using seismic waves that pass through the material. We perform a series of numerical experiments using 3D seismic wavefield simulations emulating an idealized laboratory setting of a homogeneous elastic sample surrounded by a spherical 'shell' of recording sensors. We examine the feasibility of estimating all 21 elastic parameters by considering three factors. First, we consider sensor coverage around the material. Second, we consider the proximity of the initial model to the target model; one choice of the initial model is the closest isotropic material to the target material. Third, we consider the strength of anisotropy and the class of elastic symmetry (e.g., triclinic, monoclinic, orthorhombic) of the target material. We use three-component seismic waveforms and a direct waveform difference misfit function to iteratively update the initial model toward the target model. Our study is relevant for laboratory settings, and it also provides insights into seismic imaging of well-instrumented industry field settings.

POSTER 96

Validation of a Tilted Transversely Isotropic Model of Alaska Using 3D Seismic Wavefield Simulations

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Seismic imaging of Earth's subsurface structure is challenging because the seismic stations are only located at the surface, and because the number of stations is generally sparse in comparison with the degree of heterogeneity, especially within the Earth's crust. This results in an underdetermined inverse problem, whereby there is not enough data to uniquely resolve the unknown model parameters. The seismic imaging problem is even more challenging because there are portions of the Earth, such as sedimentary strata, metamorphic terranes, oceanic crust, and cracked/dilated materials that exhibit elasticity that is transversely isotropic (TI). The symmetry axis of the TI material can be vertical (VTI), horizontal (HTI), or arbitrarily tilted (TTI). Using 3D wavefield simulations of regional earthquakes and ambient noise cross-correlation functions, we examine a recently published TTI model for Alaska. We also calculate the closest HTI, closest VTI, and closest isotropic models to the TTI model, and then perform wavefield simulations within these models to better understand which regions of complex anisotropy are required by seismic observations.

POSTER 97

Preliminary Results from the Active/Passive San Francisco Volcanic Field Nodal Seismic Experiment in Northern Arizona

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Distributed volcanic fields pose significant hazards to population centers around the world. For many of these systems, there is limited knowledge about the nature of short- and long-term magma storage in the crust and how this storage influences the composition and eruptive styles of the distributed volcanism. The San Francisco Volcanic Field (SFVF) in Northern Arizona is one of the most active cases of distributed volcanism in the western U.S. This region is distinguished by its compositional diversity of eruptive products and by the highly explosive basaltic eruption that occurred at Sunset Crater around 1085 CE. To better understand the structural details of the magmatic system that feeds the SFVF, an active/passive nodal seismic experiment was conducted between August 2023 and November 2024. The first stage of this experiment was focused on monitoring seismicity associated with the active portion of the volcanic field and involved the recording of 12 months of near-continuous data at 47 nodal seismometer locations within 30 km of the Sunset Crater eruption. The second stage expanded the array to 586 nodal seismometers to cover the entire SFVF (~17500 km^2). This array recorded four 2,000-lb. borehole shots and background seismicity during a month-long deployment. Preliminary results from this data set will be presented that characterize the distribution of seismicity associated with regional fault systems and the SFVF magmatic system. In addition, initial body wave tomography models will be presented which will be used to infer the locations of present-day magma storage as well as regions of pluton formation beneath the SFVF.

POSTER 98

Seismic Structure of the Lithosphere in SW Austratila Based on New Data From the Western Australia Array

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Lithosphere of Earth's stable continents preserves the longest available record of past geodynamic activity. Structural seismology plays a fundamental role in revealing the interior structure of the continental lithosphere, advancing our understanding of global processes such as the Wilson Cycle, guiding the search for resources that underpin modern technology, and informing the assessment of hazards to the society.

Passive source seismological techniques applied to data from dense grids of broadband seismic observatories yield progressively more detailed representations of the internal structure of stable continents. Our new results from SW Australia showcase a combination of techniques especially well-suited for probing Earth's structure at depths of 25 – 75 km, straddling the crust-mantle transition.

Using data from the recently completed Phase 1 of the WA Array, we develop a profile traversing the Proterozoic Albany-Fraser Orogen and the southwestern portion of the Archean Yilgarn Craton. We combine imaging of bulk seismic properties using ambient noise data with mode-converted body wave techniques that detect abrupt gradients in both impedance and texture of rocks composing the crust and the upper mantle. With ~40 km spacing of observing sites we seek to relate lateral variations in seismic properties to tectonic divisions of the region based on the surface studies. We showcase the opportunities presented by a dense deployment, and discuss the limitations imposed by short observatory durations at most of the sites.

Our results show that most tectonic boundaries in this stable continental region are not vertical, suggest additional divisions of the lithosphere based on seismic properties, and demonstrate the utility of detecting and interpreting directional variations in the seismic wavefield. We identify a likely cratonic fragment within the Albany-Fraser orogen, confirm existence of distinct tectonic domains in the SW part of the Yilgarn craton, and document a region of focused deformation at the crust-mantle boundary within one of them.

POSTER 99

Effects of Olivine Fabric Type on Seismic Anisotropy in the Mantle Wedge: A Wavefield Modeling Case Study

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Shear wave splitting (SWS) observations of core-refracted phases (XKS) can potentially constrain upper mantle dynamics, strain geometries, and deformation conditions, based on the relationships between strain and anisotropy for the different types of olivine fabric that could occur. Parameters that describe SWS (the fast splitting direction and the delay time between fast and slow quasi-S waves), only provide an integrated view of anisotropic fabrics traversed along the XKS path. Given the poor depth resolution of core phases, constraining the origin of anisotropy, or even the individual contribution of a specific depth region, is challenging for XKS phases. However, global wavefield simulations provide an effective tool to explore the individual and combined influence of different anisotropic regions on the splitting of XKS waveforms for synthetic models. This can be particularly helpful in complex regions such as subduction systems, in which observed XKS splits can potentially be affected by anisotropy in the overriding lithospheric plate, the mantle wedge, the lithospheric slab, and the sub-slab asthenosphere. The goal of this work is to carry out synthetic modeling of XKS splitting measurements in a generic subduction zone setting to explore the potential contributions from different olivine fabric types in different portions of the subduction system on the expected XKS SWS pattern. We implement a series of forward models in the AxiSEM3D wavefield modeling framework. Specifically, we investigate the effects on splitting parameters for different combinations of A-, B-, and E-type olivine above and below the slab, with a particular focus on the SWS patterns due to mantle wedge anisotropy and the related conditions that can be inferred from the occurrence of the different fabric types. This work will help to improve our understanding of how SWS measurements reveal deformation and dynamics in subduction systems.

POSTER 100

Crustal Imaging of the Southern Central Andes by Seismic Autocorrelation of Nodal Seismic Data

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Autocorrelation of seismic waveform or ambient noise data recorded on individual seismic stations can reveal subsurface reflectivity underneath the station. In this study, to image the major subsurface boundaries, this processing method is implemented on the data collected by a dense array of three-component nodal seismometers at ~23-24˚S, deployed as part of the TransANdean Great Orogeny (TANGO) project. The array consists of 297 nodal stations with 2-3 km node spacing on an orogen perpendicular line across the Andes that extends from the coast of Chile to the Chaco Plain in Argentina covering ~700 km distance and crossing through major Andean tectonic units such as the Chilean forearc, main volcanic arc, Puna plateau, and Eastern Cordillera fold-and-thrust belt. For the autocorrelation with earthquake waves, vertically incident P-arrivals and their coda from teleseismic events and local deep events inside the Nazca slab are used. One minute of waveform data starting 10 seconds before the P-arrival is autocorrelated for each event and stacked together to obtain a stable reflection response. For the ambient noise autocorrelation, for each station in this array, hourly traces from ~5-6 months of data are autocorrelated and stacked together using a phase-weighted approach to amplify the most coherent signals. Temporal normalization is applied to remove the effects of any active or passive impulsive seismic sources. For both ambient noise and earthquake waves, spectral whitening is used to remove the effect of the zero-lag autocorrelation signal and to amplify the subsurface reflection signals. Additionally, the ambient noise autocorrelation is also performed with only the phase information, which avoids temporal normalization and spectral whitening and is independent of the amplitude. The resulting autocorrelation traces are used to identify major subsurface boundaries within the different tectonic units including the Moho, basal detachments in the Eastern Cordillera fold-and-thrust belt, and crustal magma bodies in the volcanic arc and the Puna plateau.

POSTER 101

Imaging the Moho Topography Beneath the Northern Canadian Cordillera from Virtual Deep Seismic Sounding

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The Northern Canadian Cordillera (NCC) in northwestern Canada is a tectonically active orogenic belt known for its high topography, transpressional accretion, and complex tectonic history. The ongoing uplift seen in the Mackenzie Mountains (MM) in the NCC remains enigmatic because it is ~700 km from the Yakutat collision zone. Several geophysical studies, particularly receiver function (RF) analyses, have been conducted to better understand crustal dynamics responsible for the MM uplift from Moho depth and geometry information. However, these RF studies faced difficulties in imaging the Moho topography beneath some seismic stations along the Mackenzie Mountains EarthScope Project (MMEP) transect near the Cordilleran Deformation Front (CDF) due to thick sedimentary cover, poor stack quality, and sometimes aberrant RFs. Here, we use a recently developed passive teleseismic technique known as virtual deep seismic sounding to produce a new Moho depth model of the NCC using seismic data from 227 stations, including the past seismographic stations (2000 – 2014), the MMEP, and the recently deployed (since 2021) broadband seismographs in Yukon, British Columbia, and Alberta. Our preliminary results reveal a Moho depth in the range of 28 – 42 km beneath the MMEP transect line, with a mean Moho depth of 35 km. Crustal thickening with a Moho depth range: 30 – 42 km, and possibly crustal shortening, is observed beneath the northwestern region of the MM, which was previously attributable to crustal stacking of NCC and earlier Laurentian lithosphere. The Moho topography is relatively flat and uniform between the Denali Fault and the Cordilleran crust. However, there are localized crustal thickenings between Teslin and Tintina Faults, which is consistent with findings from previous studies. Crustal thinning is observed near the CDF, caused by deep hot mantle upwelling within the MM range, which later transitions to thickened Canadian craton. Generally, the crustal thickness within the Cordilleran is insufficient to support the overlying high topography in the NCC, accentuating the thermal isostatic buoyancy of the hot backarc.

POSTER 102

Full-waveform Tomography of Europe and Western Asia and Full-waveform Moment Tensor Inversions

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We present a continental-scale tomographic model of Europe and Western Asia of transverse isotropic seismic wavespeeds of the crust and mantle based on full-waveform inversion (FWI). A drastic increase in quantity of high quality data in the region prompted to revisit the study area from previous inversion results. The model has been inverted for a minimum period of 18 s, where developments in hardware and data-driven methodologies in Computational Seismology decreased the compute costs to make a high-resolution continental-scale model. Work on this model is tied with testing the methodologies for future applications to other model domains.

Dynamic mini-batches facilitate to reduce the inverse problem to a subset of events in a greater data set. Model updates are therefore cheaper and faster, while allowing the inclusion of more data if needed during the inversion. Meshes are adapted to the Wavefield by elongating elements azimuthally, reducing the number of elements compared to a standard cartesian mesh, while preserving gridpoints and further reducing costs for a model update. The model starts from the current generation of the Collaborative Seismic Earth Model (CSEM2) and is inverted in a multiscale approach to avoid cycle-skipping and enable monotonic misfit reduction. Misfit optimization is based on time-frequency phase misfits while gradient optimization is done through trust-region L-BFGS. For the Forward and Adjoint Simulations, the Salvus Spectral-Element Solver is used.

Full-waveform moment tensor inversions have been run on the model. For this the observable is inverted with synthetics simulated at 18 s in a least-square inversion. We compare the resolution for inverted moment tensors between PREM and the Europe model and find that 3D Earth models exhibit higher moment tensor resolution. This gives further implications on how to proceed with creating FWI Earth models when inverting for shorter periods.

POSTER 103

Large Lithospheric Seismic Velocity Variations Across the Northern Canadian Cordillera

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Global-scale seismic velocity models of the Northern Canadian Cordillera show high velocities to the east of the Cordilleran deformation front and low velocities to the west. This velocity contrast is consistent with other geophysical observables, such as regional seismological studies, that indicate a weak and thin lithosphere to the west that transitions quickly to a strong and thick craton-like lithosphere at the deformation front. We present new results using data collected by the Mackenzie Mountains EarthScope Project, which included an ~875 km-long line of 40 broadband seismographs across the Cordillera and into the craton extending from roughly Skagway, Alaska to Great Bear Lake, Northwest Territories. The 3-year overlap of this deployment with other broadband seismic stations in the region, most notably the EarthScope Transportable Array and the Yukon Northwest Seismic Network, allows for detailed imaging of the upper lithosphere. Results show large velocity variations west of the deformation front. Notably, we image a 5% Vs low that extends from the upper crust to the asthenospheric mantle. This plume-like structure, and associated weakening, may be a primary cause for the ongoing uplift of the Mackenzie Mountains at their unusually eastward location. We also image a low velocity feature in the lower crust extending to the west of the deformation front, which may facilitate eastward crustal translation along a large-scale (~800 km) decollement system driven by the Yakutat indentor consistent with the orogenic float hypothesis of Mazzotti and Hyndman (2002). We note strong lithosphere-scale lateral heterogeneity suggesting that 3-D effects are important in focusing deformation in the Mackenzie Mountain area.

POSTER 106

Tectonic Imprints of Multiscale Craton Margin Deformation on the Continental Lithosphere of the Korean Peninsula From Regional Seismicity, Seismic Traveltime and Waveform Tomography

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The imaging of detailed three-dimensional (3D) lithospheric structures is essential for understanding tectonic history, seismicity, and evaluating the influence of multi-scale crustal heterogeneities on seismic wave propagation. We applied seismic traveltime tomography and waveform inversion techniques to develop 3D crust and upper mantle structures in the southern Korean Peninsula (SKP) based on seismic records from dense seismic arrays. Despite the SKP region being considered a tectonically stable intraplate area, earthquakes of small-to-moderate magnitude (Mw 3–5) occur consistently within the peninsula and adjacent coastal areas. This necessitates a high-resolution regional seismic velocity model to estimate ground motions from potential earthquakes, facilitate seismic hazard analyses, and understand the underlying mechanisms of distinct seismic events. Crustal imaging using waveform inversion, employing the spectral-element method for accurate waveform simulations and the adjoint method, reveals prominent low-velocity structures in the upper crust beneath sedimentary basins in southeastern SKP, and NE-SW trending low-velocity anomalies in the mid-to-upper crust are associated with granite intrusions extending from the peninsula to coastal areas. Newly identified features include linear trends in radially anisotropic structures along major fold-and-thrust belts and near the boundaries of different tectonic provinces, as well as localized anisotropic features extending deeply into the lower crust in southeastern SKP, where several active fault systems are present. Distinct crustal features correlate with velocity gradients in the upper mantle, indicating heterogeneous modification across the continental lithosphere beneath Archean-Proterozoic basement. Our findings suggest that tectonic inheritance in old continental remnants, shaped by multiple deformation events under past continental margins, may control the patterns and magnitude of current intraplate seismic activities.

POSTER 107

Making Love Visible in Noise: Enhanced Surface Wave Detection Using Slepian Tapers

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Seismic interferometry has become a widely adopted method for subsurface imaging across a range of spatial scales. Since its revival in the early 2000s, much research has focused on developing algorithms to compute and extract surface wave dispersion from ambient noise correlations. These algorithms typically enhance signal quality by emphasizing time-domain techniques, such as One-Bit Normalization, Frequency-Time Normalization, and Welch Waveform Stacking (Bensen et al., 2007; Seats et al., 2012; Shen et al., 2012). However, they do not address the signal quality in the frequency domain, which is crucial for enhancing surface wave detection using the spatial autocorrelation (SPAC) method first introduced by Aki in 1957. In this study, we present an algorithm for rapid computation of high-quality (low-variance) frequency-domain SPAC based on Thompson's Multi-taper method. We calculate pairwise coherence using K-overlapping Slepian tapers that are carefully localized in both time and frequency. Preliminary results from a pair of low-quality transverse seismograms recorded in Africa demonstrate that multi-taper coherence significantly enhances the detection of Love waves and reduces uncertainty in phase and group dispersion measurements. Future work will address challenges related to memory, processing speed, and convergence when using a large number of tapers. We anticipate that this approach will enable the creation of a comprehensive high-quality catalog of short-period dispersion measurements, contributing to the refinement of global models of Earth's crust and mantle lithosphere.

POSTER 108

Seismic Computational Platform for Empowering Discovery (Scoped): Software, Containers, Workshops, Science

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Seismology is a data and model-intensive field. Data-driven computations benefit from Cloud Computing because observational seismology relies on horizontal scalability. Model-driven computation benefits from High-Performance Computing because simulations necessitate large memory and a high number of workers for efficient parallelization. In its fourth year, our project SCOPED (Seismic COmputational Platform for Empowering Discovery) has sought to bridge both observational and theoretical fields by building a CyberInfrastructure (software, data) as a service to the seismic community. The primary project components are: 1) advancing science with SCOPED-participating software codes, 2) containerizing SCOPED software, 3) training users of SCOPED codes, and 4) beginning to establish the SCOPED platform. Training highlights include hosting a hybrid workshop at the University of Washington in May 2024, involving 50 in-person and 50 remote participants working on local software, Cloud-based setups (like JupyterLab), and HPC environments (TACC Frontera). Science applications with SCOPED, demonstrating the power of integrating its components, are underway, including: ambient noise imaging and monitoring, machine-learning aided earthquake catalog computation and interpretation workflows, global-scale anisotropic tomography, and sedimentary basin ground motion amplification from local earthquakes. Community members are encouraged to participate in, contribute to, and advance SCOPED.

POSTER 109

Crustal Structure Beneath Carpathian-panonian Region by Ambient Noise Tomography and Teleseismic P Wave Coda Autocorrelation

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The Carpathian-Pannonian region (CPR) in Central Europe has significant seismic activity, highlighting the need for detailed crustal studies. Although the region has been the object of many international research efforts, the crustal structure beneath CPR remains poorly known. Previously, there were few studies that provided the crustal structure beneath this region, but all these studies were unable to provide high resolution Moho map because of the sparse coverage of seismic station. Now, dense coverage of seismic stations is available in this region and hence the crustal structure beneath this region has been improved. Although highly resolved 3-D S -wave velocity structure of the crust and crustal thickness is poorly known in this region. This study presents a new 3-D S-wave velocity structure of the crust and high-resolution Moho map by ambient noise tomography and teleseismic P wave coda autocorrelation. In this study, we used 235 broadband stations from seven different networks. The distribution of these stations provides the unprecedented dense ray-coverage that enables us to achieve the best lateral resolution in our study area so far. The results from P wave coda autocorrelation indicate a shallow Moho beneath the Pannonian, Vienna, and Danube basins, with depths between 20 and 30 km, while the deepest Moho is observed beneath the Southern Carpathians, Apuseni Mountains, and Southeast Carpathians, where it reaches depths of 45 to 55 km. The shallower Moho beneath the basins indicates crustal thinning, while thicker Moho in neighboring mountain belts indicates orogenic thickening. The ambient noise tomography further refines the velocity structure beneath each station, enabling even more precise Moho depth determinations, which are ongoing.

POSTER 110

Constraining Slab Geometry and Seismic Velocity Structure From Tillamook to Portland, Oregon

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Constraints on the location of the megathrust, as well as information about local geologic structure that may impact wave propagation (e.g., seismic wave velocities, sedimentary basins), are important for estimating ground shaking and seismic hazard. In Cascadia, precisely constraining the location of the plate interface and properties of the overriding and subducting crust has remained challenging due to the paucity of local seismicity. This is particularly true for the greater Portland area, where there have been very few attempts to constrain slab geometry and high-resolution seismic velocities at depth. In this study, we use active and passive source data recorded on 192 three-component 5-Hz Fairfield Nodal seismometers in summer 2021 and 2022. The nodes were deployed in an east-west linear array from Tillamook to Portland, Oregon, to better characterize subduction zone structure between the seismogenic zone at depth and population centers at the surface. Teleseismic receiver functions were used to interrogate the depth of the slab interface, while 2-D travel time modeling using recordings of offshore air gun shots from the Cascadia Seismic Imaging Experiment (CASIE21; Carbotte et al., 2024) was used to constrain P-wave velocities and fill a trench-perpendicular gap between the onshore receiver function results and the offshore CASIE21 multichannel seismic reflection images. Results suggest that the depth to the top of the Juan de Fuca plate is ~20 km near the coastline. In addition, we note a potentially thickened subducting crust and change in dip of the slab beneath the western edge of the Coast Range and better constrain the geometry of the western edge of the Siletz terrane. Results also provide new estimates on the depth of the Tualatin Basin near Portland. Overall, this work provides an improved understanding of the local slab geometry and seismic velocity structure beneath northwestern Oregon, which will help improve seismic hazard estimates in the region for future earthquakes.

POSTER 111

Hessian Vector Product in Transversely Isotropic Media

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Full waveform inversion (FWI) is a powerful technique for imaging Earth's subsurface structure at local, regional, and global scales, providing detailed reconstructions of geological features. However, a significant challenge in FWI is the trade-off between multiple parameters, which can lead to non-unique solutions and hinder accurate model updates (Fichtner et al., 2024). This trade-off issue is particularly important in seismic tomography, as the interplay of various parameters such as P-wave velocity, anisotropy, and subsurface heterogeneity can result in parameter cross-talk, complicating the interpretation of seismic data. Resolving these trade-offs is critical for improving the accuracy of seismic imaging and understanding the Earth's subsurface dynamics.

The Hessian vector product (HVP) has been successfully used in acoustic and elastic FWI to mitigate parameter trade-offs, but its application in transversely isotropic (TI) media has been limited due to computational challenges and the large disk space and I/O requirements associated with storing and transforming wavefields during the inversion process. In this study, we derive the HVP in TI media using the adjoint-state method and compute it by combining the on-the-fly method with checkpointing, which reduces disk space and I/O demands. This development can be implemented through finite-difference or spectral element methods. The HVP is more sensitive to small-scale structures in the Earth model compared to the gradient and highlights its importance for refining Earth tomography models. This contributes to interpreting tomography models and understanding Earth's dynamic structural evolution at multiple scales, with potential implications for seismic hazard assessment and resource exploration due to the improvement in the accuracy and resolution of the models.

POSTER 112

Anisotropic Kilometer-scale Structures With a Near-zero Poisson's Ratio on the Japan Subduction Zone Plate Interface

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Geological studies show that subduction zone plate interfaces feature complex fault structures with mixtures of different minerals and foliated rocks, but seismic observations of such near-source structures are still rare in subduction zones. Here we present evidence for localized, anisotropic structures with anomalously low Vp/Vs ratios in the medium surrounding 1-2 km-sized clusters of deep interplate earthquakes in the Kanto region, Japan. Thanks to the dense coverage of Hi-net borehole stations, we image the near-source medium using the differential P- and S-wave travel times between pairs of similar earthquakes and measure earthquake stress drops through source spectral ratios. We find a median Vp/Vs ratio of 1.44 in these earthquake source regions, equivalent to a Possion's ratio of nearly 0, suggesting the existence of a heterogeneous near-fault medium with distinct material properties from those of surrounding rocks. We also observe for the first time a strong azimuthal dependence of Vp/Vs ratios in the earthquake source region, which can be caused by a highly damaged and foliated medium. The typical stress drop values of M>3.4 earthquakes support a relatively low effective normal stress, potentially due to elevated fluid pressure in fault zones. Thus, our results from material and source imaging suggest the fault medium is damaged, foliated, and enriched with fluid. Such localized structures can cause stress perturbations on faults that in turn favor the frequent occurrence of deep interplate earthquakes in the Japan subduction zone.

Earthquake Shaking and the Geologic Record: Triggered Phenomena and Preserved Fragile Geologic Features

Oral Session • Thursday 17 April • 2:00 PM Local

Conveners: Paula Marques Figueiredo, North Carolina State University (paula_figueiredo@ncsu.edu); Devin F. McPhillips, U.S. Geological Survey, Earthquake Science Center (dmcphillips@usgs.gov); Thomas L. Pratt, U.S. Geological Survey (tpratt@usgs.gov); Mark W. Stirling, University of Otago (mark.stirling@otago.ac.nz)

Evaluating the New Zealand National Seismic Hazard Model 2022 with Fragile Geologic Features

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In the past year effort has gone into understanding and evaluating the biggest increases in estimated hazard in the New Zealand National Seismic Hazard Model 2022 (NZ NSHM 2022) relative to NZ NSHM 2010. The southeastern North Island shows greater than a factor of two increase in peak ground acceleration for the 500 year return period. In this area, the new Hikurangi subduction zone ground motion modeling has driven this increase, along with an additional increase attributed to crustal sources. Our work has involved reconnaissance of the coastal eastern North Island (above the Hikurangi subduction interface) for fragile geologic features (FGFs) such as sea stacks, balanced rocks, and unstable delaminated rock slabs. FGFs at two sites, White Rock and Cape Palliser, were subsequently studied. A greywacke FGF at Palliser is balanced on a sloping pedestal, and its fragility has been quantified according to assumptions of toppling and sliding. Fragilities of delaminated carbonate rock slabs on a large sea stack at White Rock have been quantified according to assumptions of rocking. ^{10}Be and ^{36}Cl cosmogenic exposure dating is currently being carried out on the greywacke and carbonate FGFs. Our preliminary interpretation from field observations is that they are older than the last Hikurangi subduction interface megaquake that occurred less than 1 kyr ago and will therefore provide useful constraints on the associated ground motions.

Paleoseismic Records of the Dead Sea Reveals Climatic Modulation of Seismicity Along the Continental Transform Faults

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Seismite-based paleoseismic records show that earthquakes are clustered in time. The longest records – 220-kyr-long, which was recovered from the Dead Sea depocenter and outcrops around the lake, exhibit clusters that last several millennia. The clustering phenomenon has yet to be explained. It can either be a feature of the earthquake generation process, or it might be an artifact of the recording process. The 220-ka record is recognized as subaqueous deformation in lake deposits which allows us to test the hypothesis that the temporal distribution is modulated by lake level fluctuations. The levels are influenced by climate – the levels of the Dead Sea and its predecessors were high during glacial periods and low during interglacials. Low stands expose large erosion-prone surface around the lake and promote incision of gullies. The sediments in the lake are modified as well, possibly affecting their stability and susceptibility to earthquake shaking. At the same time, the lithostatic pressure is reduced, perhaps affecting the normal stresses on fault planes at the seismogenic depths. Our preliminary comparison spanning the last 220 kyrs shows a strong correlation between earthquake frequency and lake levels. Quantifying the contributions of the varying stresses and the climate-induced changes in the sedimentary system is the goal of our ongoing research.

Directivity Effect of the 1976 Guatemala Earthquake Observed in Lacustrine Turbidites

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On 4 February 1976, a Mw 7.5 earthquake along the Motagua Fault in Guatemala ruptured more than 230 km of the North American and Caribbean plate boundary in an event that killed ~23,000 people and left ~ 1.5 million people homeless. Today, the plate boundary remains poorly monitored, with few instrumental and historical records to assess seismic hazard. In this study we present new radiometrically-dated sediment core data to evaluate the recent sedimentary record from four lakes in the vicinity of the plate boundary. Seismic shaking resulted in mass wasting and turbidity currents in all studied lakes, leaving behind a detailed record of sedimentation events triggered by the 1976 earthquake. Comparison between shaking maps and sediment core data reveals a complicated relationship between earthquake parameters and thickness of sediment gravity flow deposits. Our results show that thicker event deposits are present at lakes near the terminus of the Motagua Fault and thinner off-axis of the rupture direction. We hypothesize that this relationship between earthquake rupture direction and earthquake-induced sedimentation event thickness arises from a directivity effect of the earthquake, with more shaking experienced at the site in line with the rupture direction. The lake deposits constrain the asymmetrical distribution of shaking during large earthquakes and will help in the interpretation of long sediment records from this and related strike-slip fault systems. The observed relationship between earthquake directivity and severe seismic shaking can also help in the assessment of seismic hazard along this poorly studied plate boundary.

3D Mapping and Dynamic Analysis of Precariously Balanced Rocks for Fragility Modeling

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We investigate the 3D geometry and dynamic behavior of precariously balanced rocks (PBRs) for fragility modeling. To accurately map and analyze fields of PBRs, we use a combination of advanced technologies, including unpiloted aerial vehicle (UAV)-based Structure-from-Motion, UAV lidar, and iPhone lidar. We developed a method combining machine learning and deterministic segmentation for precise 3D extraction of PBR geometry. The machine learning component employs a deep neural network to detect PBRs in 2D imagery, facilitating their localization in point clouds. Deterministic segmentation utilizes a region-growing algorithm to separate PBRs from their pedestals, guided by user-provided basal contact curves at their interface. This cascading approach enables high-precision geometry extraction. Using the extracted 3D geometries, we perform PBR overturning analysis with the Virtual Shake Robot v2.0 (VSR2). VSR2 is built on the PyBullet physics engine and the Robot Operating System framework, validated against physical PBR overturning experiments conducted on a large-scale shake table. Our work demonstrates cutting-edge tools for PBR mapping and fragility modeling, providing critical insights into local ground motion constraints inferred from fragile geological features. Ultimately, we aim to offer an automated solution for using PBRs to refine seismic hazard curves and enhance our understanding of regional seismic risks. We apply the toolkit to the PBR fields in the Sierra Nevada, east of Fresno, California, relatively far from known fault sources. The PBRs in this region are glacial erratics, deposited by the Tioga (26–19 ka) and Tahoe (60 ka) glaciations. This recent glaciation has stripped the landscape of typical evidence used to identify active faults, and the existence of the PBRs will hopefully help constrain seismic hazard in the area.

Rapid Assessment of Precariously Balanced Rocks Using UAVs and 3D Semantic Structure from Motion

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Field assessment of fragility distributions of multiple precariously balanced rocks (PBRs) is time-intensive, but these data are potentially important for constraining the maximum intensity of past earthquake shaking. To address this challenge, we applied an automated methodology that integrated unpiloted aerial vehicles (UAVs) with semantic structure from motion (semantic SfM). Semantic segmentation is the process of categorizing all the pixels from images (or points in a point cloud) into classes of interest. Although 2D semantic segmentation is routine, 3D applications—such as those necessary for PBRs—remain at the cutting edge. Using aerial imagery collected by UAVs, we segmented PBRs with the Segment Anything Model 2 (SAM2), a state-of-the-art deep learning model trained on billions of images, which eliminated the need for domain-specific training data. The SfM process generated georeferenced point clouds and camera poses. In order to achieve 3D segmentation, we projected the points back onto the camera image planes, aligning points with the 2D PBR segmentation, and then applied an instance mosaicing algorithm to identify and merge PBRs across multiple images with different perspectives. We validated our methodology using UAV-SfM data collected at Centennial Bluff in eastern California, near the Nevada border, where PBRs have survived a 2021 M6.0 earthquake nearby. This approach enabled the rapid localization of PBRs and geometry extraction, including first-order geometrics such as scale, height-to-width ratios, and fragile orientations. These metrics provided insights into the distribution of PBR fragility, allowing for efficient identification and prioritization of the most fragile features in the field. Our results demonstrated the potential of this automated framework to rapidly assess PBR fragility, significantly reducing fieldwork while providing fragility distribution information.

Earthquake Shaking and the Geologic Record: Triggered Phenomena and Preserved Fragile Geologic Features [Poster]

Poster Session • Thursday 17 April

Conveners: Paula Marques Figueiredo, North Carolina State University (paula_figueiredo@ncsu.edu); Devin F. McPhillips, U.S. Geological Survey, Earthquake Science Center (dmcphillips@usgs.gov); Thomas L. Pratt, U.S. Geological Survey (tpratt@usgs.gov); Mark W. Stirling, University of Otago (mark.stirling@otago.ac.nz)

POSTER 25

A New Type of Paleoseismic Evidence From Lake Sediments

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Paleoseismic evidence resulting from past earthquakes can be used to infer shaking parameters using the relationships between PGA and the maximum distance of earthquake-triggered liquefaction and landslide evidence. Although this is useful information, probabilistic seismic hazard models need estimates of local shaking parameters where the potential for damage is the greatest. The most damaging earthquake ground motions are S-waves, and a new type of paleoseismic evidence has the potential to provide information about their frequency and duration. Preliminary results from a deposit sequence representing the 1873 CE Brookings earthquake sequence from lower Acorn Woman Lake suggests that, whereas the lower deposit is the result of a landslide likely formed in response to a crustal earthquake, the upper deposit was formed in response to shaking that lasted longer, supporting a published inference that the upper deposit was formed in response to a southern Cascadia subduction earthquake.

This new paleoseismic evidence is the presence of a long organic-rich deposit tail. Evidence suggests that organic tail deposits may form if liquefaction releases ground water and fine-grained sediment into the lake, which, during sustained shaking, results in flocculation and the rapid settling. Previous laboratory studies have suggested that flocculation can occur when stirring occurs at a frequency of ~4 Hz or less, for a long duration (a minute or longer). If shaking is shorter, flocs may not form, and if shaking is too strong, flocs may break apart. Because the upper deposit of the 1873 CE Brookings earthquake sequence has a tail, it supports the interpretation that this deposit was the result of a southern Cascadia subduction earthquake. These results are preliminary, and experiments are planned to quantify the range of S-wave frequencies and duration required to produce this type of paleoseismic evidence. This type of evidence could be extremely useful in regions where both crustal and subduction earthquakes occur, such as in Cascadia, where little information is known about the amount of shaking inland where most people live.

POSTER 26

New Methods for Analyzing Precariously Balanced Rocks in the Eastern U.S.

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We are systematically studying precariously balanced rocks (PBRs) in the eastern U.S. to estimate maximum ground motions since the rocks became precarious. We have now analyzed 47 PBRs in the northeastern U.S. that were set in place during the ~21,800 ka to ~13 ka retreat of the continental ice sheet. The keys for PBR analysis are to locate the center of mass from a 3D model made using lidar or photogrammetry, and to estimate the width of the base to determine the slenderness angles and radii. The ground motions that will topple the PBR can then be computed and compared to those predicted in hazard curves using the method of Baker et al. (2013). For our PBR analyses we have developed and refined a number of novel methods. The simplest of these is wrapping a wire around the base to measure the circumference, which allows for more accurate interpretation of the contact surface. We also place seismometers on top of the PBRs and give them gentle pushes to measure the frequency of rocking and the direction of rocking, the latter of which is especially useful for determining the directions of the slenderness angles. The decay in the amplitude of rocking with time also allows for computing the slenderness angles, as outlined in Anooshehpoor et al. (2004), with preliminary results showing close matches with measured angles. The slenderness angles determined from seismometer records may be more accurate than measurements made using other methods. In addition to comparing the ground motions to hazard curves from the National Seismic Hazard Model (NSHM), we determine the probability of PBR survival by using the magnitude-distance pairs in the NSHM disaggregation files as scenario earthquakes. This latter estimate of survival probability provides an independent check on the comparison with the NSHM hazard curves. A final method we have developed is to map maximum magnitudes of earthquakes that could have occurred near the PBR without toppling it. Using this mapping method for the 47 PBRs we have studied provides a contour map of maximum earthquake magnitudes in the northeastern U.S. since ice retreat.

POSTER 28

Developing a New Intensity Measure for USGS's ShakeMap: Cumulative Absolute Velocity (CAV)

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The U.S. Geological Survey's (USGS) ShakeMap has been providing rapid, global estimates of earthquake shaking metrics for decades. The USGS has provided ground shaking metrics as maps of intensity measures (IM) such as peak ground velocity, peak ground acceleration, spectral acceleration (at three periods), and macroseismic intensity. These products have been effectively used by emergency managers, loss modelers, engineers concerned about post-event structural performance, and by risk analysts for insurance products. However, more advanced IMs offer important benefits for characterizing the ground shaking intensity by accounting for energy and duration of shaking, which have the potential to be useful for applications that include assessing the potential for failure involving landslides, liquefaction, and critical infrastructure. These metrics include cumulative absolute velocity (CAV), Arias intensity, significant duration, and permanent static displacement. Since the USGS produces ShakeMaps for events around the globe, we present a framework for implementing CAV in ShakeMap. Fortunately, there are numerous ground motion models (GMMs) models to estimate CAV that are applicable to several regions and tectonic environments. We start by developing the tools to calculate CAV from earthquake records in the software package *gmprocess*. We then develop a database of recorded CAV values from the conterminous United States, Alaska, and Hawaii along with predicted CAV values from GMMs that include quality control. We use OpenQuake to predict CAV values for a total of five existing and new contributed GMMs for CAV. One complicating factor is that some CAV GMMs are conditional models, which had not yet been implemented in OpenQuake. It is also imperative that we test and expand the suitability of the CAV models for all possible regions and tectonic environments with our new database which will be used to develop the necessary spatial correlation models for ShakeMap. We expect our work to improve assessment of liquefaction hazards, impacts to infrastructure, and to advance earthquake science and operations.

POSTER 29

Precariously Balanced Rocks in Northern New York and Vermont, U.S.A.: Ground-motion Constraints and Implications for Fault Sources

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Precariously balanced rocks (PBRs) and other fragile geologic features have the potential to constrain the maximum intensity of earthquake ground shaking over millennia. Such constraints may be particularly useful in the eastern United States (U.S.), where few earthquake-source faults are reliably identified, and moderate earthquakes can be felt at great distances due to low seismic attenuation. We describe five PBRs in northern New York and Vermont—a region of elevated seismic hazard associated with historical seismicity. These boulders appear to be among the most fragile PBRs in the region, based on reports from hobbyists. The PBRs are glacial erratics, best evidenced by glacial striations on bedrock pedestals. The pedestals themselves are locally high knobs, often situated on regionally high topography; this setting limits soil development and indicates that any outwash deposits were likely ephemeral. As a result, PBR ages can be reliably established by the retreat of the last continental ice sheet, ~15–13 ka. To quantify the fragility of the PBRs, we surveyed them with ground-based light detection and ranging and calculated geometric parameters from the point clouds, field observations, and seismic responses. Preliminary validation of the 2023 time-independent U.S. National Seismic Hazard Model (NSHM) shows that the existence of PBRs is generally consistent with the median site-specific hazard curves. Only the Blue Ridge Road site suggests a modest reduction in hazard. To visualize the ensemble of data, we mapped the minimum permissible distance to potential source faults around each PBR site as a function of source magnitude by using the ground-motion models from the 2023 NSHM. Viewed in this manner, our data are consistent with potential M 6.5 earthquake-source faults in many parts of the Lake Champlain Valley and northern Adirondack Mountains. Our work illustrates a potential pathway for better constraining earthquake-source faults in regions of cryptic faults.

Earthquake-triggered Ground Failure: Data, Hazards, Impacts and Models

Oral Session • Thursday 17 April • 8:00 AM Local

Conveners: Laurie Baise, Tufts University (laurie.baise@tufts.edu); Alex Grant, U.S. Geological Survey (agrant@usgs.gov); Meera Kota, University of California, Los Angeles (meerakota@g.ucla.edu); Andrew Makdisi, U.S. Geological Survey (amakdisi@usgs.gov)

Earthquake-induced Landslides Susceptibility and Controlling Factors in Vancouver Island, British Columbia, Canada

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The 1946 Vancouver Island (Comox) earthquake (M 7.2) is Canada's largest recorded onshore seismic event, with its epicentre in central Vancouver Island. This earthquake triggered hundreds of landslides across the island's mountainous regions and coastal liquefaction-induced ground failures, causing significant infrastructure damage and felt as far as Portland, Oregon, and Prince Rupert, B.C. A focal depth of less than 30 km and the inferred fault mechanism—a combination of right-lateral strike-slip and normal dip-slip on the northwest-trending Beaufort Fault—highlight its potential for surface rupture. This study developed an updated inventory of earthquake-induced landslides using historical aerial photographs and field checks. In total, 118 landslides were identified, forming clusters in the study area with the highest landslide density, predominantly rock falls (56%) and rock slides (37%), debris avalanches (4%), and mixed rock fall-rock slides (3%), mainly occurring in granitoids (52%) and volcaniclastic rocks (41%).

A logistic regression-based susceptibility analysis, incorporating geological, geomorphological, hydrological, and seismic parameters, allowed us to develop susceptibility maps with high predictive accuracy (AUC = 0.91–0.92). Controlling factors influencing landslide susceptibility included slope (>30°), aspect (SSW), and geology (granodioritic and metamorphic rocks). Seismic parameters such as peak ground acceleration (PGA) and peak ground velocity (PGV) obtained from USGS ShakeMaps contributed minimally to the models, suggesting potential effects of topographic amplification or frequency content not yet accounted for. The slope aspect controls showing a preferred SSW orientation might suggest near-fault effects, such as directivity or fling step effects, which could further contribute to understanding the rupture propagation mechanisms of this earthquake. This research emphasizes the need for an improved understanding of earthquake-induced landslide mechanisms and their integration into hazard mitigation strategies for seismically active regions like the Cascadia Subduction Zone.

Sea Level Rise Effects on Earthquake-induced Soil Liquefaction

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Global sea levels are expected to increase up to five meters by the year 2150. Higher marine water levels as well as ocean fluctuations will also raise unconfined coastal groundwater levels. These fluctuations pose multiple interrelated coastal hazards. Currently, there has been minimal attention paid to the effects of sea level rise on groundwater, specifically how rising groundwater levels interact with hazards such as earthquake-induced soil liquefaction. We propose to use a probabilistic liquefaction hazard assessment (PLHA) to obtain annual rates of nonexceedance of factor of safety of liquefaction. Our approach integrates the liquefaction uncertainty into the hazard calculation by performing a PLHA for every event in the PSHA. Existing codes for performing PLHA are decoupled as first a probabilistic seismic hazard analysis (PSHA) is required to obtain a hazard curve. Drawbacks of this method are it only accounts for the influence of magnitude on liquefaction because it uses a small number of magnitudes and selection of the magnitudes requires judgment. We adopt the UCERF3 source model, which uses over a million events. For each event, ground motion at the site is a random variable that is used to compute cyclic stress ratio (CSR). Cyclic resistance ratio (CRR) is also a random variable obtained from a liquefaction triggering model. Because CSR and CRR are log normally distributed, we can use a closed-form solution to obtain a distribution for factor of safety (FoS). The rate of the event is then multiplied by the cumulative distribution function (CDF) of FoS and the rate-weighted CDF's are summed over all events to compute the liquefaction hazard curve. Using efficient vectorized operations, the PLHA runs within seconds for a single site despite the large number of calculations. The code is used to compute the PLHA for an example soil profile at Cardiff State Beach in Southern California for current groundwater conditions and for a 1-meter sea level rise scenario.

Duration Matters: Impacts of Ground Motion Selection on Seismic Slope Displacement Analyses

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Seismic slope displacement analyses are crucial for assessing the performance of earthen structures and natural slopes under earthquake loading. Input ground motions are important components of such analyses and represent one of the main sources of variability in estimated values of slope displacement. Most studies on seismic slope displacement analyses have been conducted using shallow crustal earthquake motions. However, ground motions from subduction zones are known to have comparatively longer durations. This study demonstrates the effect of ground motion duration on seismic slope displacements using short- and long-duration motions from subduction tectonic environments. The duration is isolated from other ground motion characteristics by selecting pairs of ground motions with the same amplitude and similar spectral shape, but with different significant durations. These spectrally equivalent short- and long-duration suites of motions are then used in nonlinear finite element analyses to assess their effects on slope displacement. We find that the long-duration motions cause larger permanent displacements compared to their short-duration counterparts, especially at higher ground shaking intensity levels. Comparisons with simplified analyses show that the simplified methods can underestimate or overestimate the permanent displacement of design-level long-duration motions. Our findings demonstrate the need to consider ground-motion duration along with other ground motion characteristics (amplitude and spectral shape) to properly assess seismic slope displacement, and the damage potential of ground motions, particularly from subduction events.

Liquefaction and Ground Failure Considerations During Long-duration, Subduction Zone Earthquakes

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Recent efforts by researchers, governmental organizations, and engineers have focused on studying and mitigating the effects of long-duration, large-magnitude earthquakes, such as those originating from the Cascadia subduction zone in the Pacific Northwest. However, a persistent challenge for geotechnical engineers remains: case histories and research studies on liquefaction triggering and ground failure have primarily focused on lower-magnitude earthquakes due to their higher frequency of occurrence. These data have informed simplified triggering procedures and served as validation data for non-linear effective stress numerical models. Recently, this has created challenges for high-risk and complex projects, where state-of-the-art numerical models often predict deformations larger than previously recorded, leading to costly remediation designs. Without validation data and a sound understanding of how liquefaction triggers and ground failure accumulates during long-duration, large-magnitude earthquakes, engineers are left with limited options.

In this presentation, we share the results from a centrifuge experimental testing program designed to study the effects of long-duration, large-magnitude earthquake shaking on a gently sloping submerged deposit of Ottawa F-65 sand at a relative density of 65%. The ground motions used in the study were selected based on their intensity parameters and source conditions to evaluate the factors contributing to liquefaction triggering and deformation. The experimental findings demonstrated that the velocity of the ground motion and cumulative energy are strong predictors of liquefaction triggering and slope deformations. We conclude the presentation by discussing how findings will aid engineers through improving analysis tools and providing a benchmark dataset of system-level experiments for numerical and analytical model validation efforts.

Synergic Use of Radar and Optical Sensor Data for Mapping Earthquake Triggered Landform Changes

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Earthquakes are natural geophysical events that transform the Earth surface. These changes can be detected and monitored through satellite imagery. The study will incorporate fusion of Optical (Copenicus Sentinel-2) and Radar (Copernicus Sentinel-1) datasets using for change detection caused by earthquakes situated in the North-Western part of Afghanistan in the Herat province. Combining Sentinel-1 amplitude-based change detection and Sentinel-2 based identification of landform changes using different fusion techniques for earthquake impact assessment.

The study focuses on Herat earthquake (Mw 6.3), Afghan block for an in-depth exploration of geological phenomena and seismic dynamics allowing automatic detection of vertical displacements and deformations. The results can be obtained within days after an event, providing complex view of the surface changes caused by an event. It will provide significant insights into earthquake impact assessment and may also be helpful for further field studies.

Earthquake-triggered Ground Failure: Data, Hazards, Impacts and Models [Poster]

Poster Session • Thursday 17 April

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POSTER 1

Regionalized Geospatial Liquefaction Model for California Using Bayesian Logistic Regression

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Liquefaction poses a significant geotechnical risk during earthquakes, threatening infrastructure and communities. Global geospatial liquefaction models have been used effectively in rapid response and risk studies to quantify regional liquefaction extent but have been found to have regional bias as a result of variation on the quality of global parameters. Developing accurate, regionalized models for predicting liquefaction is crucial for effective risk mitigation. This study introduces a Bayesian logistic regression approach to create a regional geospatial liquefaction model for California. By starting with a global liquefaction dataset as a prior, we integrate detailed observations from California-specific seismic events, including the M6.9 1989 Loma Prieta, 1994 M6.6 Northridge, 2003 M6.6 San Simeon, 2014 M6.0 Napa, 2019 M6.4 and M7.1 Ridgecrest, and the recent 2024 M7 Offshore Cape Mendocino earthquakes where liquefaction was observed and documented. Earthquakes such as 2000 M5.0 Yountville, 2008 M5.4, Chino Hills, 2015 M4 Piedmont, and M7.1 Hector Mine earthquakes where no liquefaction was observed are also included to constrain the model. Our methodology uses a logistic regression model trained on the global dataset as a baseline. We then apply the Laplace approximation to derive the covariance matrix, which serves as the prior for our Bayesian model. The model is subsequently refined using California's regional data, examining the impact of various weighting strategies on the balance between global insights and local specifics to avoid overfitting. This approach offers a framework for creating more accurate regional geospatial liquefaction models. This research underscores the critical balance between leveraging prior knowledge and incorporating new data to produce reliable, context-specific hazard assessments.

POSTER 2

Site-characterization Vis-À-vis Surface-consistent Probabilistic Seismic Hazard From Kashmir Himalaya to Northwest Himalaya

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Abstract: The incidences of earthquakes in Kashmir Himalaya to Northwest Himalaya are broadly associated with presence of active faults. The study region falls under Seismic Zone IV and V according to Bureau of Indian Standards, and has been struck by several devastating earthquakes viz. 1905 Kangra earthquake of MW 7.8, 1975 Kinnaur earthquake of MW 6.8, 1991 Uttarkashi earthquake of MW 6.8 and 2005 Kashmir earthquake of MW 7.6 causing widespread damage and destruction in the terrain. The region has undergone unprecedented development and population growth, emphasizing the importance of Probabilistic Seismic Hazard Assessment (PSHA) to ensure safe and secure progress in such a seismically vulnerable region. This study performs a PSHA on firm rock conditions, incorporating both tectonic and polygonal sources at the hypocentral depth ranges of 0-25km, 25-70km, 70-180km, and 180-300km. The analysis utilizes and Next Generation Attenuation models within a logic tree framework estimated Peak Ground Acceleration (PGA) ranges from 0.21g to 0.95g for 475years of return period, emphasizing a site-specific study for seismic site characterization. Seismic site classification has been done based on an enriched geophysical, geotechnical database and topographic gradient derived shear wave velocity categorizing the terrain into 11 Site Classes from E to A. Site response analysis has been performed to derive absolute site amplification, which is used to calculate the surface-consistent PGA varying from 0.29g to 1.78g. The Liquefaction Potential and Landslide Susceptibility Index serve as secondary hazards, complementing both geohazard and seismic hazard frameworks to enable a comprehensive seismic hazard microzonation of the capital cities of Srinagar and Shimla. As an implication of the seismic hazard, Damage Potential Modeling for the cities have been performed. Thus the results of this investigation are expected to play vital roles in the earthquake prone county to pre disaster mitigation and post disaster management.

Keyword: Probabilistic Seismic Hazard Assessment; Site Class; Microzonation; Damage Potential Modeling.

POSTER 4

Earthquake Damage Assessment Empowered by AI Remote Sensing: Case Studies in 2023 M7.8 Kahramanmaraş Earthquake, 2023 M6.0 Jishishan Earthquake and 2025 M7.1 Southern Tibetan Plateau Earthquake

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Big earthquakes can result in multiple types of secondary damage, including surface ruptures, structural cracks or failures, landslides, and liquefaction. These damages present immediate risks to human safety. Nevertheless, assessing earthquake damage is often limited by site accessibility and subjective assessment. Remote sensing offers a crucial means to conduct rapid and large-scale earthquake damage assessment. Utilizing various electromagnetic frequencies, remote sensing exhibits different sensitivities to surface features, with microwave capable of penetrating rains and clouds. Here we extract indices of surface disturbances from a range of remote sensing images that cover the periods of the earthquakes. We synergize these damage proxies with PGA, Vs30, geology, topography, and proximity to fault strands. Utilizing specialized machine learning techniques, we quantitatively analyze 24k+ building pixels (approximately 30 m posting) affected by M7.8 Kahramanmaraş earthquake around Turkey-Syria borders on February 6, 2023, 16k+ landslides from M6.0 earthquake in Jishishan County, located between the Qinghai-Tibet Plateau and the Loess Plateau on December 18, 2023, and hundreds of landslides along with tens of thousands of liquefaction events from M7.1 earthquake in Tingri County, Southern Tibetan Plateau on January 7, 2025. In particular, the damage proxy obtained from InSAR coherence differences effectively illustrates surface disturbances caused by ground shaking. At a compound hazard site triggered by the Jishishan earthquake, variations in soil moisture identified through optical imagery indicate that winter flood irrigation on terraced fields may exacerbate the liquefaction process and mudflows upon shaking. The compound hazard resulting from the Jishishan earthquake offers insights into the devastation experienced by the Lajia Settlement, located less than 5 km away, which is associated with the Qijia Culture from the Neolithic to Bronze Age. Both locations bury houses and individuals, with evidence of adults shielding children with their bodies, suggesting the abruptness and similarity of the events.

POSTER 5

Nonergodic-based Risk Assessment of Liquefaction-induced Ground Damage

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The seismic risk assessment of liquefaction-induced ground damage requires the hazard estimation of ground motion intensity measures (IMs) through probabilistic seismic hazard analyses (PSHA). Current practice implements PSHA using ground motion models (GMMs) developed under the ergodic assumption, which considers that the distribution of ground motion IMs over time at a single site is the same as the distribution of ground motion IMs over space. With the rapid growth of ground motion databases, recent efforts have shown that ground motion recordings are affected by location-specific systematic and repeatable effects favoring the transition to non-ergodic approaches. However, the impact of using ergodic versus non-ergodic PSHA (accounting for source, path, and site repeatable effects) on the risk assessment of liquefaction-induced damage has not been explored, which is the objective of this study. We consider three sites in California with different availability of ground motion data to investigate the effects of the amount of available information on constraining repeatable effects and how this affects the final risk estimates within a non-ergodic approach. In this context, the non-ergodic-based estimates are compared against their ergodic counterparts, and insights are shared. The results from the assessments show important differences between ergodic and non-ergodic estimates in terms of the mean risk and its uncertainty; the differences are dependent on the amount of data, and highlight the value of information (i.e., data) in non-ergodic approaches.

POSTER 6

Mathematical Support for Slope Processes Risk Zoning Using Data About Possible Earthquakes

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Seismic slope processes may be more dangerous than temblors by themselves. Such as, an avalanche, occurred after four earthquakes struck central Italy, swept over a small resort hotel in January 2017 [1]. In March 2003 an earthquake in the Himalayan ranges, triggered the avalanches, which buried more than two dozen Indian soldiers and porters [2]. Therefore, slope processes risk zoning, taking into account information about possible seismic events, presents some features of interest. Wherein, these phenomena induced by earthquakes may be considerably larger than such slope processes without temblors. Besides, avalanche wind may create additional load on structure during seismic events.

Current Canadian Building Code describes the earthquake as a stochastic process. Earthquake intensity corresponding given probability of its springing up at the known area can be calculated. Acceptable level of probability of an accident death is 0.000001. And it must less, if the slope process results in loss of life of more persons. Therefore, it is possible to compute probability of the temblor, which can cause an avalanche. Method Monte Carlo is utilized.

Slope processes risk zoning based on such approach permits to prepare maps providing high level of safety in regions, where both earthquake and slope processes are not impossible. It prevents loss of life and property damage.

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Earthquakes, Lithospheric Structure, and Dynamics in Stable Continental Region

Oral Session • Thursday 17 April • 8:00 AM Local

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Imaging Intraplate Faults in Puerto Rico With New Aeromagnetic Data: The Roles of Fault Reactivation and Tectonic Inheritance

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Puerto Rico experiences damaging shallow (< 10 km) intraplate earthquakes, such as the 2019-ongoing earthquake sequence (up to Mw6.4) in the SW part of the island, as part of a complex deformation zone associated with oblique subduction ~200 km to the north. We use new high-resolution airborne magnetic and radiometric data over Puerto Rico and the surrounding shelf, mapped Quaternary-active faults, and a new geologic map compilation to better understand relations between intraplate seismicity and geologic features.

Aeromagnetic data show a dominant NW-SE fabric, with most lineaments trending N55W-N80W, but with exceptions. The Great Northern and Great Southern Puerto Rico fault zones (GNPRFZ and GSPRFZ, resp.) form the island's structural framework; they are expressed as complex, 4-8-km wide zones of parallel and sub-parallel lineaments that terminate to the west in curved patterns resembling horsetail structures. The GNPRFZ extends farther east than previously mapped curving to the north to trend ENE near and past Culebra Island. The GSPRFZ appears to extend offshore to the SE near Salinas, possibly beyond the survey area.

Contrasting that dominant NW-SE structural grain, Quaternary-active fault mapping (based on lidar, aerial photography, and various field observations) shows the importance of ~E-W-striking faults, such as the previously mapped Salinas and South Lajas faults and additional faults mapped in the Lajas Valley and near the southern part of the GSPRFZ. These faults are rarely aligned directly with magnetic anomalies along their full length; they more commonly overlap small sections of larger NW-SE-trending anomalies, especially where mapped at the surface. A key exception is the N70W-striking Punta Montalva (PM) fault, which is well-aligned with a >20 km-long magnetic lineament extending from offshore to La Parguera; we note that the PM fault was seismically active along 5-6 km of its length during the 2019-ongoing sequence. Comparisons between these different datasets suggest the importance of tectonic inheritance, where pre-existing zones of weakness are reactivated in an evolving stress regime.

A Railway-spotters Guide to Earthquakes: Coseismic Slip, Dynamic Strain and Ground Motion Intensity

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Railroads that cross active faults can provide a striking visual record of surface rupture in large earthquakes, similar to the offset fences that led Reid (1908) to develop elastic rebound theory. Railroads, once offset, may provide a precise measure coseismic offset long after they are repaired, since repairs are typically confined to the region of damage near the fault. We provide examples from a subset of railroads damaged by historical and recent earthquakes: the M > 7 1886 Charleston earthquake (doi.org/10.1785/0320230022), the ;M 6.8 1892 Chaman and M 7.7 1935 Quetta earthquakes in Pakistan (doi.org/10.1785/0220190148), the M 7.4 1944 Bolu, and the M 7.6 1999 Izmit and M 7.8 2023 Kharamanmaras earthquakes in Turkey. Railroads can, however, provide more than just a measure of coseismic offset. They act as distributed strainmeters in the meizoseismal region of an earthquake (doi.org/10.1785/0120240025). As an astute contemporary geologist deduced following the 1886 Charleston earthquake, railroad tracks respond to the transient strain associated with the outward propagation of surface waves. Prior to the implementation of continuously welded rail, early railroads incorporated expansion gaps sufficient to accommodate ~10^{-4} of thermoelastic strain. Transient dynamic strain contraction exceeding this amount following an earthquake results in track buckling, and transient extension results in track separation. Once formed, buckled track cannot be straightened by the tensile phase of transient strain, since the forces required are typically far higher than those needed to create the buckle. Damaged railroad tracks can thus provide a max/min measure of dynamic strain in an earthquake. Because peak dynamic strain is proportional to peak ground velocity and conventional macroseismic shaking intensity at strong shaking levels is proportional to the logarithm of peak velocity, it follows that macroseismic intensity can be estimated from dynamic strain: $2x10^{-4}$ strain is approximately equivalent to MMI 7.5, and 10^{-3} strain is equivalent to MMI 9.

Velocity and Fault Structure of the New Madrid Seismic Zone

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New detailed P- and S-wave velocity (Vp and Vs) models and hypocenter relocations for the New Madrid seismic zone (NMSZ) indicate that the Reelfoot axial intrusion strongly influences velocity and fault structure. The velocity models and hypocenter relocations are determined using local earthquake tomography based on arrival time data in the Cooperative New Madrid seismic network catalog for the period January 1, 2000 through July 17, 2024. The dataset consists of 5,181 earthquakes, 82,645 P-wave phases and 58,946 S-wave phases recorded at 59 stations. Northern Reelfoot fault earthquakes in the depth range 4.65 – 6.65 km occur along the steep northeastern edge of the Reelfoot intrusion and deeper earthquakes occur within the intrusion in a high Vp/Vs ratio region indicative of high pore pressure. The southern Reelfoot fault occurs in a portion of the intrusion with low magnetic intensity and is cut by northeast trending faults including the Axial and Ridgely faults. Three-dimensional views of the seismicity and planes fit to the hypocenters indicate that the southern and northern Reelfoot fault contain numerous northeast trending faults, in agreement with a recent focal mechanism study. We suggest that both strike-slip and reverse motion occur on the Reelfoot fault during large earthquakes. A significant amount of strike-slip motion would help reconcile the small amount of uplift on the Reelfoot fault (Lake County uplift) with the larger amount of strike-slip motion determined on the Axial fault. The unknown amount of partitioning between thrusting and strike-slip fault motion along the Reelfoot fault impacts the use of topography on the Lake County uplift for estimating the age of the seismic zone.

High-resolution Seismic Imaging of Crustal and Upper Mantle Structures Across the Southern Eastern North American Passive Margin

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The southern portion of the Eastern North American margin (ENAM) is an archetypical volcanic passive margin formed during Mesozoic rifting. How past syn- and post-rifting deformations, along with related magmatic events, had affected the southern ENAM lithospheric structures remains an open question of fundamental importance. Seismic data from the onshore and offshore deployment in this region offer a unique opportunity to investigate these questions. In this study, we present high-resolution lithospheric velocity models across the southern ENAM based on multimodal Rayleigh wave inversion and full-wave ambient noise tomography.

Our tomographic results reveal a ~70 km-wide transitional crust at the ocean-continent boundary. Beneath this transitional crust, we identify a lower-than-average mantle anomaly, interpreted as a remnant of enriched mantle underplated during early rifting stages. Additionally, a columnar low-velocity anomaly beneath the Virginia volcanic region suggests localized lithospheric delamination and asthenospheric upwelling. Within the crust, we identify three high-velocity anomalies that likely represent solidified plutons related to the Virginia volcanoes and the Central Atlantic Magmatic Province.

These findings provide new insights into the tectonic and magmatic evolution of the southern ENAM lithosphere.

Indications of Earthquake Activity in Northeastern North American from Native Americans

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Historical records from European explorers and then settlers provide indications of earthquakes in northeastern North America over the past 400 or so years. Extending information about the earthquake activity in this region further back in time can be done by looking for indications of prehistoric earthquake activity in languages of native American tribes. This can be done in three ways. The first way is to document which tribes have a word for earthquake in their language. In northeastern North America tribes ranging from the Seneca and Cayuga in western New York to the Natick tribe in eastern Massachusetts to the Mi'kmaq tribe in eastern Maine all have a word for earthquake in their languages, suggesting that earthquakes were common enough in these areas that the local tribes needed a word for this phenomenon as part of their vocabulary. A second way to look for earthquake activity is in place names assigned by the local natives. For example, Moodus in Connecticut means "place of noises" and is an area where swarms of small earthquakes have been heard and felt. In Massachusetts a hill called Nashoba means "hill that shakes" in the local language of the Native Americans. Over the past several decades, regional seismic network monitoring has indicated that small earthquakes regularly take place near Nashoba. Finally, legends of Native Americans can preserve information on past earthquakes. In 1638 Roger Williams learned from local natives that four strong earthquakes had been felt in Rhode Island over the previous 80 or so years. Interdisciplinary research into words and legends related to earthquakes in eastern North America could extend information about the earthquake activity into pre-European times.

Deep Quakes Beneath the Moho: Insights From the Wind River Basin, Wyoming

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Earthquakes occurring below the brittle-ductile transition zone are rare, raising questions about how rupture can extend into depths traditionally regarded as ductile. The M_W 4.8 mainshock and M_W 3.0 aftershock on September 21, 2013, near the Wind River Basin in central Wyoming, nucleated beneath the Moho and underscored key uncertainties regarding the rheological properties of the lithospheric mantle. An additional M_L 1.5 event in 2010 from the same area further confirms that these mantle earthquakes were not isolated anomalies. In this study, we analyzed USArray data (2007–2010) using a deep-learning phase picker and back-projection associator, detecting roughly 19,000 events that included quarry explosions and high seismicity in the Yellowstone region. After meticulous seismogram review, we identified at least six additional mantle earthquakes near the Wind River Basin. Their hypocenters are spatially distinct from the nearby crustal seismicity, and temperatures at those depths may have reached up to 950°C. We also note that some mantle earthquakes occurred in closely spaced pairs, suggesting self-sustained failure and structural or stress heterogeneity. We propose that thermal runaway is a more plausible mechanism for these deep earthquakes than dehydration or transformational faulting, although long-term observations will be required for further verification.

The Seismic Sources of Northeastern US: New Insights Into Their Detailed Geological Structure and Reactivation Mechanics

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Major seismic events along the northeastern US commonly rupture previously unmapped basement-hosted faults, among which only a few have been subsequently studied in detail. The high population density of this region elevates its seismic risk. Availability of bedrock outcrops in the vicinity of seismicity provides a natural laboratory to explore how the nature of seismic sources and the mechanics of strain release implicate the seismic hazards of stable continental regions. We focus on the Ramapo Seismic Zone in New York-New Jersey, which hosted the2003 Mw3.4 Milford, NJ earthquake, and the recent 2024 Mw4.8 Tewksbury, NJ earthquake, and evaluate the relationships between seismicity clusters, hypocentral slip planes, and the geological structure of the [projected] surface exposures of the ruptured faults. Further, we analyze over three decades of local seismicity predating 2024 with wave paths entirely in the upper crust (<10 km) to explore the relationships between the ENE-WSW regional maximum horizontal compressive stress, basement discontinuities, and fault reactivation. In this talk, we will show results demonstrating that: 1) the causative faults of these earthquakes are oriented NNW-to-NNE or NW-SE, striking at high angles to the presumably inactive large Ramapo Fault, 2) the surface exposures of the causative faults are characterized by gougeless, poorly coalesced paleo-slip surfaces, indicating rough, immature faults, and 3) NNW-to-NNE fast shear wave polarization directions dominate the upper crust of the seismic zone, along with WNW-ESE and NE-SW secondary trends. Most intriguing, our results show that events with propagation paths that sample the source region of the 2024 Mw4.8 Tewksbury earthquake have ~NNE-striking dominant fast-splitting direction parallel to the ruptured fault, indicating aseismic shear dilatancy of the fault zone prior to the Mw4.8 event. The seismic anisotropy-based illumination of critically stressed, potentially seismogenic, elusive immature faults presents a promising direction for seismic hazard mitigation in stable continental regions.

Long-term Erosion as a Catalyst of Shallow Seismicity in Stable Continental Regions – a Global View

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The causes of seismicity and present-day deformation in Stable Continental Regions (SCRs) remain an open scientific question. Numerous driving mechanisms and local conditions may be at play, from steady-state far-field plate tectonic stresses to transient effects associated with Late Pleistocene glaciations, or structural weakening from tectonic inheritance. Here, we study the effects of long-term erosion on crustal stresses and the potential promotion of seismicity in SCRs. A theoretical analysis is performed using 2D numerical mechanical models of SCR lithosphere of various rheological properties subjected to a variety of steady-state localized erosion rates over 1 – 10 Myr. Predicted crustal stresses vary depending on geotherms, lithologies and erosion rates, but all models show a common pattern of horizontal tension in the upper crust (0 – 10 km depth) of up to a few 10s of MPa over a few Myr. A simple Mohr-Coulomb analysis shows that these erosion-driven stress perturbations can promote seismicity of all faulting styles (normal, strike-slip, reverse) in SCRs associated with very low reliefs and mostly homogeneous erosion rates, such as Western Australia or central North America. In other settings associated with more complex topography and erosion patterns, geometrical relationships between background stresses and erosion-driven stresses must be considered. We show a few examples, including the western Alps and the Appalachian Mountains, where long-term erosion rates promote local seismicity and its specific faulting style. In some cases, erosion may even be the overarching cause of the local upper crust stress field and seismicity. Because the lithosphere response to long-term localized erosion is close to that of an elastic plate, the maximum stress perturbations are focussed in the uppermost crust (ca. 0 – 5 km depth). This effect may thus provide an explanation for the tendency of SCRs earthquakes to concentrate at very shallow depths, as observed in large events but also increasingly in small-magnitude background seismicity.

Old News Papers, New Felt Reports, New Earthquakes, New Ways to Look for Old Earthquakes

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Finding information about pre instrumental earthquakes in the Central United states has always been hobbled by a scarcity of sources coupled with the scattering of those sources across a wide geographic area inconvenient to researchers seeking to find them. In recent years this problem has been mitigated by the digitization of archival information and making it accessible via the internet. One of the most accessible resources are the digital libraries of 19th century newspapers. Modern databases of these newspapers have search engines that can unveil previously unknown seismic events and find more information on previously known events. Using these databases has helped to develop more information on the New Madrid earthquakes of 1811-1812 and other seismic events in the Central United States.

Many earthquake catalogs that were done in the 20th century on a state by state basis have events that are noted as being isolated earthquakes. A cursory search of these newer resources has shown that these isolated events might be in fact reports of a larger event that was felt in a multi state area. In addition some earthquakes have been found that were not recorded in any state catalog and point to the need of adding them to those catalogs. This wealth of new information has the potential to flesh out the seismic history of the Central United States and act as model for doing the same for other sections of the country.

A pioneering effort in using archival resources to further understand historic seismic events was done by building on the efforts of Otto Nuttli of St. Louis University to document felt report information on the New Madrid earthquakes of 1811-1812. A follow on effort conducted by Arch Johnston and Nathan K. Moran of the University of Memphis developed the New Madrid Compendium Far Field Database. This effort is ongoing and continues to uncover information on the New Madrid earthquakes and other seismic events that followed in the New Madrid seismic zone in the 19th Century.

Well Logs from the South Florida Basin

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In November 2023 USF received original well logs from the South Florida Basin. Approximately 50 wells were drilled, mostly to depths of 11,300 to 11,600 ft. Three were drilled to 17,000 ft to reach basement. The wells were drilled from the years 1943 to 1991. Thirteen of the wells succeeded to reach oil from five fields, and 137 million barrels of oil were recovered. The well logs were prepared by Mr. Raymond Ocamb of Marshland Petroleum Corporation in Lafayette, Louisiana. The logs include information on density, resistivity, lithology and other factors. Upon Mr. Ocamb's retirement, the original logs were transferred to Griffin Petroleum in Midlands, Texas. Mr. David Griffin subsequently donated them to the School of Geosciences at the University of South Florida. As of this writing, arrangements are being made to transfer the logs to the Florida Geological Survey in Tallahassee. There they will be scanned and digitized and made available to the public. The historic geologic records prepared by Ray Ocamb are of significant value to present day hydrogeologists and seismologists because they describe subsurface conditions from the eye of a trained professional in the 1940s. Ocamb's well logging was the first to describe the deep and complex geology of the South Florida Basin. These records will be of assistance in programs to re-enter and plug these old wells to eliminate the potential for inter-aquifer contamination, aquifer storage, underground injection of wastes and CO2 storage.

Florida is a growing state with a population of 23 million people with many more anticipated. Water is the key planning element to supply residents. Florida sources approximately 80% of the freshwater needs from the aquifer known as the Floridan Aquifer System, a complex hydrostratigraphic system that extends to depths of nearly 4,000 feet in south Florida. Water quality for drinking purposes is generally good but the complex hydrogeology of many producing zones and confining layers needs to be understood to manage groundwater resources. Ocamb's records describe the plugging and abandonment procedures for these wells.

Earthquakes, Lithospheric Structure, and Dynamics in Stable Continental Region [Poster]

Poster Session • Thursday 17 April

Conveners: Oluwaseyifunmi Adeboboye, Georgia Institute of Technology (oadeboboye3@gatech.edu); Oliver S. Boyd, U.S. Geological Survey, (olboyd@usgs.gov); John E. Ebel, Weston Observatory, Boston College (ebel@bc.edu); Susan Hough, U.S. Geological Survey (hough@usgs.gov); Jessica T. Jobe, U.S. Geological Survey(jjobe@usgs.gov); Will Levandowski, Tetra Tech, Inc. (will.levandowski@tetratech.com); Anjana Shah, U.S. Geological Survey (ashah@usgs.gov); Xiaotao Yang, Purdue University (xtyang@purdue.edu)

POSTER 62

The February 2024 M4.1 Earthquake Offshore Cape Canaveral, Florida

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A rare seismic event occurred at 03:48 UTC on 8 February 2024, about 100 miles offshore east of Cape Canaveral, Florida. The M_L 4.1 event was felt along the Florida Space Coast, raising the question of whether this was a tectonic earthquake. The USGS location at 28.55°N and 78.87°W places the event beneath the Blake Plateau, providing a landslide. An explosive source could not be discarded initially as U.S. Navy "Full Ship Shock Trial" detonations equivalent to M_L 3.9 were conducted as recently as August 2023 at a similar distance from the shore as the 8 February event, about 100 miles NNW of the 2024 epicenter. A comparison of seismic waveforms with the 2021 Navy explosions provides compelling evidence for a tectonic origin for the 2024 event. The explosions show strong, late arrivals due to water reverberations from shallow detonations. Late arrivals are absent in the 2024 records, suggesting a deeper crustal hypocenter. We relocated the event after adding the closest station, a Raspberry Shake instrument, placing the epicenter slightly farther north (28.6°-28.65°N) but event longitude remains ill-constrained due to the one-sided station distribution and the large station distances (D≥200 km). Regional moment tensor analysis in the 15-20 s band results in M_w 3.7, explaining low amplitudes relative to M_L 4.1. Signal amplitudes constrain the magnitude, but the small number of good S/N waveforms hampers source mechanism resolution. Our preferred solution has a thrust mechanism at 11 km depth with large uncertainties. The mechanism and its ~NE-trending P-axis are consistent with focal mechanisms along the eastern seaboard, which generally have a NE-trending SH_{max} direction. The 2024 event likely represents a rare tectonic earthquake in the greater Florida region providing a 'teachable moment' to consider active tectonics in a very slowly deforming compressional regime.

POSTER 63

A New Fault Characterization in Lajas Valley, Southwestern Puerto Rico

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Southwestern Puerto Rico (SWPR) received significant attention after the 2020-ongoing earthquake sequence, which included events located near offshore Guayanilla Canyon. Previous research suggested that this seismicity migrated onshore along left-lateral strike slip and transtensional faults, including the Punta Montalva and South Lajas faults, respectively. Most of previous geophysical work in this region was conducted through offshore seismic reflection surveys, leaving significant gaps for understanding the subsurface character of onshore faults. Strikes, dips, and depths of potentially active fault planes are critical factors to comprehensively characterize faults in tectonically active regions and for updating future seismic hazard assessments. Seismic reflection profiles were collected in the Spring of 2023 and 2024 across Lajas Valley, SWPR, to produce a new onshore fault characterization of the South Lajas Fault and other associated faults. Two phases of data acquisition were completed using a 216-channel seismic system with a weight-drop source. Profiles were collected perpendicular to the strike of the valley, and spanned the entire valley. Seismic data processing and data analyses were carried out using the Seismic Unix processing system. Ground Penetrating Radar (GPR) surveys were completed in Fall 2024 along the same profile location to characterize structures and potential faulting in the upper 20 m of the valley's subsurface using the open-source R language processing software RGPR. Preliminary seismic results showed excellent imaging of southward-thickening stratigraphy that record faulting associated with the South Lajas Fault up to 250 m depth along with interpretation of depositional events before, during, and after tectonic activity in Lajas Valley. GPR data displayed near-surface layers and two discontinuous features possibly related to faulting to at least 10 m depth. This information will help illuminate the structure and tectonic evolution of Lajas Valley along the SWPR boundary.

POSTER 64

Stress and Slip Potential of Quaternary Faults and Possible Tectonic Features in the Central and Eastern U.S.

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There are more than 60 known or suspected Quaternary tectonic features in the central and eastern United States, ranging from well-studied seismic zones and faults to nebulous uplifts and liquefaction deposits. Crustal stress data in the region were sparse when this list was drafted 25 years ago, but the number of available focal mechanisms has since increased 15-fold. This project develops a site-specific stress model for each of these 60 features that quantifies the slip potential of local faults as a function of orientation, predicting sense of slip and rake. For the most enigmatic features, this tests whether the suspected faults and proposed motion are compatible with the modern stress field. This work documents the slip compatibility of normal faults in South Dakota and the Brockton-Froid zone (MT) and likely incompatibility of proposed faulting in the Champlain Lowlands (VT), New York Bight, Pembroke/Lindside/Stanley-Villa Heights (WV/VA), Wiggins Uplift (MS), and Monroe Uplift (LA). In many liquefaction and seismic zones, the causative faults have not been identified. Digitizing geologic maps and computing the slip potential of mapped faults illuminates candidate faults for the Moodus, CT swarm, 1727 Newburyport, MA liquefaction features, and 1886 Charleston earthquake, while several previously proposed faults are found to be poorly oriented. Short-wavelength stress variations in active areas influence fault activity and fault network connectivity. Transpression and clockwise stress rotation pervade the New Madrid (NMSZ) and Wabash Seismic Zones but do not impact immediately adjacent features (Ste. Genevieve, Cape Girardeau, Thebes Gap, West fault, western AR liquefaction). Moreover, dynamic rupture simulations suggest that second-order stress variations within the NMSZ may control rupture linkage vs. segmentation across the fault network and thus the occurrence of M7.5+ earthquakes.

POSTER 65

New Seismotectonic Models of Metropolitan France and Neighboring Intraplate Regions for Seismic Hazard Assessment

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Seismotectonic zoning is one of the elementary blocks of seismic hazard assessment. It is typically used to define areas in which earthquake attributes, such as frequency-magnitude relations, are considered homogeneous, based primarily on local active tectonic characteristics. Yet, seismotectonic zoning can prove a major challenge in Stable Continental Regions where, by definition, active tectonics are extremely subdued. In this study, we develop new seismotectonic models of metropolitan France and neighboring regions of intraplate Western Europe, which will serve for seismotectonic zoning and source characterization for the new probabilisitic seismic hazard assessment (PSHA) for metropolitan France. These new seismotectonic models are based on classical data sets, such as instrumental and historical earthquake catalogs, or crustal structure information, but also on alternative data and information that are not usually considered in intraplate settings. We consider geodetic (GNSS) strain rates derived from several different solutions to help define areas of consistent deformation and tectonic styles. In addition, because the causes of present-day deformation and seismicity are not simply due to plate tectonics, we also consider geodynamic models of alternative driving mechanisms, specifically glacial isostatic rebound from the Weichselian-Würm Glaciation and isostatic response to Quaternary – Holocene erosion and sedimentation rates. These different data sets and models allow us to delineate areas of well-defined tectonic styles and rates (e.g., most of the Pyrenees Mountains) and others where the expected deformation and seismicity are more poorly defined, or where the different data sets are not compatible. The seismotectonic models will in turn be used as input branches for the PSHA logic tree.

POSTER 66

Long-term Erosion as a Catalyst of Shallow Seismicity in Stable Continental Regions – Examples of Metropolitan France

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In this study, we test the impact of long-term erosion rates on potential fault activity and seismicity in a specific regions of metropolitan France and neighboring intraplate Western Europe. We first develop models of long-term (Holocene to Quaternary) erosion rates based on statistical analyses of measured denudation rates from cosmogenic nuclide concentrations, complemented by weathering rates from river load data and sedimentation rates from offshore surveys. These erosion rate models are used as a driving force on 2D planar models of lithospheric deformation based on an elastic plate approximation, with a variety of lithosphere rigidity models to account for spatial variations in geotherms and lithologies. The predicted stress perturbations are then combined with models of the background stress field to derive 2D planar models of local stress tensors that include the effects of erosion rates. These can then be projected on any given fault geometry to compute the full Coulomb stress and the fault tendency to slip in response to the effect of erosion. We apply this approach to subsets of faults and tectonic structures in different regions of metropolitan France with various seismicity and tectonic characteristics: the Western Alps - Rhone Valley (including the fault associated with the 2019 Le Teil earthquake), northern France and the Paris Basin, and the Armorican Massif. In most cases, stress perturbations due to long-term erosion promote fault instability in agreement with the observed tectonic style from earthquake focal mechanisms, with the most significant effects limited to the uppermost crust (0 – 5 km depth). Thus, long-term erosion rates may act as a catalyst – and potentially as a primary driver – of shallow seismicity in these regions. Further modeling analyses, including more detailed considerations of the various sources of uncertainties, are required to strengthen these preliminary conclusions.

POSTER 67

Three Earthquakes in the Baltimore Gneiss

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Three events in June and August of 2021 (2021/06/21, 2021/06/27 and 2021/08/15) were reported inside the Baltimore beltway in the Maryland Piedmont Baltimore Precambrian Gneiss (above the fall line). Station coverage is sparse in the Baltimore urban area and the closest station used to locate, SDMD, is 14-18 km from the reported epicenters. Multiple RaspberryShakes recorded data within 50 km and the closest, R0ECF, at 9-10 km. Comparison of waveforms at R0ECF and SDMD indicate that all three events were very closely related. Relocation using P & S waves from 5 RaspberryShakes places all events within 1 km of each other. ML magnitudes of the events were recomputed using the relocations and local stations. These events demonstrate values of citizen scientist hosted seismic stations such in this sparsely monitored urban area.

POSTER 68

Spatial Distribution of the Mohorövicic Discontinuity Beneath Northeastern Mexico Based on Receiver Functions From Acceleration and Velocity Records

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We obtained 805 receiver functions from velocity data of four permanent and six temporary seismic stations and 38 from acceleration data of three permanent stations located in northeastern Mexico to get the spatial distribution of the Mohorövicic (Moho) discontinuity in that region. To prove the feasibility of using acceleration records to obtain receiver functions, we obtain receiver functions from velocity and acceleration records from instruments located less than 1 m from each other at the permanent stations. We conclude that it is possible to use the acceleration data by filtering and integrating it. We estimated the depth of the Moho discontinuity under each station. We observed that the thickness of the crust is thicker under the Basin and Range and Sierra Madre Oriental provinces to the west, reaching values greater than 33 km and being, on average, 32 ± 2 km. Then, the crust gets thinner in the Sabinas and Magiscatzin basins to the east, with an average thickness of 29 ± 2 km.

POSTER 69

Maryland Seismicity: Insights From Moment Tensor Inversion With a Sparse Seismic Network

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Small, 1.5 – 3.6 magnitude earthquakes occur up to several times a year in Maryland and the surrounding areas. These earthquakes are mostly confined to the Piedmont geological province. Because of their small size and the sparsity of permanent seismic stations operating in the region, source characterization is difficult, and even first motion mechanisms are rarely available. Therefore, it is not known how these events relate to local geology and pre-existing faults, or whether their mechanisms are consistent with local or regional stress fields. To better understand the nature of Maryland seismicity, we investigate the source depths and mechanisms for a cluster of M ~ 2 earthquakes by performing full waveform moment tensor inversions.

The velocity structure used to construct Green's functions is constrained using a collection of local 1D models as well as an inversion from surface wave dispersion data. The range of reasonable 1D models is used to assess the sensitivity of moment tensor inversion to variations in velocity structure.

Additionally, we systematically assess moment tensor error resulting from perturbations introduced to the velocity model, as a function of station position.

We interpret the focal mechanisms in the context of information available on local and regional tectonic stresses and faulting regimes. Finally, we discuss the implications of our results for seismicity across the Mid-Atlantic region of the United States.

POSTER 70

Magnetotelluric (MT) Upper Mantle Resistivity Structure of the Mississippi Embayment and Alabama-Oklahoma Lineament

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We investigate the upper mantle resistivity structure of the Mississippi Embayment (ME) and the Alabama-Oklahoma Lineament (AOL) using USMTArray and USGS long-period MT data. The ME is a deep sedimentary structure that includes the New Madrid seismic zone (NMSZ) and the AOL is a Precambrian to Paleozoic relic of plate tectonic events. Our investigation uses 2D profiles and the Occam2D inversion method. Due to the low resistivity sedimentary cover and mantle resistivity values, the long period MT data only provides good depth resolution up to about 100 km. The station spacing of 70 km also limits the horizontal spatial resolution of resistivity features. The upper ME upper mantle structure shows resistivity values around 1000 Ohm-m and with few distinct features. There is a NW-SE trending feature with lower resistivity (100 Ohm-m or less) west of ME in Arkansas corresponding to a low velocity zone at 80-120 km. A second more E-W low resistivity feature between 35N and 36N appears associated with a low velocity structure at 100-150 km. The AOL appears as a NW-SE trending feature with low resistivity (100 Ohm-m or less) that cuts off the ME trends to the north from the Gulf Coast (GC) features. The region corresponding to Bahamas Fracture seismic zone shows a higher resistivity of greater than 1000 Ohm-m from the depth of 50 km to 120 km in SW-NE profiles. The gulf coast low resistivity features appear associated with higher heat flow, possibly due to gulf coast crustal thinning, suggesting the dominance of temperature on mantle resistivity to the south. High heat flow with low resitivity may indicate a potential zone of weakness. Heat flow near and north of AOL is relatively low. Gravity data suggests lower densities are associated with the ME low resistivity features north of and including the AOL hence the possible influence of mantle fluids. Further measurements and research are needed to better define these mantle resistivity features.

POSTER 71

Event Detection and Hypocenter Uncertainty Analysis of Induced Earthquakes the Rome Trough, West Virginia

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Recent induced seismicity (IS) studies in the central and eastern United States found that most earthquakes induced by fracking or wastewater disposal were associated with fluid injections in intervals ≤~1 km above Precambrian basement. However, an IS sequence from 2010 to 2013 in Gilmer County, West Virginia, appears to defy this trend. Earthquakes in this sequence were associated with fracking in the Rome Trough in an interval ~4-5 km above basement. Accurately characterizing this sequence is thus important toward determining existing fault structures that may be activated by future subsurface injections in the region. Earthquakes in the Gilmer County sequence were initially located at shallow depths relative to basement (~3.5–4.5 km above) and because epicenter-to-station distances are relatively large (>~14 km), the calculated focal depths have large uncertainties (+/− 5.8 km). To improve hypocenter determinations and their accuracies and to investigate the causal fault(s), we detected additional events and we determined relative relocations. We used machine learning (ML) packages PhaseNet and GaMMA for phase detection and event association. We used waveform templates derived from the original and ML catalogs within EQcorrscan to match other smaller events. We then leveraged HypoInverse and HypoDD to respectively locate and relocate all verified earthquakes. Preliminary analysis of the Gilmer County sequence revealed >80 located events and nearly 30 relocated events. Relocated hypocenters remain shallow and depict a potential ~4 km long, ~4 km wide fault that strikes ~110° N and dips steeply to the SE and is preferential to failure in the local stress field. However, depth errors for these events remain high after relocation (+/− 2.8 km). Further refinement of our preliminary Gilmer IS results, results from the equivalent analyses of the Braxton County, West Virginia, IS sequence, and quantitative assessments of the location uncertainties will be presented.

POSTER 72

Reassessing Tectono-structural Units and Crustal Thickness Variations in Southwest Cameroon Using Gravity and Seismic Data

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Southwest Cameroon is characterized by inadequately detailed geological data, prompting an investigation into its geological and tectonic features through innovative edge detection techniques applied to gravity data. This study employs methods such as the Analytical Signal (AS), Tilt Angle (TDR), Total Horizontal Gradient of the Tilt Angle (TDR_THDR), and Logistic Filter (IL) to delineate lineaments and geological contacts from derived gravity anomaly maps. A key contribution is the identification of significant tectonic boundaries, including the Kribi-Campo faults and the Ebolowa pseudo-karstic circular network. This represents the first comprehensive mapping of the Ebolowa network, integrating links to the Mbilibekon and Mfuda caves, thereby enhancing our understanding of the region's pseudo-karstic landscape and geological evolution.Moreover, the detailed delineation of the north-south extension of the Kribi-Campo faults, extending into both oceanic and terrestrial domains, aligns with the geophysical mapping of the eastern Congo Craton margin. This underscores the fault system's role as a transition zone between stable cratonic cores and dynamic mobile belts, suggesting a reevaluation of regional tectonic models. To enhance the interpretation of edge detection results, we estimated Moho depths by combining gravity and seismic data. The average Moho depth of 46 km, with maximum depths reaching 48 km, correlates with regions exhibiting pronounced faulting and sedimentary features. Intermediate Moho depths (40-42 km) near Akom II, Eséka, and Lolodorf indicate thrusting contacts between the Pan-African Yaoundé nappe and the Paleoproterozoic Nyong Complex, validating the tectonic structures identified by edge detection techniques. Our findings enhance understanding of the subsurface structural features of Southwestern Cameroon while also offering a robust foundation for future geological and geophysical research in the region, emphasizing the critical link between surface and subsurface geological processes.

POSTER 73

Source Characteristics of the 2020 Mw 5.1 Sparta, North Carolina, Earthquake Sequence

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The Mw 5.1 Sparta, North Carolina earthquake on August 9, 2020 is the largest earthquake to occur in the Appalachian Blue Ridge province since 1916. It produced notable ground shaking and damage to infrastructure. Significantly, this moderate-magnitude event generated the first documented surface rupture due to faulting in the eastern United States. The ~2-km-long rupture occurred along a previously unmapped, ESE-striking, SSW-dipping reverse fault, now named the Little River fault. Detailed analyses of the earthquake sequence, including foreshocks, aftershocks, and the mainshock, provide critical insights into the mechanics of this intraplate event. Moment tensor inversion reveals a shallow (1 km depth) oblique reverse fault mechanism (strike N118°E, dip 52° SW) consistent with the observed surface deformation. Spectral analysis of the mainshock indicates an unusually low Brune stress drop (5.7 MPa) for an eastern U.S. earthquake, with a source radius of 1.5 km and average slip of 20 cm, both corroborating field observations. To improve hypocenter locations, we combine machine learning and template matching techniques to relocate over 1,000 events using a double-difference algorithm. The relocated seismicity delineates not only the NW-SE striking mainshock fault but also a conjugate NE-trending fault intersecting the primary structure near the northwest edge of the surface rupture. Further analysis of focal mechanisms and stress drop estimates for smaller events within the sequence will provide a more comprehensive understanding of the rupture process and its implications for seismic hazard assessment in this low strain rate tectonic setting.

POSTER 74

3D Shear-wave Velocity Structure of the North American Midcontinental Lithosphere

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Despite being relatively stable, the interiors of global cratons preserve evidence of structural modification on geologic timescales. The North American midcontinent is the locality of a series of rifts, basins, arches, and domes. Geologic evidence suggests that these features formed throughout the Paleozoic or earlier with limited subsequent deformation. However, the mechanism(s) that drove the uplift and subsidence of these intracratonic features is poorly understood. Linking these surface tectonic features with deep crustal and upper mantle processes is important in understanding the evolution of cratons. Here we present a new 3-D shear-wave velocity model of the crust and uppermost mantle (10-100 km) of the North American midcontinent, using full-wave ambient noise tomography. Our results show a heterogeneous crustal structure across the midcontinent, with scattered low-velocity zones in the uppermost mantle. These low-velocity zones are concentrated below major rifting structures, including the Midcontinent Rift, the central Michigan Basin, the La Salle Deformation Belt within the Illinois Basin, and the Reelfoot Rift. Except for below the Reelfoot Rift, where a localized thin crust is imaged, these low velocities are imaged below a thicker crust than the regional average. These low-velocity anomalies may reflect the remnants of magmatic underplating or frozen hydrated mantle lithosphere, formed during the early rifting stage. These materials were stagnant when the rifting stopped. Below the Michigan and Illinois Basins, the relatively deep Moho may be the consequence of subsidence in the basins. These observations suggest that rifting of the midcontinent created lithospheric weak zones, serving as the pathways for magma or other hydrothermal fluids or partial melts to rise and accumulate below the crust. The findings in this study imply strong modifications within the cratonic interior that are preserved in the present-day lithospheric structure.

ESC-SSA Joint Session:Seismology in the Global Oceans: Advances in Methods and Observations

Oral Session • Tuesday 15 April • 4:30 PM Local

Conveners: Takeshi Akuhara, University of Tokyo (akuhara@eri.u-tokyo.ac.jp); William Ellsworth, Stanford University (wellsworth@stanford.edu); Margaret Hellweg, University of California, Berkeley (hellweg@berkeley.edu); Tolulope Olugboji, University of Rochester (tolulope.olugboji@rochester.edu); Matteo Picozzi, University of Naples Federico II (matteo.picozzi@unina.it); Karin Sigloch, Géoazur Laboratory (karin.sigloch@geoazur.unice.fr); Youqiang Yu, Tongji University (yuyouqiang@tongji.edu.cn); Ziqi Zhang, University of Maryland, College Park (evan.z.0920@gmail.com)

The Cascadia Offshore Subduction Zone Observatory Infrastructure Project: A Year 2 Update

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The Cascadia Offshore Subduction Zone Observatory (COSZO) is an NSF-funded mid-scale infrastructure project that is on track to add new seismic and geodetic capabilities in 2026 to the Ocean Observatories Initiative (OOI) Regional Cabled Array (RCA) off Newport, Oregon. Geophysical observations show that the Cascadia megathrust is mostly locked from the coastline to the deformation front, but off central Oregon they are consistent with a narrowly locked megathrust near the deformation front that transitions to creeping behavior beneath the shelf where there are two clusters of earthquakes on the megathrust, including repeating and very low frequency earthquakes. COSZO is constructing updated science junction boxes to be added to three primary nodes on the continental slope and shelf that currently do not support seafloor geophysical observations. We are procuring a newly developed ocean bottom seismic package, which houses a broadband seismometer and strong motion accelerometer and connects directly to a low-frequency hydrophone and a differential pressure gauge, for each new junction box and an additional site on the shelf with an existing science junction box. Two types of calibrated pressure gauges are under construction and we will also procure absolute pressure gauges and current meters. Together with sensors already on the OOI RCA at the Slope Base and Hydrate Ridge sites, the infrastructure will form a "critical mass" offshore geophysical observatory to study fault coupling and deformation of the Cascadia megathrust and the overlying accretionary prism and support efforts to prototype offshore earthquake and tsunami early warning. In Fall 2024, our Science Advisory Committee held its first meeting. One recommendation is to improve the awareness and usability of existing OOI RCA geophysical data at the Slope Base and Hydrate Ridge sites. To this end, we will duplicate existing seafloor pressure data from the OOI database into Earthscope Data Services (formerly the IRIS DMC) and evaluate whether any unused contingency funds can be prioritized to enhance the geophysical instrumentation at these sites.

PACSAFE: Preliminary Results from Deployment of Ocean Bottom Seismometers Off Canada's West Coast

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The Pacific Coast Seismic Assessment for Faults and Earthquakes (PACSAFE) multi-year ocean bottom seismometer (OBS) program conducted its Leg 1 deployment in October 2023 off the west coast of British Columbia, Canada, and Leg 2 recovery and redeployment in July 2024. This collaborative project between federal and academic institutions across Canada targets an enhanced characterization of seismicity and fault structure around the northern terminus of the Cascadia subduction zone and its transition to the Queen Charlotte transform fault offshore northern Vancouver Island and Haida Gwaii. The acquired data will facilitate precise earthquake locations and structural imaging, provide data for regional tectonic and geodynamic studies, and ultimately contribute to enhanced assessment of seismic and tsunami hazard along British Columbia's central coastline.

During the Leg 1 cruise in October 2023, 26 new broad-band OBS from the National Facility for Seismological Investigations run by Dalhousie University, were deployed in the Queen Charlotte Triple Junction region. However, during mid-November 2023, two of these OBS self-released from the seafloor and drifted into Hecate Strait, with only one being recovered. A third instrument also self-released at the end of May 2024, and was successfully recovered. During the Leg 2 cruise in July 2024, all of the remaining 23 OBS instruments were successfully recovered. A total of 23 OBS instruments were re-deployed during Leg 2, though two self-released with two weeks. While data were recovered from all 23 instruments, three were not re-deployed due to instrumental issues discovered during turn around.

Here we present a summary of the project, introduce the Leg 1 and 2 cruises, present the current concept for Leg 3 in August 2025, and discuss potential causes for the early-release instruments. Finally, we present preliminary analysis and results from the Leg 1 network, including noise levels, component orientations, and progress towards an updated earthquake catalogue with more precise locations for events included in the National Earthquake Database over the same time period.

Detection, Characterization and Interpretation of Diverse Seismic Signals in Submarine Hotspot-ridge Interaction Settings

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Ocean bottom seismometers (OBS) placed on mid-ocean ridges record a broad spectrum of signals that originate from diverse solid Earth processes and other sources, including whale calls, anthropogenic activity (e.g., ship noise, air guns), and ocean noise. Detection, discrimination, and characterization of these signals is challenging because of their complexity and because they are often recorded concurrently. This is especially true in periods leading up to and during eruptions when local OBS data are inundated with seismic events. Furthermore, phase conversions and reverberations complicate the interpretation of seismic phases. Here we show examples from the East Pacific Rise at 9°50′N and from Axial Seamount, an active submarine volcano on the Juan de Fuca Ridge which last erupted in April 2015. We focus on the 7-station, cabled OOI OBS network at Axial where we employ an extensive suite of methods to automatically detect and characterize events from various sources in near real-time: kurtosis, machine learning and waveform cross-correlation for event detection as well as polarity, phase arrival and delay time measurement; inversion and grid search for absolute hypocenter location; double-difference for precise relative location. In addition, we use unsupervised machine learning to characterize time-dependent variations in spectrograms to effectively discriminate between different source origins and types of brittle failure. This allows us, for example, to monitor precursory mixed frequency earthquakes which were observed before the 2015 eruption, or impulsive seafloor events that track lava flow during eruptions. Analysis of the ambient noise over 7-years reveals a long-term trend of decreasing velocity during rapid inflation, followed by an increase in velocities leading up to the next eruption. These complementary observations, when combined and interpreted together with results from active source seismics, lead to significant improvement of our understanding of the structure, mechanics, and dynamics of this hotspot-ridge system, and help forecast the timing of Axial's next, imminent eruption.

Seismotectonics of the Puerto Rico Subduction Zone: Leveraging Machine Learning Analysis of Ocean Bottom Seismometers

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The Puerto Rico Trench (PRT) is characterized by highly oblique subduction that transitions from predominantly perpendicular convergence in the eastern segment to increasingly oblique convergence toward the western segment. Despite its significance as a tectonic boundary and its history of generating large earthquakes and tsunamis—such as the 1918 Mw 7.3 San Fermín earthquake and the 1943 Mw 7.6 Mona Passage earthquake—the PRT remains insufficiently studied. The absence of a comprehensive seismic catalog and significant uncertainties in the locations of offshore earthquakes and swarms hinder a critical understanding of subduction dynamics and associated hazards. By leveraging automated machine learning (ML) pickers, this study integrates data from six ocean bottom seismometers (OBS) deployed north of Puerto Rico by the USGS to generate a comprehensive, high-resolution earthquake catalog.

Using SeisBench, we applied PhaseNet, a deep neural network-based seismic arrival picker (Zhu and Beroza, 2019), and the phase-associator GaMMA, in conjunction with the Pick-Blue model trained on OBS datasets (Bornstein et al., 2024), to analyze waveforms from both the ocean bottom seismometers (OBS) and the Puerto Rico Seismic Network (PRSN) from mid-2015 to mid-2016. This effort resulted in the detection of 6,335 earthquakes with 64,319 associated seismic phases. The machine learning (ML)-derived catalog for the OBS dataset includes 12,840 P-wave and 6,575 S-wave arrival times, a significant improvement over the USGS catalog (DOI: 10.5066/P13485PX), which documented 9,368 OBS phase arrivals. Our preliminary relocated catalog demonstrates notable enhancements in both the number of detected events and the accuracy of earthquake locations. Future work will focus on processing the PRSN catalog from mid-2016 onward, incorporating differential travel times using cross-correlation techniques, and relocating earthquakes. This approach aims to calibrate phase arrivals and improve relative location uncertainties offshore through spatial clustering of earthquakes during and beyond the OBS deployment period.

Innovative Approaches to Subsea Orientation of Seismic Instrumentation

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The quality of ocean bottom seismic data is presently limited by uncertainty in the azimuth of the horizontal channels. While various methods exist to determine azimuth orientation, all of them have practical limitations. The obvious method of a magnetic compass is inaccurate because of the presence of magnets in seismic sensors and motors, and ferrous metals such as in anchors for station systems. The most common method is to calculate azimuth based on polarization of seismic signals propagating from a known source direction, however this method is affected by heterogeneity of material properties along the source-receiver path and at the station, so that neither the direction of propagation nor the resulting polarization may be determined with reliable accuracy. When the station is installed with an ROV (Remotely Operated Vehicle), it is possible to use the gyrocompass in the ROV navigation system to orient the seismic package, although a means to accurately orient the seismic instrument with respect to the ROV during installation has often been lacking. Regardless of the method used to determine the initial azimuth, it is possible for the system to move later on during operation, introducing additional error.

The ideal way to determine azimuth would be to have a gyrocompass included as one of the instruments at each seismic station, and periodically measure true azimuth throughout operation. However the size, cost, and power consumption of a gyrocompass has historically been similar to that of a broadband seismometer, so it was generally not practical to add a gyrocompass at each OBS station, although some proof-of-concept experiments have been done (e.g. D'Alessandro and D'Anna, 2014). Recent developments in gyrocompass technology have made it possible to reduce size, cost, and power to the point where commercialization may become practical for OBS. This presentation details the results of recent research to develop this concept.

ESC-SSA Joint Session:Seismology in the Global Oceans: Advances in Methods and Observations [Poster]

Poster Session • Tuesday 15 April

Conveners: Takeshi Akuhara, University of Tokyo (akuhara@eri.u-tokyo.ac.jp); William Ellsworth, Stanford University (wellsworth@stanford.edu); Margaret Hellweg, University of California, Berkeley (hellweg@berkeley.edu); Tolulope Olugboji, University of Rochester (tolulope.olugboji@rochester.edu); Matteo Picozzi, University of Naples Federico II (matteo.picozzi@unina.it); Karin Sigloch, Géoazur Laboratory (karin.sigloch@geoazur.unice.fr); Youqiang Yu, Tongji University (yuyouqiang@tongji.edu.cn); Ziqi Zhang, University of Maryland, College Park (evan.z.0920@gmail.com)

POSTER 1

Measurement of Seafloor Rayleigh Ellipticity From Unoriented Seismic Data and Its Significance for Seismic Imaging in the Ocean

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Observations of seafloor Rayleigh ellipticity play a important role in seismic imaging in the ocean. To extract these observables from arbitrarily oriented ocean-bottom seismometer data, we introduce an orthogonal-regression-based approach for measuring waveform amplitude ratios between the unoriented horizontal and vertical components of surface waves. These amplitude ratios are subsequently used to calculate the Rayleigh ellipticity and determine the sensor orientation angle.

The robustness of our method is validated through applications to both unoriented OBS data and well-oriented on-land seismic data. By directly deriving Rayleigh ellipticity from the unoriented three-component data, our approach circumvents challenges associated with surface wave non-great-circle effects and uncertainties in OBS sensor orientation angles.

Overall the Rayleigh ellipticity measurements from our method are systematically higher than those by conventional analysis and show less uncertainties. Our analyses suggest that the Rayleigh ellipticity curve (14–60 s), which could be retrieved from the raw broadband OBS data, is effective to constrain the oceanic lithosphere structure. The potential of seafloor Rayleigh ellipticity for seismic imaging in the ocean is evidenced by a case study of the Japan Basin, the Sea of Japan. Considering the insufficient station coverage in the ocean, the single-station measurement of seafloor Rayleigh ellipticity is of significance for OBS community.

POSTER 2

Exploring Local Seafloor Pressure Changes Along the Nankai Trough: Insights Into Fluid Reservoir Dynamics

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The Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) is a system of seafloor sensors that monitors earthquake and tsunami activity. Observations from this network, positioned above the area where the 1944 Tonankai earthquake originated, have shown that slow slip events (SSEs)—a type of gradual tectonic movement—occur in the shallow areas of the fault where megathrust earthquakes take place. However, these SSEs have mostly been detected near the D-node of the network, with only a few exceptions. For instance, one study reported detecting an SSE near the B-node, but other related phenomena like low-frequency tremors or very low-frequency earthquakes haven't been observed there yet. This is likely due to the way the network's sensors are distributed.

Most of the sensors that measure crustal deformation are arranged in a straight line between the C and D nodes, which doesn't cover the B-node area well. Additionally, the geology near the B-node is unique. Studies suggest that a seamount (an underwater mountain) has been pushed beneath the continental plate in this area, and that fluids are moving upwards through faults and mud volcanoes.

In this study, we explored an alternative explanation for a pressure change detected near the B-node in 2013. Our analysis suggests that the pressure change could be due to local changes in cylindrical fluid reservoirs. These reservoirs might be connected by pathways that temporarily opened due to changes in ocean conditions. This finding highlights the importance of closely monitoring ocean activity and studying the structure of the seafloor to better understand and detect these kinds of pressure changes.

POSTER 3

Potential Tectonic Tremor Detected on a Single Ocean Bottom Seismometer Offshore Cascadia

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Observations of tectonic tremor, an emergent seismic signal associated with slow slip, provide important constraints on the plate locking state and associated seismic hazards at subduction zones and other plate boundaries. However, detecting tectonic tremor offshore with ocean bottom seismometers (OBSs) is often complicated by large station spacing and marine-specific emergent noise signals, including T-phases and ship noise. To address these challenges, we develop a single-station tremor detection method that employs a two-stage triggering and classification approach to minimize misdetections caused by marine-specific noise. We validate our method using OBSs in the Hikurangi subduction zone, demonstrating that we can effectively identify network-confirmed offshore tectonic tremor with just one OBS. We then apply this approach to two cabled, buried OBSs located near the deformation front of the Cascadia subduction zone at ~44.5°N. Our results show that shallow OBS burial effectively eliminates bottom current-generated noise, which disrupts tectonic tremor detection. Over 2015-2024, we find evidence for tectonic tremor signals at just one station, 5 km seaward of the deformation front. These signals cannot be easily attributed to instrumental or environmental noise and they are not measured on the other station, 20 km landward. We therefore suggest they are associated with either localized slow slip very near the deformation front or deformation in the outermost wedge. Additional observations are needed to confirm the signal source, but our findings may be the first observation of shallow tremor in Cascadia. Our single-station approach could be adapted elsewhere to search for tectonic tremor where OBS coverage is limited, helping to illuminate fault slip modes in hard-to-reach offshore regions.

POSTER 4

From Autonomous Deployments to SMART Cables: Challenges and Innovations in Ocean Bottom Sensing

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Although earthquake-prone regions are densely monitored by over 26,000 registered terrestrial seismograph stations, the scientific community needs data from the 71% of Earth's surface covered by oceans to better understand Earth's structure, tectonic processes, and potential hazards. Ocean-bottom seismic (OBS) data acquisition, however, presents engineering challenges due to the deep-sea environment. Recent advancements in OBS platforms have enabled innovative solutions to address data quality, completeness, system reliability, and ease of deployment, expanding the scope of oceanographic studies.

This poster explores engineering challenges in OBS platforms and the technological solutions Nanometrics has developed to meet the needs of diverse marine environments and use cases. The company's innovations, such as integrated kinematic gimbals for levelling and designs certified for 6,000m depths, enable seamless multidisciplinary data collection supported by various sensing instruments and data loggers.

POSTER 5

Localizing Very Long Period (VLP) Enigmatic Microseismic Sources and Associated Gliding Tremors in the Gulf of Guinea Using Numerical Matched Field Processing

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Two persistent, narrow band microseismic sources, with peak periods at 26 s and 28 s, and associated gliding tremors in the primary microseism band have been reported in cross-correlation and spectrogram analyses of ambient noise records from US, European, and African stations. Beamforming analysis of data from from temporary seismic deployments in Cameroon and Morocco help constrain the backazimuths to these sources. The backprojection along the estimated backazimuths points toward the Gulf of Guinea. To localize these sources in the Gulf of Guinea, we use data from a temporary broadband deployment in Cameroon to perform numerical Matched Field Processing (nMFP). nMFP is an array processing method that conducts a grid search of correlations between the recorded wavefield and a synthetic wavefield generated by forward numerical simulations.

We obtain topography and bathymetry data for this region with 15 arc second resolution from OpenTopography. This dataset was downsampled by a factor of 30 to retain 48000 points with spatial resolution of ~15 km. These 48000 points are considered as potential source locations for nMFP. For each potential source location, an estimate of the phase match, also known as a Bartlett Processor, is computed between both wavefields for a certain frequency band, taking the coherency of the wavefield across stations into account. We use SW4, a finite difference based 3D seismic wave propagation simulator which solves the seismic wave propagation in displacement formulation, to compute the forward correlation wavefield for each source location under consideration. The observed array covariance matrices, computed for hourly windows for 10-15 days, are stacked. The gliding tremors are unusually long duration events, up to several days, with frequency always gliding up from the Very Long Period (VLP) band to Long Period (LP) band. Our analysis of monthly data indicates that both microseismic sources, with peaks at 26 s and 28 s, share a common source region in the Gulf of Guinea.

POSTER 6

Imaging of the Global Oceanic Lithospheric Structure With Probabilistic Deconvolution of SS Waves

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Previous studies using the SS precursor technique mostly target the mantle transition zone by applying a narrow bandpass filter with long periods to the time-domain waveforms and interpreting seismic structures directly from the waveform stacks. While this treatment has been proven successful when targeting various mantle structures, alternate data processing methods are required when investigating lithospheric structures because the effect of these shallow seismic discontinuities is usually non-separable from the main SS phase. In this study, we propose to image the lithospheric structure by the deconvolution of SS waves using a transdimensional probabilistic Bayesian inference. The signature of seismic discontinuities is characterized by a reflectivity series consisting of an unknown number of Gaussian pairs, the time delay, amplitude, and width of which represent the depth, velocity difference, and gradient of the discontinuities. We also invert for noise parameters simultaneously in the Bayesian process, using a reversible-jump Markov-chain Monte Carlo (rj-McMC) implementation. Synthetic tests show that our approach can effectively recover the lithospheric operators for both single-discontinuity and multi-discontinuity models even when realistic background noise is present. In real data experiments, we propose to use the Hilbert transform of the direct S phase as the reference waveform in the deconvolution, as it resembles the shape of the SS arrival but does not carry information about the structures at the bounce point. Preliminary results from the NoMelt region southeast of Hawaii in the normal Pacific Ocean resolve a consistent seismic LAB (lithosphere-asthenosphere boundary) structure across different chains, showing promising potential for accurately imaging lithospheric structures using the proposed approach. We anticipate our approach will enable high-resolution lithospheric imaging, especially in the global oceans where seismic stations are sparsely deployed.

POSTER 7

Guralp Ocean Bottom Monitoring Solutions: Autonomous Nodes, Cabled Observatories and SMART

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Autonomous free-fall OBS units allow users flexibility in deployment and the ability to redeploy in different locations. The Güralp Aquarius functions at any angle without using a gimbal system, and can wirelessly transmit SOH and seismic data to the surface via an integrated acoustic modem. These features allow researchers to monitor and transmit data packets without offshore cabling, reducing logistical challenges whilst maintaining some degree of real-time data transmission. This broad functionality and connectivity has made the Aquarius well-suited for OBS pool use, such as with the National Facility for Seismic Imaging in Canada.

Alternatively, cabled solutions provide access to high-resolution data in real time via a physical link to on-shore infrastructure. As an example, the Güralp Orcus provides a complete underwater seismic station with observatory-grade seismometer and strong-motion accelerometer in a single package. The slimline Guralp Maris also provides a more versatile solution, using the same omnidirectional sensor as the Aquarius and can be installed either on the seabed or in a narrow-diameter subsea borehole. Both systems are deployed globally as part of multi-disciplinary observatories such as the Neptune array operated by Ocean Networks Canada.

SMART cables show great potential for increasing the number of cabled ocean observatory deployments in the future with substantially reduced deployment costs. Combining several applications into a single system, including seismology, oceanography and telecommunications, large scale monitoring networks can be created cost-effectively by combining logistical and fundraising efforts from multiple industries. Güralp is leading the way with a wet demonstration SMART Cable system in the Ionian Sea in collaboration with Instituto Nazionale Di Geofisica e Vulcanologia (INGV). This has proven to be the first practical demonstration of this technology and there are plans for additional projects in the future by leveraging new low-volume and low-power iterations of Guralp sensors and data acquisition modules.

Exploring Planetary Interiors and Seismology: Observations, Models, Experiments and Future Missions

Oral Session • Thursday 17 April • 8:00 AM Local

Conveners: Andrea Bryant, Brown University (andrea_bryant@brown.edu); Doyeon Kim, Imperial College London (doyeon.kim@imperial.ac.uk); Jiaqi Li, Peking University (lijiaqi315@gmail.com); Nicholas Schmerr, University of Maryland (nschmerr@umd.edu)

Reading a Marsquake Seismogram: A Case Study of S1222a

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Detailed analysis and interpretation of seismic waveforms has yielded countless discoveries about earthquake source mechanisms and the Earth's interior. Commonly, this seismogram "reading" is facilitated by comparisons with predictions from geologically-motivated proposed structures and by constraints on ray parameters provided by seismic arrays. Additionally, polarization attributes of individual seismic phases can also aid in seismogram interpretation. While the analysis of waveforms of impacts and marsquakes recorded by the *InSight* mission have yielded new insights into the internal structure and seismo-tectonic activity of the red planet, several factors have conspired to stymie detailed interpretation of the waveforms. First, the existence of only a single seismic station on Mars makes receiver array methods impossible. Second, prior geological constraints on subsurface layering are far weaker than on Earth. Third, strong scattering produces extended codas that are more challenging to interpret. Finally, contamination by wind noise and both sustained and transient signals presents pitfalls for seismogram analysis.

Here, we primarily focus on S1222a, the largest marsquake that occurred during the InSight mission, which was recorded with by far the highest signal-to-noise levels, mitigating the fourth challenge identified above. We first constrain the event's source spectrum in order to estimate its stress drop and spectral fall-off. By leveraging frequency-dependent polarization analysis and synthetic waveforms computed for sub-surface structures constrained by prior converted wave and surface wave dispersion analyses, we then carry out detailed seismogram interpretation to associate individual arrivals with specific paths through the subsurface. We discuss the implications of these analyses for inferences of subsurface structure, for the source characteristics of S1222a, and place the event's source characteristics and aftershock productivity in the context of other marsquakes.

Quantitative Assessment of Atmospheric and Teleseismic Excitation of a 2.4 Hz Resonance in Insight Data From Mars

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InSight landed on Mars in November, 2018, and spent the next few months deploying a sensitive seismometer package (Seismic Experiment for Interior Structure; SEIS) and a heat flow probe to the surface. For more than two Martian years it recorded over 1300 cataloged marsquakes and other seismic events. Among the many signals recorded by SEIS is a prominent mode around 2.4 Hz. Possible explanations for this signal include a specific lander mode due to the solar arrays, or a local ground substructure as described notably in Hobiger et al. (2021). A different approach to modeling the basic observation of the structure of the SEIS background noise Horizontal to Vertical (H/V) ratio was taken by Carrasco et al. (2023), producing a suite of models matching or excluding the prominent 2.4 Hz resonance. Both studies suggest that models explaining the 2.4 Hz resonance using a subsurface structure require a significant Low Velocity Zone (LVZ) within the top 100 m.

In this study, we test the hypothesis that the 2.4 Hz signal in both ambient background noise and teleseismic marsquakes are caused by a seismic LVZ by simulating the amplitude of the 2.4Hz peak observed during marsquakes and during the quiet Martian night. We generate Green's functions of the ground substructure for high-incidence-angle teleseismic events and for regional surface sources through models derived from both Hobiger et al. (2021) and Carrasco et al. (2023). Subsequently we test the ground response to these excitations by convolving the simulated sources with the appropriate Green's functions considering sources from above for the atmospheric excitation, or from below for the teleseismic excitation. We demonstrate that a range of models matching the 2.4 Hz H/V ratios can produce reasonable amplitudes of excitation driven by measured pressure fields above noise levels during the night, but not detectable during the day, as well as matching the relative excitation in teleseismic data.

Lems-A3: The Lunar Environmental Monitoring Station—a Seismometer Station for the Moon Deployed by Artemis III Astronauts

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The Lunar Environment Monitoring Station for Artemis III (LEMS-A3) was selected by NASA as a Deployed Instrument for the Artemis III (A3) mission and will be deployed in mid-2027 by astronauts near the lunar South Pole at the margin of the South Pole–Aitken basin (SPA). LEMS-A3 is a compact, autonomous, and self-sustaining seismometer suite designed to carry out continuous (day and night), long-term, monitoring of the lunar seismic environment at the South Polar region. The South Pole affords us the chance to study seismicity in highlands terrane and examine farside moonquakes, neither of which were detected in detail by Apollo seismometers. The three-month threshold mission and two-year baseline operation of LEMS-A3 will provide a new moonquake catalog that contains impacts, thermal, shallow, and deep moonquake activity. The detection and location of 3–4 high signal-to-noise moonquake events, together with the application of single-station data processing techniques developed and advanced during the InSight mission, will provide new information on the thickness of the lunar crust and properties of the mantle and core.

Once deployed on the surface and activated by the A3 crew, LEMS-A3 requires no support (power, thermal, commanding, or data) from the Human Landing System/Starship or the A3 crew to operate. The package has three elements: (a) a three-axis Short Period Seismometer (SP); (b) a complementary three-axis Broad Band Seismometer (BB); and (c) an Instrument Suite Platform (ISP) that provides data digitization and storage, power, thermal, and communication resources. Subsurface burial of the of the LEMS-A3 seismometers into the lunar regolith by the A3 crew will provide thermal stability, improved coupling to the ground, and reduced scattered seismic noise, all issues that plague surface-emplaced seismometer packages. LEMS-A3 is a technical demonstrator of a low-cost, self-sustaining, long-lived geophysical station at the Moon and could serve as the beginning of a *global* network of geophysical instruments, i.e., in coordination with the Farside Seismic Suite and/or a future Lunar Geophysical Network.

Along-trajectory Infrasound Signals Generated by the OSIRIS-REx Sample Return Capsule Re-entry

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The re-entry of NASA's OSIRIS-REx Sample Return Capsule (SRC) into Earth's atmosphere in 2023 provided a unique opportunity to detect and analyze infrasound generated by a controlled atmospheric entry. As the SRC traversed denser atmospheric layers at hypervelocity, it produced shock waves that decayed into acoustic signals. The strategic placement of ground-based and airborne sensors along the SRC's trajectory enabled the detection of signals from a substantial portion of the object's path. This data set offers an unprecedented foundation for refining atmospheric entry and shock wave propagation models. The well-defined parameters of the SRC (mass, size, velocity) allowed for comprehensive analysis, validating the critical role of acoustic monitoring in characterizing high-altitude phenomena. The findings in this study can be leveraged for differentiating anthropogenic atmospheric events from natural meteoroid and asteroid entries. Furthermore, the results demonstrate the strategic value of infrasound within regional and global monitoring systems for detecting and characterizing atmospheric events of both natural and human origin.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Examining Acoustic Arrivals From the OSIRIS-REx Capsule Reentry Recorded on a Large-N Infrasound Array

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Artificial object reentry from interplanetary space at speeds exceeding the escape velocity of Earth are exceptionally rare. Sources of this type that scientists have detailed foreknowledge of, including a well-constrained reentry trajectory, touchdown location, and accurately defined physical parameters is something that has only happened a handful of times since the end of the Apollo era. Meeting all of these requirements made the OSIRIS-REx sample return capsule (SRC) reentry on September 24, 2023 and its subsequent landing in Utah a singularly important event. In this study, we investigate low frequency acoustic signals generated by the SRC as it passed over a large-N infrasound array. This densely packed 121 element array was deployed across a 100 m^2 area at the Eureka Airport in Nevada, nearly directly under the point of maximum heating (and therefore maximum acoustic energy) of the OSIRIS-REx SRC. We first confirm that a signal from the SRC is present across the entire array, and constrain frequency content, duration, and waveform shape variability across different array elements. We then conduct statistical analyses of beamformed detections from a broad range of subarrays within the large-N configuration to determine differences in detection quality between array shapes and sizes. Our goal is to determine how much information can be gleaned about the rapidly changing backazimuth of the SRC in relation to the array using various subarrays. Additionally, we work to ascertain the incidence angle of the SRC's acoustic pulse as it travels across the array via atmospheric temperature profiles and apparent trace velocity. To better understand the capabilities of the experimental instruments that large-N data is recorded on, we complete a comparative analysis with infrasound signals recorded on Hyperion sensors, which have well-constrained instrument response curves and dynamic ranges.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Exploring Planetary Interiors and Seismology: Observations, Models, Experiments and Future Missions [Poster]

Poster Session • Thursday 17 April

Conveners: Andrea Bryant, Brown University (andrea_bryant@brown.edu); Doyeon Kim, Imperial College London (doyeon.kim@imperial.ac.uk); Jiaqi Li, Peking University (lijiaqi315@gmail.com); Nicholas Schmerr, University of Maryland (nschmerr@umd.edu)

POSTER 102

What, When, Why? An Overview of InSight Operations on Mars and Available Datasets

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NASA's InSight lander was operational on the surface of Mars from November 26th 2018 until December 16th 2022 – a total of 1446 sols. InSight was equipped with a 6-component seismometer; temperature and wind sensors; a pressure sensor; a heat flow probe; a magnetometer; and two x-band radio antennae (for geodesy measurements). Throughout the mission these instruments were turned on whenever possible and throughout much of the first 700 sols there is a near-continuous data record from all instruments. Seismic data was recorded right up until the mission ended and the catalogue of Marsquakes produced by the Marsquake Service has been instrumental to our understanding of the interior structure of Mars and the seismicity and impact rates. Beyond the marsquakes there is a continuous seismic dataset waiting to be mined but this is contaminated with spurious signals from necessary operational procedures performed by the lander which also had a robotic arm with a camera, a scoop and a grapple. The arm was essential for instrument deployment and troubleshooting but created distinct signals and resonances within the seismic dataset. The mission involved several nominal activities including imaging the surrounding area, deploying the seismometer and heat flow probe to the surface, hammering by the heat flow probe, burying the seismic tether and performing soil elasticity experiments. There were also many more ad hoc activities including attempting to assist the probe in its burial and innovative ways to clean the solar panels. All these activities influence the data.

We will share a sol-by-sol guide to the operational activities of the mission and an accompanying catalogue of all available data – both scientific and housekeeping – throughout the mission with examples of characteristic signals generated by specific activities. This database will be an invaluable resource allowing future generations to avoid - or target - these spurious signals and so correctly use and interpret the entire dataset from this amazing mission.

POSTER 103

A New Lunar Crustal Thickness Constrained by Converted Seismic Waves Detected Beneath the Apollo Seismic Network

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Analysis of conversions between compressional and shear waves is a workhorse method for constraining crustal and lithospheric structure on Earth; yet, such converted waves have not been unequivocally identified in seismic data from the largest events on the Moon, due to the highly scattered waveforms of shallow seismic events. We reanalyze the polarization attributes of waveforms recorded by the Apollo seismic network to identify signals with rectilinear particle motion below 1 Hz, arising from conversions across the crust-mantle boundary. Delay times of these converted waves are then inverted to estimate crustal thickness and wave speeds beneath the seismometers. Combined with gravimetric modeling, these new crustal thickness tie-points yield an updated lunar crustal model with an average thickness of 29–47 km. The model provides critical context for future lunar exploration and geophysical studies, predicting a 15-36 km thick crust at Schrödinger basin and 29–52 km at potential Artemis III landing locations.

POSTER 104

Exploring Uncertainty of Single-station Focal Mechanism Inversions of Cerberus Fossae Marsquakes

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From 2019 to 2022, the SEIS instrument of the InSight lander recorded over 1300 seismic events, including tectonic marsquakes and meteorite impacts. Although marsquake focal mechanisms provide key insight into tectonic stresses in the Martian interior, robust solutions have only been possible for a small number of high-quality low-frequency family events. Many of these events are located in the Cerberus Fossae extensional region, approximately 30 degrees east of InSight's landing site in Elysium Planitia. Past studies broadly agree that some of the largest magnitude Cerberus Fossae marsquakes are the result of normal faulting with fault orientations approximately aligned with the fossae system, although more complex solutions have been suggested. Here, we explore some of the unique challenges of single-station focal mechanism inversions of marsquakes in order to better understand their uncertainties and to develop an optimal inversion approach. In particular, we investigate i) the effect of the relatively unknown subsurface velocity structure, and ii) the influence of body-wave window duration and weighting schemes on waveform-based focal mechanism inversions. Additionally, using our preferred inversion parameters, we present focal mechanisms for several Cerberus Fossae marsquakes that do not yet have published solutions.

POSTER 105

Studying the Coupling of Unburied Distributed Acoustic Sensing (DAS) for Lunar Seismology

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Seismic data from previous Moon missions has been invaluable for improving our understanding of the lunar structure. However, the seismometers of the Apollo missions faced challenges due to the highly scattering lunar environment. Distributed Acoustic Sensing (DAS) offers a potential solution with its dense spatial sampling that allows the use of array methods. Typically, DAS cables are buried to enhance coupling and to reduce atmospheric noise, but this is impractical for lunar deployment. Fortunately, the Moon lacks an atmosphere, which eliminates the concern of atmospheric noise. This makes unburied deployment a consideration, although coupling remains to be investigated.

We conduct experiments to study the cable-ground coupling of both buried and unburied fibers in a lunar regolith simulant. Using a passive approach, we deploy fibers in a trough filled with the simulant and record seismic signals from naturally occurring earthquakes. These experiments assess the impact of burial on signal quality and the influence of atmospheric noise. Additionally, we compare the signals measured with different cable types in the simulant. We successfully recorded signals from both local and regional earthquakes. The unburied DAS cable was able to record both of them. These findings suggest that unburied DAS could be a viable and efficient tool for lunar seismology, potentially simplifying deployment and overcoming scattering issues.

POSTER 106

A Transdimensional Framework for Array-based Seismic Phase Detection and Characterization

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Identifying seismic phases present in seismic waveforms and measuring their attributes is essential to seismic modeling and imaging of the planetary interior. For example, robust measurement of ray parameters can differentiate depth phases from surface-reflected ones, yielding more accurate velocity models and temperature and compositional inferences based on those models. In addition, polarization parameters can facilitate phase identification and provide information on wave type, propagation path anisotropy, and subsurface structural variations such as dipping layers or local heterogeneities. In this study, we present a novel transdimensional inversion framework designed to infer arrival time, slowness, and polarization parameters of seismic phases from three-component seismograms collected in either a source array or receiver array setting. Our proposed method leverages a probabilistic Bayesian approach to infer the number of phases that can be robustly identified in noisy seismograms while providing robust uncertainty quantification on their polarization and ray parameter attributes. Synthetic tests show promising results in accurately recovering phase attributes, while preliminary experiments with terrestrial seismic data successfully recover seismic arrivals consistent with traditional vespagram techniques, but without the need for specifying detection thresholds for phase arrivals. This work can be applied to the analysis of Martian seismic data, where single-station observations and limited marsquake coverage present unique challenges to seismic waveform interpretation. Applying this method to marsquake waveforms from the *InSight* mission could enhance the identification of Martian crustal and mantle phases, providing new insights into the planet's seismic structure and thermal evolution.

Exploring the Complexity of Fault Discontinuities

Oral Session • Thursday 17 April • 2:00 PM Local

Conveners: Catherine Hanagan, U.S. Geological Survey (chanagan@usgs.gov); Aubrey LaPlante, Northern Arizona University (aal382@nau.edu); Emerson M. Lynch, U.S. Geological Survey (elynch@usgs.gov)

How Wide Are Faults?

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Fault zones are often represented as an hourglass shape, wider at the surface, narrow through the seismogenic zone, and wider ductile shear zones at depth. This conceptual model predates decades of observations of the width of deformation zones in continental strike slip faults. We compiled the width of seismic and aseismic strain zones from 0-30 km depth using rupture maps from single earthquakes, creeping zone widths from repeat monument surveys and InSAR, aftershock locations, low velocity and high anisotropy zones, as well as widths of pseudotachylyte, ultramylonite, and mylonite zones in exhumed faults. We assert that ultramylonites are the down-dip equivalent of fast creeping zones measured at the surface. We equate the width of pseudotachylyte-bearing zones to the width of primary coeseismic surface rupture traces over geologic time. To date, we have not observed systematic width-depth trends in the seismogenic width, creeping zone width, or total fault zone width, suggesting no clear "hourglass" narrowing across faults through the seismogenic zone. The fast-creeping zones are somewhat thinner than the maximum width of single earthquake ruptures at the surface and in the exhumed faults. The width of rupture zones measured at surface from individual earthquakes is similar to the width of fast creeping zones at the surface and at depth. The width of damage zones measured in the upper 10 km is similar to the width of lower strain mylonite zones at 20-30 km depth. These dimensions may be important for parameterizing faults zones within probabilistic fault displacement hazard analyses and for earthquake cycle modeling that considers post-seismic recovery and viscous relaxation. The compiled fault zone widths in this study may help constrain appropriate rheologies and deforming zone widths for interseismic and off-fault deformation.

Building Non-planar 3D Fault Models From Earthquake Hypocenters

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Accurately characterizing three-dimensional (3D) fault geometry is vital for improving understanding of earthquake behavior and informing the development of seismic hazard models. Despite their importance, subsurface fault structures tend to be poorly constrained due to limitations in observational data. We present an automated approach to constructing 3D fault geometries directly from hypocentral seismicity patterns. This method begins with clustering events based on their spatial density, allowing us to identify coherent patterns. Nearby clusters are then merged based on the similarity of their orientations. Unlike traditional methods that rely on planar approximations, we employ surface fitting using support vector regression to balance surface accuracy with minimal deviations from planarity. To assess the quality of these models, we compute the spatial density of seismicity relative to the faults and evaluate how well it matches the documented tendency for hypocentral density to decrease with distance from the fault following a modified power-law. The verified fault models are output as triangular meshes at user-defined resolution.

As a proof of concept, we apply this approach to the San Andreas-Calaveras Fault junction region and the 2019 Ridgecrest earthquake sequence, both in California. These case studies demonstrate the method's ability to delineate complex fault structures, including long continuous fault surfaces, crossing faults, variably dipping segments, and subparallel faults. We test the method on both standard network catalogs and double-difference relocated catalogs. We find that our seismicity-based fault model results align with published 3D models that incorporate additional constraints and interpretations (Aagaard & Hirakawa, 2021; Plesch et al., 2020). This workflow provides a low-user-input solution for reconstructing fault geometries at depth from earthquake catalogs.

Sentinel-1 InSAR Analysis Reveals Longer Periods of Creep and the Segmentation of Enriquillo Plantain Garden Fault Following the 2021 M7 Nippes, Haiti

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The 14 August 2021 M_w 7.2 Nippes, Haiti earthquake ruptured the Enriquillo Plantain Garden Fault zone (EPGF) on the Southern Peninsula of Haiti. Following the mainshock, postseismic investigations using L-band ALOS-2 and C-band Sentinel-1 Interferometric Synthetic Aperture Radar (InSAR) have identified triggered creeping segments of the EPGF and thrust faults. These segments either took part in the rupture or were adjacent to the rupture. Using Sentinel-1 time series analysis we show that triggered shallow creep continued longer both in time and space than previously estimated. We found segments of the EPGF that creep for up to 300 days and the creeping segments extend from the rupture area to well into the Miragoâne pull-apart. We also found along-strike variability in the duration of creep, highlighting the segmentation of the EPGF. We compare the observed creep to the relocated aftershocks of Douilly et al. (2023) and the series of M5+ earthquakes that occurred on the Southern Peninsula 4 months after the mainshock. We find that the creep is not aseismic and possibly triggered the M5+ earthquake series. This has implications for the loading and seismogenic potential of the off-EPGF faults following large earthquakes and the velocity strengthening or weakening properties of the fault system and the seismogenic potential of the fault system.

Fault Geometric Complexity and Displacements of 2016 Kaikōura Earthquake Surface-ruptures, New Zealand

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The Kaikōura Earthquake ruptured a complex system of more than 20 faults in the northeastern South Island of New Zealand. These faults display a wide range of orientations, lengths, displacements, slip types and slip rates. We draw together information from the literature for fault-trace maps, displacement measurements, uplift and bedrock geology to examine controls on fault geometries and displacements in the Kaikōura Earthquake. The 2016 ruptures cross a tectonic domain boundary and their overall geometry is neither controlled by slip rate on individual faults nor by regional shear-strain rates. Instead, the complexity of 2016 faulting reflects the variable orientations of discontinuities in the underlying bedrock. The earthquake utilised a range of pre-existing zones of bedrock weakness including basement bedding/structures, Cretaceous normal faults, Miocene reverse faults and Cenozoic bedding planes. The resulting fault network is highly connected, with thrust faulting linking strike-slip faults at depths of 5-25 km and 'jump' distances < 1 km. High slip gradients approaching fault tips reflect slip transfer between faults and kinematic coherence across the fault system during the earthquake. Despite the geometric complexity of faulting, the sense of slip on each fault is broadly consistent with a ~120° regional principal horizontal shortening direction. However, many of the 2016 faults have orientations misfit for slip in the contemporary regional stress field, suggesting either local rotation of the principal stresses and/or dynamically triggered slip on misoriented faults. Complex multi-fault geometries are common for historical large-magnitude earthquakes in New Zealand and suggest that our observations have wide application.

The Impact of Pre-existing Weaknesses on Early Strike-slip Fault Evolution

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The 2019 Ridgecrest mainshock produced a complex rupture pattern of cross faults at the northwest end of the dextral rupture where a set of disconnected pre-existing faults that trend perpendicular to the strike of the mainshock fault had sinistral slip. The highly segmented geometry of active faulting at the northwest end of the rupture may reflect very immature faulting that provides insights into the early development of strike-slip faults. Why did the rupture reactivate these NE striking sinistral faults rather than developing a new NW trending dextral fault that could accommodate the coseismic strain? Understanding how the orientation of pre-existing cross-faults can influence the early evolution of strike-slip faults and strain localization over geologic time scales can inform future seismic hazard assessments of regions with pre-existing structures. Physical experiments that simulate upper crustal deformation using scaled analog materials, such as wet kaolin, allow us to control loading and material rheology, and directly document the complete evolution of fault systems. We vary three aspects of the experimental set up to assess the impact of pre-existing weaknesses on strike-slip fault evolution: initial orientation and spacing of the vertical surfaces, and nature of basal shear loading (localized and distributed). Cross faults oriented 60° and 90° from the applied dextral loading showed negligible reactivation while cross faults oriented 120° reactivated with sinistral slip and cross faults oriented 150° had dextral slip. Experiments that developed sinistral slip along cross-faults (120°) showed significant rotation of material, including cross-faults, within the shear zone. The amount of off-fault deformation and shear zone width depends on the presence of pre-existing weaknesses (even if they had low slip during reactivation) and the persistence of fault irregularities that arose from the early reactivation of pre-existing faults. Tracking fault geometry and off-fault deformation during experiments of strike-slip fault evolution provides insight that can guide interpretations of crustal faults.

Exploring the Complexity of Fault Discontinuities [Poster]

Poster Session • Thursday 17 April

Conveners: Catherine Hanagan, U.S. Geological Survey (chanagan@usgs.gov); Aubrey LaPlante, Northern Arizona University (aal382@nau.edu); Emerson M. Lynch, U.S. Geological Survey (elynch@usgs.gov)

POSTER 79

Refining 3D Fault Geometry for the Hayward-calaveras Fault Connection in the Bay Area of Northern California

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The Bay Area of northern California stands on a major transform plate boundary and seismic hazard is a concern as over 7.7 million people are vulnerable to earthquakes in this region. Modeling helps us understand the mechanics of fault systems, including fault displacement and the surrounding strain and stress fields, which are critical for assessing fault interactions and seismic hazard. By incorporating improved field observations of fault geometry from Light Detection and Ranging (LiDAR) remote sensing data into three-dimensional (3D) mechanical models that honor how faults interact, we aim to improve model slip rate correlations with observed slip ratest. As fault shape at depth is not well known, this study focuses on improving the 3D geometry of the Hayward-Calaveras fault connection, a high-hazard area in the Bay Area of northern California. This work also will provide better understanding of how these faults behave at depth. Essentially, we will test two hypotheses: (1) that interacting fault segments will result in surface structures that reveal the 3D geometry; (2) that incorrect fault geometry will cause misalignment between model slip rates and observed slip rates. The integration of field observations and LiDAR data allows for a better representation of fault geometry, enabling modeled slip rates to align with field slip rates. Ultimately, this study utilizes mechanical models to simulate fault slip and stress interactions, providing insights into how fault geometry affects fault behavior and how faults interact. The overarching aim is to advance seismic hazard mitigation by improving models of fault slip rates.

POSTER 80

Creeping Through a Stepover: Top-down View From Geomorphology, Seismology, and Geodesy

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The geomorphic record preserves various stages of fault development, typically thought to evolve toward simpler geometries with slip accrual, though the relationship between past and presently active surface faulting with slip at depth is not always clear. This has implications for isolating which mapped structures are most relevant to current slip displacement hazard potential. The central San Andreas fault, extending ~150 km north of Parkfield, is a prime example of a mature fault, with large net right-lateral slip (~600 km). Today, the fault creeps with surface rates approaching 3 cm/yr. The aseismic behavior is attributed to frictionally weak, velocity-strengthening fault-gouge minerals and an overall well-developed, straight fault geometry. The fault, however, takes an uncharacteristic 1 km right step through a network of geomorphically well-preserved, subsidiary en echelon normal faults over a distance of several kms on top of Mustang Ridge. Similar complexity is reflected in historical deep seismicity, highlighting bends in the fault geometry from ~5-10 km depth. The absence of seismicity in the upper ~ 5 km when compared to the south along-strike, as well as the ambiguity of current activity from the geomorphic expression of surface faulting, leave open questions regarding the distribution of active shallow subsurface slip and surface creep. With three-dimensional displacements from improved, higher spatial resolution (0.5 m) lidar differencing (2007 to 2018) complemented by UAVSAR measurements (2009 to 2022), we aim to connect the surficial geologic, deep seismologic, and historic geodetic records to present day deformation. Results both connect present day cumulative slip signature from the surface to seismogenic depths, and illuminate the structural evolution of the stepover through geologic timescales.

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Plate Boundary Geomechanical Model of Northern California Bay Area

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This project aims to improve understanding of fault slip rates at the complex and hazardous tectonic plate boundary in the Bay Area of northern California. Fault slip rates are the average movement along a fault per year. In order to better understand observed fault slip rate data and generate representative fault slip rates to improve seismic hazard mitigation, we are building a mechanical model that produces fault slip rates across this complex, plate-bounding fault system. This quasistatic model accounts for the constitutive behavior of the rocks surrounding the faults, as well as the conservation of mass and momentum. The complex, segmented, non-planar, 3D faults are free to slip together in response to applied plate motions. In this way, the model accounts for the communication of segmented faults with one another through stress transfer, as slip is partitioned across the complex system.

To generate this model, we used fault traces from the Geologic Deformation Model used in the 2023 National Seismic Hazard Model. Selecting the fault traces within a 200 km by 200 km region across the Bay Area, we translate our filtered fault traces to the Universal Transverse Coordinator system and use a Python script to convert the traces into a readable format for our meshing program. Subsequently, we verified our structural model by visually comparing our new faults to the original model. To run the mechanical models we will use Tandem, an elastostatic solver that utilizes a discontinuous Galerkin method and is optimized for High Performance Computing platforms. We will then compare our simulated slip rates with those gathered in the field that are included in the Geologic Deformation Model. Adjustments will be made to fault connectivity in order to achieve the most accurate seismic deformation model. With these efforts, we aim to better understand the 3D fault geometry of this region and improve seismic hazard mitigation in the Bay Area.

Fiber-optic Sensing Applications in Seismology

Oral Session • Tuesday 15 April • 8:00 AM Local

Conveners: Ettore Biondi, Stanford University, California Institute of Technology (ebiondi@caltech.edu); Xiaowei Chen, Texas A&M University (xiaowei.chen@tamu.edu); Jiaxuan Li, University of Houston (jli74@uh.edu); Yan Yang, University of California, San Diego (yanyang@ucsd.edu); Qiushi Zhai, California Institute of Technology (qzhai@caltech.edu)

Applications of Distributed Acoustic Sensing Using Dark Fiber in Dallas, Texas

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Distributed Acoustic Sensing (DAS) has recently been applied across a variety of geological and environmental conditions, including glacial, volcanic, borehole, submarine, and urban environments. Seismic monitoring using conventional broadband seismometers can be particularly challenging in urban areas due to limitations of land access. To evaluate the use of fiber optic sensing for seismic monitoring in urban environments, we monitored seismoacoustic signals in two neighborhoods of Dallas, Texas, using different configurations of Distributed Acoustic Sensing (DAS). For a 9-day pilot project in Plano, we tested a ~95 km pre-existing dark-fiber loop with an OptaSense QuantX strain Interrogator Unit (IU). Since August 2023, we have also been continuously experimenting with DAS on a ~2 km dark fiber at the Southern Methodist University (SMU) campus, deploying different configurations. The SMU DAS experiment captured both natural (e.g., earthquakes, thunderstorms) and anthropogenic signals (e.g., vehicular movements, building demolitions, subwoofers, football games). For several events, infrasound and conventional broadband measurements were made alongside the DAS measurements, enabling us to explore coupling effects. During these experiments, we observed some known and unknown challenges with using the commercial dark fiber to retrieve reliable estimates of ground motion. These include the presence of aerial fiber sections, slack fiber in handholes, and varying fiber cable coupling with the ground. We developed a computational solution to identify fiber sections unsuitable for ground motion retrieval and proposed criteria for applying frequency-wavenumber (F-K) transformation to convert DAS strain to ground velocities under different coupling conditions. The research works summarize the variety of signals we have detected and explore some applications of the signals for exploring seismoacoustic sources and subsurface structure.

Daily Groundwater Monitoring Using Vehicle-DAS Elastic Full-waveform Inversion

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Continuous groundwater monitoring is paramount for comprehending the hydrologic cycle and ensuring sustainable water management, particularly as climate extremes intensify. Despite advancements in geophysical monitoring techniques, limited high-resolution imaging and subsurface monitoring constrain our understanding of aquifer structures and dynamics. We introduce a novel, non-invasive method for high-resolution groundwater monitoring, enabling daily measurements of groundwater table fluctuations through time-lapse elastic Full-Waveform Inversion (FWI). This approach leverages existing telecommunication fiber-optic cables as dense seismic sensor networks and vehicular traffic as repeatable Rayleigh wave sources.

We demonstrated this method over a two-year monitoring period along Sandhill Road, California, capturing spatiotemporal variations in S-wave velocity. Our results revealed a 2.9% decrease in S-wave velocity, corresponding to an estimated 9.0-meter water table rise, driven by severe atmospheric river storms during Water Year 2022-2023. Notably, we detected a rapid water table increase following the intense rainfall on December 31, 2022. Spatial variability in seismic velocity changes correlated with surface conditions, showing minimal reductions beneath paved areas and more significant decreases under permeable grassy regions. This highlights the role of land use in modulating groundwater recharge. Our findings, validated through in-situ hydraulic head measurements and poroelastic simulations, demonstrate the potential of employing daily FWI with Vehicle-DAS surface waves for high-resolution groundwater monitoring, with the capability of quantitative aquifer characterization.

Detection and Source Characterisation of Crevasse Icequakes at an Alpine Glacier Using Distributed Acoustic Sensing

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Crevassing is an important mechanism that controls the stability of glaciers. If ice flows over suitable topography or pre-existing fractures are exposed to meltwater, then the ice can fracture. If these fractures open all the way to the bed, then they can provide pathways for meltwater to reach the bed, potentially driving further speed up of the glacier downhill and enhanced melting. Crevasse fracturing generates icequakes. However, studying the source characteristics of such icequakes is challenging as it is not normally feasible to deploy seismic instrumentation in crevasse fields. Fibreoptic sensing now makes deployments in crevasse fields logistically feasible. We present results from a dense 2D grid deployment of fibre within a crevasse field at Gornergletscher, Switzerland. Icequakes are first detected and located using back-migration, with 951 icequakes detected and located. We then explore new full-waveform inversion methods to refine event depths and obtain focal mechanisms. Furthermore, we quantify fracture mode and volumetric opening extent. We find that events typically exhibit tensile crack opening, consistent with expected crevasse fracture mechanisms. As well as direct P-wave and surface-wave energy, the waveforms contain strong coda. We attempt to isolate the origin of this coda, to decipher if it is associated with either: fluid resonance at the crevasse fracture site, or wavefield scattering off other crevasses within the wider crevasse field. Coincident seismic nodes were also deployed as part of the experiment, allowing us to compare the value of a dense, horizontally-sensitive 2D fibreoptic grid to an array of seismic nodes sensitive only to the vertical wavefield. As well as providing observations for assessing glacier damage due to crevassing, our work exemplifies the application of a new generation of tools for interrogating seismic source properties using fibreoptic sensing techniques. These tools will likely be applicable for studying fracture in other geological settings, from geothermal stimulation to CO_2 storage integrity monitoring.

Englacial Ice Quake Cascades in the Northeast Greenland Ice Stream - DAS Observations and Implications for Ice Stream Dynamics

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Ice streams are major contributors to ice sheet mass loss and critical regulators of sea level change. Despite their important, standard viscous flow simulations of ice stream deformation and evolution have limited predictive power, mostly because our understanding of the involved processes is limited. This leads, for instance, to widely varying predictions of sea level rise during the next decades.

Here we report on a Distributed Acoustic Sensing experiment conducted in the borehole of the East Greenland Ice Core Project (EastGRIP) on the Northeast Greenland Ice Stream. For the first time, our observations reveal a brittle deformation mode that is incompatible with viscous flow over length scales similar to the resolution of modern ice sheet models: englacial ice quake cascades that are not being recorded at the surface. A comparison with ice core analyses shows that ice quakes preferentially nucleate near volcanism-related impurities, such as thin layers of tephra or sulfate anomalies. These are likely to promote grain boundary cracking, and appear as a macroscopic form of crystal-scale wild plasticity. A conservative estimate indicates that seismic cascades are likely to produce strain rates that are comparable in amplitude to those measured geodetically, thereby bridging the well-documented gap between current ice sheet models and observations.

Monitoring of Tele-seismic Events Using Multiple Trans-oceanic Telecom Cables and Distributed Fiber Sensing

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We report the first demonstration of simultaneous measurement of teleseismic events on multiple operational telecommunication cables in the Atlantic and Pacific oceans. The total cable length exceeds 13,000km, creating a large-scale continuous deep-ocean seismic monitoring system with about 250 real-time stations. This is enabled by equipping each cable with a distributed fiber optic sensing (DFOS) prototype capable of measuring the integrated strain between each repeater (typically 40-80km) along the entire cable length. It is designed to be compatible with telecom traffic and does not impose any penalty in terms of bandwidth/performance. We form a roughly L-shaped array in the northern Atlantic by monitoring the 1770km IRIS subsea cable with 17 repeaters and a trans-Atlantic cable measuring about 6,500 km using around 120 repeaters. We also use a cable in the northern Pacific ocean with about 100 active repeaters. All cables are continuously monitored over a measurement period of several months.

Using several tele-seismic events, including the Dec 5th 2024 M7.0 earthquake in California, we analyze the response measured on each cable and compare it with land-based seismic stations close to the shore. We show the difference in sensitivity, both between separate cables as well as between different segments of the cable. Impact of cable deployment aspects on the sensitivity is investigated, showing that while each cable has areas with poor sensitivity, a substantial part of the available "sensors" record useful seismic data. We also provide quantitative analysis of the sensitivity of directionality of each cable. This is the first demonstration of simultaneous measurement of teleseismic events on multiple subsea cables in multiple oceans, showing that the technology is scalable beyond individual cables. The three cables used account for <1% of all cables world-wide, showing that DFOS over active telecom cables could be deployed to leverage hundreds of deployed telecom cables to create a global network with several thousands of stations on the ocean floor.

Characterizing Microearthquakes and Shallow Attenuation With Downhole Optical Fibers in the Cape Modern Geothermal Field

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We use Distributed Acoustic Sensing (DAS) on the borehole optical fibers to characterize microearthquakes at the Cape Modern geothermal field in Utah. The Cape Modern geothermal site is an enhanced geothermal system. In 2024, a series of stimulations at a 2.5 km depth generated events with M<3 between 1.5 and 3.5 km depth. The downhole fibers provide a dense network that records the wavefield between 0.5 and 2.5 km depth. The body-wave event spectra contain the high-frequency (< 500 Hz) energy required to characterize these small events. We use these spectra to estimate spectral stress drop, source radius, and moment magnitude with Brune's source spectral model. The spectral-ratio approach for source modeling is advantageous as it accounts for the wave propagation effects and instrument responses using a co-located small event as the empirical Green's Function (eGF). However, a qualified eGF-target event pair is often not available for microearthquakes. For source modeling using individual spectra, we need the medium properties to estimate the wave propagation effects. We obtain depth-varying attenuation, which was rarely directly observed from seismic data before DAS, by deconvolving event arrivals between DAS channels. The attenuation decreases with depth in the top 1.5 km of sediments. We investigate the source parameters as well as their variabilities between events and channels to estimate the uncertainties and to understand if there is a potential difference in the source physics. We examine the conversion between DAS strain and particle motions, which might distort the shape of the spectra depending on the gauge length and the medium properties. Stress drop for small events has been difficult to measure as shallow attenuating sediments suppress the high-frequency signals and limit the bandwidth crucial for characterizing small events. The downhole DAS, which provides broadband observations and a dense network for sampling the wavefield and the depth-varying medium properties, has great potential to advance our knowledge of the physics of microearthquakes.

Rapid Earthquake Magnitude Estimation From P-wave Strains: Comparing Borehole Strain Meters and DAS

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Distributed acoustic sensing (DAS) is a promising sensing technology for improving earthquake early warning (EEW) in offshore settings where maintaining seismic networks remains prohibitively expensive. Ascertaining precise earthquake locations using DAS data, however, remains a difficult task given the poor azimuthal coverage of these typically semi-linear arrays, and estimating earthquake magnitudes with DAS strain measurements is an unresolved problem requiring more research. Here, we introduce a method for discriminating large, potentially damaging, earthquakes from smaller events based on the first 4 seconds of strain waveform after a P-wave arrival without calculating earthquake locations. We train a suite of ensemble random forest machine learning models to predict whether borehole strain meter waveforms generated by local earthquakes (3.5<=M<=7.1) are from M>=5.4 events, then test the predictive models on DAS data (3.5<=M<=7). Our random forest features include the median, max, range, and minimum of continuous wavelet transforms scalograms filtered at three different bandwidths (0.2-0.5 Hz, 0.5-2 Hz, and 2-5 Hz) calculated over 4-second sliding windows and using 10 wavelet families (variations of Gaussian and Morlet wavelets), as well as the max and range of the strain amplitude, and whether the maximum strain is >= 10^5, 10^6, or 10^7. We discover that the power of coefficients of continuous wavelet transforms filtered at the lowest (0.2-0.5 Hz) frequencies is the strongest predictor of larger magnitudes, capturing both long-period dynamic strains and near-field, static deformation. The reliability and precision of our offline results are comparable to real-time EEW operational systems and could be a useful strategy for employing DAS for EEW in both terrestrial and offshore environments.

Detecting and Locating Earthquakes using Machine Learning Workflow and Offshore Distributed Acoustic Sensing

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Offshore distributed acoustic sensing (DAS) has emerged as a powerful tool for seismic monitoring, but its application to continuous regional earthquake detection and location faces several major challenges. First, the earthquake data on offshore DAS is often contaminated by complex noise signals originating from ocean dynamics and instrumentation. Second, the spatial coverage of DAS observations is constrained by the sensing range. Third, the limited availability of offshore dark fibers for long-term deployments poses practical challenges.

To address these issues, we developed a machine-learning-based workflow that denoises DAS data, picks seismo-acoustic phases from both DAS and ocean-bottom seismometer (OBS) recordings, and integrates DAS and seismic networks for earthquake association and location. Using DAS recordings from fiber-optic cables in the Cook Inlet, Alaska, the denoising model was trained with randomly masked channels. The denoised data exhibited a 2.5 dB average increase in S-wave signal-to-noise ratio, enabling 2.7 times more S picks for 1 month of cataloged earthquakes compared to the raw data. Over six months, the generated earthquake catalog delineated the Alaska subduction zone plate interface from the surface to a depth of 150 km, revealing ~50% new events not included in the ANSS catalog.

Building on this work, we explored the feasibility of using optical multiplexing to overcome the limitations of dark fiber availability. In May 2024, we conducted a four-day DAS experiment on the Ocean Observatories Initiative's Regional Cabled Array offshore Oregon, employing an L-band DAS interrogation with optical multiplexing. The collected data maintained the same high quality as traditional dark fiber DAS while preserving full telecommunication functionality. Applying the same monitoring workflow, we identified T waves and the S waves of 31 regional earthquakes, demonstrating the potential of multiplexed DAS for continuous seismic monitoring. These studies highlight the transformative potential of advanced machine learning workflows to improve offshore earthquake monitoring.

Coherence-based Earthquake Location Using Integrated Fiber-optic and Conventional Seismic Networks

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Distributed Fiber-Optic Sensing (DFOS) is an emerging technology able to provide detailed images of the seismic wavefield. Although standard (channel-wise) seismic data analysis procedures based on phase picks can be adapted for DFOS systems, their performances may be hindered by the effects of optical noise, cable coupling, and axial directivity. Furthermore, pick-based approaches do not fully exploit the primary advantage of DFOS, the high-density spatial sampling along the fiber.

Coherence-based approaches, which stack energy along theoretical travel-times, provide significant advantages for dense seismometer networks in constraining event locations on a 3D grid. However, DFOS systems have far more channels than conventional networks of seismometers, hence the direct use of coherence-based methods on DFOS data can be computationally demanding. Despite these challenges, the integration of DFOS and standard seismometers represents the next-generation paradigm for seismic monitoring. Possible solutions comprise a) improvements in computational efficiency and/or b) DFOS automatic data selection and decimation.

Here, we present preliminary tests of a coherence-based locator that better adapts to DFOS alongside standard seismometers. Efficiency of the method on DFOS data is achieved considering a cylindrical symmetry to compute 2D travel-time lookup tables (horizontal distance, depth), while retaining a 3D grid to sum the contributions of the individual DFOS waveforms (coherence map). We mitigate potential bias in event location when using DFOS and seismometers, arising from the different number of measurement sites, by assigning a balancing weight. Data sub-sampling is additionally considered for rectilinear cable sections.

Deep Learning for Distributed Acoustic Sensing Data Compression

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Distributed acoustic sensing (DAS) is emerging in seismic monitoring due to its ultra-dense spatial sampling, durability to harsh environments, and sensitivity to weak ground vibration. Compared with traditional nodal geophones that are normally sparsely distributed, DAS offers unprecedented detectability for small-magnitude earthquake events, very subtle reservoir dynamics, and other weak signals among various applications. The appealing detectability of weak signals is compromised by the terabyte-scale daily continuous record that causes prohibitive storage problems. The current solution is to save only the segmented data of interest, e.g., a certain length around a target event. Here, we tackle the urgent storage problem of DAS monitoring by designing a deep-learning (DL) based compression algorithm. The compression algorithm can be split into two major components. The first part is the encoder based on the vision transformer architecture, where the input multi-channel DAS dataset goes through an encoding process to output the key features from the input. The second part is the decoder, where the features are optimally combined to reconstruct the data of the original scale. The optimal network parameters are obtained via an unsupervised training process, aiming at minimizing the difference between the reconstructed and input data. In the proposed DL-based compression algorithm, only the decoder's weight parameters and extracted features from the input data through the encoder are saved on the disk, which is sufficient to reconstruct a high-fidelity dataset. The proposed compression algorithm can reach around 50 times the compression rate for a gigabyte-scale DAS dataset without unsatisfactory reconstruction performance.

Fiber-optic Sensing Applications in Seismology [Poster]

Poster Session • Tuesday 15 April

Conveners: Ettore Biondi, Stanford University, California Institute of Technology (ebiondi@caltech.edu); Xiaowei Chen, Texas A&M University (xiaowei.chen@tamu.edu); Jiaxuan Li, University of Houston (jli74@uh.edu); Yan Yang, University of California, San Diego (yanyang@ucsd.edu); Qiushi Zhai, California Institute of Technology (qzhai@caltech.edu)

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Detection and Characterization of Ice-related Seismic Signals Using Distributed Acoustic Sensing Offshore Beaufort Sea, Alaska

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The Arctic is a relatively inaccessible environment, covered in ice nearly year-round, which poses logistical challenges for instrumentation and operations. Sandia National Laboratories currently operates a fully remote distributed acoustic and temperature sensing system along a pre-existing segment of telecommunication fiber optic cable extending from Oliktok Point, Alaska ~37 km into the Beaufort Sea. This provides a unique opportunity for bottom-up monitoring, including subsurface permafrost and sea ice, with direct implications for climate and national security. Here we focus on ice related signals we recorded over five months during the 2023 PEMDATS deployment. These events span three Arctic seasons, when the Beaufort Sea is entirely covered in ice (February through April), during ice break up (July through August), and during a period of open water (September). DAS signals are dominated by icequakes during the full ice coverage season, many of which occur in distinct swarms resulting from thermal variations in ice driven primarily by changes in air temperature. Acoustic signals during ice break up reflect icequakes, ice collisions, and ice grounding events. The open water season contains few acoustic events, highlighting the ice-driven nature behind the quantity of acoustic signals recorded in the shallow Arctic during this time range. This multi-season catalog of ice-related signals demonstrates the utility of DAS in monitoring ice behavior in the Arctic. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

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Subsurface Source Characterization Using Distributed Acoustic Sensing

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Accurate characterization of underground seismic energy sources is crucial for understanding seismic wave propogation in subsurface tunnels and mitigating the impact of anthropogenic noise on desired signals. In this study, we utilize a subsurface distributed acoustic sensing (DAS) array to monitor and characterize various underground facility operations, including drilling, ventilation fans, conveyor systems, and personnel movements. Traditional seismic detection and geolocation methods are optimized for high-energy energetic impulsive signals (e.g., blasts and earthquakes) under stationary noise conditions. However, machine operations typically generate continuous, low-amplitude, spectrally discrete signals, posing unique challenges. We demonstrate a technique that leverages changes in specific regions of the power spectral density (PSD) to detect and characterzie anthropogenic activity in DAS data. This PSD-based approach effectively identifies events with distinct frequency signatures, even when signals overlap temporally or exhibit dynamic frequency content. Given the inherit sensitivity of DAS to axial strain, we also analyze amplitude attenuation with distance to assess wave propogation effects from anthopogenic activities. Leveraging the high spatial resolution and 3D geometry of the DAS array provides valuable insights into source propagation dynamics in the subsurface. Understanding the frequency characteristics and amplitude attenuation of anthopogneic sources enhances the ability to interpret source propogation effects, enabling better isolation of signals in complex underground environments.

POSTER 54

Mapping Fault Dynamics: Very High Seismicity Detected Along the Kefalonia Transform Faul With DAS and Template Matching

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The Kefalonia Transform Fault (KTF), a 150-km long tectonic boundary connecting the Adriatic and Aegean plates, is characterized by slab tearing and significant seismic activity. Earthquake sequences in the region are clustered along the fault, yet the local earthquake catalog records remain sparse.

From April 23 to June 22, 2024, we conducted a two-month Distributed Acoustic Sensing (DAS) experiment on Kefalonia Island using a 15 km dark fiber network—7 km along a roadway and 8 km across the seafloor. By applying the STA/LTA method to marine DAS data, we detected ~10,000 high-frequency (5–20 Hz) events. Event clustering using pairwise correlations, combined with the local earthquake catalog, revealed six spatially distinct seismic clusters, each associated with specific fault segments.

Using these clusters as templates, we developed a new template matching workflow to expand the earthquake catalog to ~20,000 events, significantly increasing the detection of small-magnitude earthquakes. Each cluster highlights seismic activity on distinct fault segments and reveals foreshock and aftershock sequences for ML >2.5 events.

The refined catalog, with 100 times more events than the original local catalog, provides unprecedented temporal and spatial resolution of seismicity along the KTF. These results offer new insights into fault segment interactions and the processes of stress accumulation and release in the KTF system.

POSTER 55

Chirped-pulse DAS for Ambient Noise Tomography

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Subsurface imaging is a powerful tool for terrain studies, revealing essential information about geological processes and material composition of the soil. Ambient noise interferometry (ANI) has emerged as a reliable technique to extract subsurface information without the need for active seismic sources. As high-resolution ambient noise tomography requires an extensive and dense detector array, distributed acoustic sensing (DAS) results in a cost-effective solution to seismic noise measurements. It provides high spatial resolution (~10m) and large distance measurement capabilities (10s of km) with a simple and non-invasive deployment. While DAS is a powerful tool for seismic measurement, it presents several inherent disadvantages such as non-linear measurements, non-uniform SNR and the presence of random fading points along the measured fiber. Chirped-Pulse DAS technology overcomes all these challenges, providing a linear and quantitative measurement.

For this study, a dark fiber on the trackside of a high-speed railway in Spain was monitored for a full 24-hour period. Raw data from the interrogator unit was then analyzed with a full ANI algorithm as follows. Firstly, data was filtered both in the frequency and spatial domain, restricting the range of interest to common frequencies and wavelengths for surface seismic waves. After that, FK filtering was applied, which allowed for a dispersion velocity filtering, enabling for low velocity signals such as trains to be discarded. Temporal normalization and spectral whitening were then applied to the dataset, so all noise sources contribute to the final data equally. Cross-correlations between signal from adjacent spatial points were then computed, obtaining a full map where signals propagating through the surface can be observed. Phase-weight stacking was employed to reduce the total number of needed files to obtain a clear correlation map. Once the 24-hour period was analyzed and stacked, slant-stacking was employed to compute a dispersion velocity map, showing at least two different dispersion relationships, revealing different layers of the surface structure.

POSTER 56

Submarine Volcano Monitoring With Distributed Acoustic Sensing at Kolumbo, Greece

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We present the results of an experiment with Distributed Acoustic Sensing (DAS) at Santorini and Kolumbo in Greece and the potential of DAS to augment existing seismic monitoring networks. Kolumbo is an active submarine volcano in the Aegean Sea, and its vicinity to the densely populated island of Santorini emphasizes the need for continuous monitoring.

A 45 km long fiber-optic cable connects the islands of Santorini and Ios, where we acquired data for two months (October – December 2021). Here, we discovered around one thousand events, using an automated earthquake detection algorithm that is based on image processing techniques. DAS reveals an approximate doubling in the number of events detected. Surprisingly, DAS detects many distant events of low magnitudes, while it also misses several larger and nearby events that the existing network does record. Manually picked first arrivals are combined with a travel-time look-up table based on a 1D velocity model to conduct a grid search to locate the events. The ability to locate events depends heavily on the fiber layout and source location, which we verify with synthetic tests. Finally, we compare the performance of DAS to the existing seismic network to locate events, showing that the addition of DAS can refine the event localization.

The results of our experiment highlight the potential of DAS to complement existing monitoring networks to study active submarine volcanoes by locally lowering the detection threshold of a network and decreasing the uncertainty in the event locations.

POSTER 58

Aquifer Monitoring With DAS: A Case Study From Lyon Water Catchment

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Distributed Acoustic Sensing (DAS) arrays combined with passive seismic techniques provide a novel and effective method for subsurface imaging and monitoring. This study focuses on leveraging ambient seismic noise recorded by a spiral DAS array to monitor groundwater dynamics in a shallow aquifer. The research was conducted at the Crépieux-Charmy water catchment, a critical site for water supply in the Lyon metropolitan area, in France.

Our study aimed at tracking the spatiotemporal dynamics of the hydraulic dome induced by controlled infiltration in a basin. Over a period of four weeks, a controlled water infiltration experiment was carried out by the site operators. During this period, DAS ambient noise data were collected from a 3 km spiral fiber-optic array surrounding the infiltration basin. By analyzing traffic noise in the 2–20 Hz frequency band, we performed time-lapse 2D surface wave tomography to map velocity variations in the vadose zone.

The results showed a strong correlation between seismic velocity variations and independent piezometric measurements, highlighting changes in the water table and unsaturated zone water saturation. This pilot study demonstrates the potential of combining DAS with passive seismic for high-resolution monitoring of aquifer dynamics.

POSTER 59

A Hybrid Deep Learning Framework for Denoising Distributed Acoustic Sensing Data

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Distributed Acoustic Sensing (DAS) is a powerful tool in seismic monitoring, enabling high-resolution strain detection over long distances with fiber-optic cables. This cost-effective technology has diverse applications in seismology, but DAS recordings are often affected by erratic and horizontal noise, compromising their effectiveness in seismic analyses.

To address these challenges, we propose a hybrid denoising framework that combines traditional signal processing techniques with advanced deep learning. The core of the framework builds on Deep Image Prior (DIP), an unsupervised deep learning method that excels at mitigating random noise. However, DIP struggles with complex, overlapping noise types due to limitations in network design and hyperparameter sensitivity. To overcome these issues, we integrate DIP with a Multi-Head Attention Regression Network (MH-ARN), which incorporates fully connected layers and multi-head self-attention blocks to capture significant details in DAS data.

Our approach starts with dynamic patch-based processing using Non-Local Means (NLM) for high-frequency noise suppression. A variance-based patch selection targets signal-rich regions for training. Horizontal noise is mitigated through a frequency-wavenumber dip (FK-dip) filter applied after the first iteration, with iterative MH-ARN refinements ensuring effective noise suppression.

Applications to synthetic and real-world DAS datasets from the FORGE geothermal field show that our framework significantly improves the signal-to-noise ratio while preserving key details. It outperforms conventional DIP and integrated denoising methods, which combine operators like band-pass, structure-oriented median, and FK-dip filters. This multi-step process enhances signal quality and overcomes the limitations of traditional DIP methods, offering a robust solution for complex noise in DAS applications.

POSTER 60

Preliminary Shallow Seismic Imaging at Los Alamos National Laboratory Using Distributed Acoustic Sensing

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The characterization of near-surface geology is crucial for assessing seismic hazards and monitoring transient signals. Distributed acoustic sensing (DAS) has proven to be an effective tool for generating the high-resolution imaging needed for detailed near-surface studies. In this work, we examine the challenges of using DAS for shallow imaging in the highly attenuative geologic environment at Los Alamos National Laboratory (LANL). LANL is located on the eastern edge of the Valles Caldera in northern New Mexico, USA, a caldera formed by two major eruptions approximately 1.6 and 1.2 million years ago, which produced ~330 m thick units of tuff on which the lab presently resides on. The tuff's high seismic attenuation has made it difficult to accurately image subsurface fault structure, with many previous active seismic surveys yielding limited results. In this study we use data from two DAS interrogators, a Silixa iDAS v2 and Terra15 Treble+, deployed on 5.6 km of dark fiber at LANL in 2024 to compute dispersion curves from ambient noise cross-correlated channels along the fiber. Preliminary findings reveal robust cross-correlation functions along approximately 4 km of the fiber at frequencies of 1 to 25 Hz. The interrogators record data in different units, strain rate (Silixa iDAS v2) and velocity (Terra15 Treble+) allowing for us to assess the impact on our dispersion analysis.

POSTER 61

Bayesian Inversion of Microseismic Events at the FORGE Geothermal Site

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Enhanced geothermal systems (EGS) show great potential as a possible source of low-carbon energy. However, they are only economically feasible where the hot rock is sufficiently permeable for economical amounts of fluid to pass through and accumulate heat. In EGS systems, hydraulic fracturing is used to create this permeability. Accurately characterizing the locations of microseismic events during hydraulic fracturing in EGS allows for a better understanding of the fracturing process and provides guidance to EGS operators. Limited understanding of velocity models and limited spatial coverage of monitoring stations can lead to significant microseismic location uncertainty. Bayesian inference is a widely used approach in inverse problems and model parameter estimation which yields estimates with uncertainty analysis.

We applied the Slice Sampling method to locate events in the Utah FORGE April 2022 microseismic data, which includes both downhole and surface monitoring using both distributed acoustic sensing and traditional seismometers. Our analysis provides a posterior distribution of the source locations. To better understand the limitations of this technique, we present several synthetic test results to evaluate the localization uncertainty under varying receiver geometries and noise levels in the arrival time data.

Results indicate that the Slice Sampling method successfully captured the uncertainty in event locations, and the joint analysis of surface and downhole data significantly reduced the uncertainty of event location. This improved location accuracy may enable better mapping of fractures and more efficient optimization of hydraulic stimulation strategies. Our findings demonstrate the potential of integrated Bayesian approaches for advancing EGS monitoring and development.

POSTER 62

Preliminary Analyses of Source Mechanism Effects on Fracture Dynamics in Mines Using Distributed Acoustic Sensing

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Distributed Acoustic Sensing (DAS) has emerged as a potentially transformative technology for seismic monitoring in mining environments, leveraging fiber-optic cables to provide real-time, cost-effective, and scalable insights into rock rupture processes. This study employs synthetic seismic modeling to explore the efficacy of DAS in analyzing fracture dynamics and seismic source mechanisms in an underground mine setting. Using the numerical solver ELM2D-DAS, we perform waveform simulations of DAS data from different source-receiver geometries.

We model seismic events within the mine using DAS receiver arrays strategically deployed on the surface and in boreholes. Early results suggest DAS can record a wide range of frequencies with high resolution, giving important insights into rock behavior and rupture processes essential for early failure. Key challenges include seismic velocity model uncertainty, accurately representing geometry and parameters and addressing uncertainties in source mechanism inversion.

Our approach provides a baseline for designing underground DAS arrays for source mechanism inversion, assessing the reliability of DAS-based seismic interpretations to inform safer mining practices. Future work will integrate this study with field seismic data, focusing on the challenges posed by seismic velocity model accuracy and source characterization uncertainty in three dimensions.

POSTER 63

Imaging the Fault Zone Structure of the Shanchio Fault in Taipei Metropolis Using Dark Fiber Distributed Acoustic Sensing

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The Taipei Metropolis that accommodates around a quarter of Taiwan's population sits on a sedimentary basin bounded by an active normal Fault, the Shanchiao Fault, to the west. While the Shanchiao Fault is capable of generating M 6+ earthquakes, its geometrical and structural characteristics remain poorly constrained due to the absence of outcrops covered by Quaternary alluvial deposits and the lack of high-resolution seismic data. The presence of soft sediments within sedimentary basins and the complex structure of the fault zone both play key roles in modulating seismic waves, resulting in strong amplification and prolonged durations of ground shaking to Taipei city. Here, we utilize the emerging Distributed Acoustic Sensing (DAS) technology to turn an existing telecommunication cable into an ultra-dense linear array across the Shanchiao Fault to investigate the fault and basin structure at unprecedented resolution. We use the ambient noise cross-correlation and beamforming analysis to measure Rayleigh-wave phase velocity dispersion curves along the cable, which are then inverted to obtain a high-resolution 2-D shear-wave velocity profile across the fault. The results show a clear velocity contrast between the Taipei Basin and the Linkou Tableland, delineating the east-dipping geometry and possible damage zone of the Shanchiao Fault. Further spectral ratio analysis also shows obvious frequency-dependent site amplifications on the side of the Taipei Basin. Our results demonstrate the capability of using ubiquitously existing telecom cables to map detailed fault zone structure and ground motion amplification, which are crucial for urban hazard reduction.

POSTER 64

Fiber-optic Sensing of Repeating Icequakes and Firnquake Swarms at the South Pole

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Glacier seismic activity, ranging from deep ice to shallow firn (rounded and well-bonded snow that is older than one year), provides critical insights into cryospheric dynamics and offers a means to study its responses to and impacts on climate change. In this study, we employed distributed acoustic sensing (DAS) technology, which transformed an 8-km optical fiber into a dense array of thousands of strain sensors, for long-term seismic monitoring at the South Pole. Over one year of continuous recordings in 2023, we detected tens of icequakes and hundreds of firnquakes. Two groups of repeating icequakes were identified, likely driven by basal glacial stick-slip in this slow-moving glacier zone of the Antarctic interior. Our findings also revealed the strong impact of extreme atmospheric weather events on firn activity in the shallow cryosphere. Specifically, the coldest weather events triggered three swarms of firnquakes near the Amundsen–Scott South Pole Station. By applying array processing techniques to the DAS data, we detailed these icequakes and firnquakes and investigated their physical mechanisms. This study demonstrates the potential of long-term DAS observations to advance the understanding of cryoseismic events driven by interactions among the atmosphere, cryosphere, and lithosphere in polar and glacial regions.

Fifty Years and Beyond of Broadband Seismic Instrumentation: Performance, Precision and Uncertainties

Oral Session • Wednesday 16 April • 4:30 PM Local

Conveners: Akobuije Chijioke, National Institute of Standards and Technology (akobuije.chijioke@nist.gov); Margaret Hellweg, University of California, Berkeley (hellweg@berkeley.edu); John Merchant, Sandia National

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Low-uncertainty SI-traceable Seismic Measurements

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Traceable measurements provide results in terms of known references and with a quantified uncertainty. We will present an overview of SI-traceability, its benefits, and with particular attention to seismometry. We will consider the various contributors to the uncertainty of a measurement, and contrast primary and secondary measurements. Following this, we will outline ongoing work at NIST that is relevant to seismic measurements.

Methods for Laboratory Seismometer Calibration Traceable to the Si – a Current Overview of Challenges and Solutions

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Over the past 5 to 10 years the topic of traceable calibration of broadband seismometers gained more and more attention from the vibration metrologists from various national metrology institutes (NMI). As a consequence an increasing global effort could be seen in the development of calibration methods and and calibration chains with the goal to link seismic measurements to the international system of units. PTB, the German NMI was among the active protagonists of this development taking the lead in regional research projects and setting up several adapted national standards in its own laboratories.

This contribution will give an overview of the current state of the art in laser-interferometric and tilt-based primary calibration as well as in secondary calibration of broadband seismometers as far as measurements in the laboratry are concerned. we will explain the challenges and experimental efforts and summarize the final steps needed to establish a complete traceability chain for seimological measurements.

Challenges in Seismometer Electrical Calibration

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Seismometer electrical calibration at IMS stations has long been depended upon to ensure the accuracy of seismometer performance. At best, electrical calibrations provide confidence that the seismometer performance has not changed since the time of installation. However, as an absolute measure, electrical calibrations may not result in a sufficiently accurate or traceable measure of seismometer performance, even when accounting for the manufacturer provided response models. As an example, we consider the instrumentation configuration for the planned recapitalization of the primary seismic station PS47, NVAR. The NVAR array is comprised of multiple elements with short-period Geotech GS13 seismometers in boreholes and recorded on Geotech Smart24 digitizers. The plan is to replace the Smart24 data recorder with a high-gain Nanometrics Centaur digitizer. Here we show the results from a primary traceable calibration of a GS13 seismometer from NVAR to validate the nominal response, confirm the influence of the digitizer replacement on the seismometer performance, and quantify the impact of these changes on the electrical calibration.

Advancements in Quality Assurance for the Comprehensive Nuclear-test-ban Treaty International Monitoring System and Calibration Challenges for Seismic and Infrasound Technologies

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The International Monitoring System (IMS) network of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) relies on four technologies: seismic, infrasound, hydroacoustic and radionuclide. The draft IMS Operational Manuals for waveform technologies outline the requirements for establishing, maintaining and verifying the performance of IMS stations. Since 2011, the Provisional Technical Secretariat (PTS) for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) has collaborated with the global community to establish a robust quality assurance framework for IMS measurements, with focus on infrasound technology: significant progress in setting standards and refining calibration methods was achieved.

Recent PTS activities focused on seismic technology. The IMS seismic stations are required to perform regular calibration, maintaining a maximum deviation of five percent in amplitude and five degrees in phase over the frequency range relevant for detecting nuclear explosions. This necessitates precise calibration processes to ensure consistent measurement standards between IMS facilities.

Currently, seismic stations undergo electrical calibration once a year. However, this approach is not traceable and may not capture long-term trends influenced by multiple factors. Alternative or complementary methods, such as calibration by comparison already used in infrasound technology, might provide additional insights and support long-term measurement accuracy for seismic technology.

This work reviews recent advancements in seismic sensor quality assurance and invites the seismic community to collaborate on developing alternative calibration methods to improve traceability and measurement reliability.

Calibration Techniques in the Manufacture and Field Use of Seismic Instruments

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Calibration of seismic networks relies on cooperation of manufacturers, network operators, and certified laboratories. These parties must work together to measure key instrument parameters, quantifying errors that affect accuracy and precision, ideally with traceability to SI standards. Some techniques used in manufacturing cannot be used in the field, such as calibration at the internal sub-assembly or component level. Some techniques must be applied in the field to reconfirm correct in-situ operation, quantify any change in parameters due to aging or equipment degradation, and optionally apply corrections for environmental variables such as temperature. Testing seismic instruments at certified laboratories provides an independent reference.

Considerations in the manufacturing process include: (1) Uncertainties: how they arise and the impact on accuracy and precision; (2) Calibration methodologies available and their practical implementation; (3) Quality assurance in the factory calibration process; (4) Metrics to consider: sensitivity, relative transfer function, timing, calibrator features, alignment.

We discuss how these methods can be adapted for field use, with a focus on two challenges:

(1) Electrical versus ground motion calibration. Electrical calibration measures some parameters more accurately, but does not provide an independent measurement of all parameters. Ground motion should ideally be the measure of seismic performance, but has large errors in practice due to factors such as difficulty in separating site response from instrument response. We propose a combination of techniques, with use of multiple sensors to cross-check measurements.

(2) Temperature dependence of instrument sensitivity, as recently highlighted in two presentations at AGU 2024 (Slad; Shimoda). This is attributable to temperature dependence of permanent magnets used in force-feedback seismic sensors. This small effect can be characterized, and corrected if desired by periodically updating sensitivity metadata, using modern seismic sensors that include an internal temperature reporting capability.

Fifty Years and Beyond of Broadband Seismic Instrumentation: Performance, Precision and Uncertainties [Poster]

Poster Session • Wednesday 16 April

Conveners: Akobuije Chijioke, National Institute of Standards and Technology (akobuije.chijioke@nist.gov); Margaret Hellweg, University of California, Berkeley (hellweg@berkeley.edu); John Merchant, Sandia National Laboratories (bjmerch@sandia.gov); Xyoli Pérez-Campos, Comprehensive Test Ban Treaty Organization (xyoli.perez.campos@ctbto.org)

POSTER 138

Comparison of the Performance of a Wide Range of Sensors in Various Applications in the Field of Earthquake Engineering, From Low-noise to 2 G

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There are no bad seismic sensors... but there are sometimes bad uses for them! Seismic instrumentation plays an important role in many areas of seismic hazard, from the measurement of weak ambient vibrations (e.g. for the implementation of non-invasive site characterization methods) to the recording of strong seismic motions. The most sensitive, high-performance instruments are often the most expensive, and when the number of sensors required for a study increases but budgets remain constant, low-cost sensors can also be a welcome addition. We present various tests carried out on a wide range of sensors, from broadband seismometers to MEMS accelerometers, including geophones and force-balanced accelerometers. These studies range from self-noise measurements in a low-noise seismic vault up to shake-table tests at 2g. We comment on our results, not only in terms of the intrinsic quality of each sensor, but also from the viewpoint of their suitability for different applications. Our study focuses on the 0.1-100 Hz frequency band.

POSTER 139

Guralp Stratis - a Commercial 6 Degree of Freedom Seismometer for Academic and Research Applications

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Traditional research grade 3-component seismic sensors by their very design are sensitive to both translational ground movement as well as rotational (or tilt) motion. This is most prevalent in the horizontal components of sensors which are most sensitive to tilt of the ground. The outputs of traditional seismometers represent a sum of rotation and displacement information. Most applications processing the data make the assumption that the outputs are proportional to purely displacement although this is not strictly the case in commercial devices.

New technologies are now allowing for accurate and precise discrimination between the two components which make up the vast majority of seismic records.

Stratis is the world's first integrated seismic sensor offering simultaneous output of both rotational and displacement data in all 3 axis. Stratis offers six concurrent outputs providing Z, N and E ground displacement channels proportional to velocity (Metres/second) and rotation channels in the Z, N and E planes proportional to velocity in rotation (Radians/Second). The provision of the measurement of the six degree of freedom now permits derivation of the Elasticity Tensor from a single sensor.

The Stratis displacement output removes these rotation effects and gives a 'pure' displacement measurement. This is unique in the seismic sensor marketplace, providing true displacement data that is uncontaminated by rotational signals. This will therefore allow for higher fidelity seismic measurements, improving our analysis and understanding of earthquake processes.

These six parameters are measured at a single point in the geometric center of the sensor. Use of multiple separated sensors to derive rotation can only approximate true rotation at the same point as displacement. By integrating these measurements into a single instrument, the installation process is also greatly simplified thereby enabling wider access to rotational seismic data. Naturally, the separation of rotational information from the displacement outputs also gives a pure displacement sensor – something unique for the seismological community.

From Physics to Forecasts: Advancements and Future Directions of Induced Seismicity Research

Oral Session • Tuesday 15 April • 8:00 AM Local

Conveners: Stanislav Glubokovskikh, Lawrence Berkeley National Laboratory (sglubokovskikh@lbl.gov); Jeremy Gosselin, Natural Resources Canada, Geological Survey of Canada–Pacific (jeremy.gosselin@nrcanrncan.gc.ca); Ian Main, University of Edinburgh (Ian.Main@ed.ac.uk); Alexandros Savvaidis, University of Texas at Austin (alexandros.savvaidis@beg.utexas.edu); Jake Walter, Oklahoma Geological Survey, University of Oklahoma (jwalter@ou.edu)

Interpretable Deep Learning Framework for Forecasting Induced Seismicity in Geothermal Fields

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Induced seismicity presents a critical challenge in geothermal reservoir management. The occurrence of large seismic events poses public safety concerns. Forecasting induced seismicity provides valuable information for operators as well as better insights of the mechanisms of induced seismicity. Current physics-based approaches require heavy computation and detailed knowledge of the subsurface structure for accurate modeling of induced seismicity. Statistics-based approaches often provide better accuracy, but nonlinear relationship between injection parameters and seismicity provide difficulties.

In this study, we adopt a data-driven deep learning framework to forecast induced seismicity rates in geothermal fields such as Utah FORGE and the Geysers fields. Building on a modified Temporal Fusion Transformer (TFT) architecture, this approach integrates all the available geological and operational parameters, including historical seismicity and operational metadata, to predict future rates of induced seismicity. The model$B!G(Bs built-in attention mechanism identifies key contributing factors, enabling interpretable insights into the induced seismicity, without requiring prior assumptions about the importance of input features. Our approach forecasts the spatiotemporal distribution of seismicity rates by partitioning the study region into grids and associating input data with corresponding grid locations. The model processes static covariates (e.g., well locations), time-dependent past observations (e.g., historical seismicity and injection rates), and known future inputs (e.g., planned injection schedules). Outputs include probabilistic predictions across multiple quantiles, providing a estimation of uncertainty under various operational scenarios. This interpretable framework not only demonstrates superior predictive performance but also enhances understanding of the mechanisms underlying induced seismicity. It serves as a robust tool for risk mitigation and improved reservoir management strategies in geothermal operations.

Modeling and Forecasting Wastewater Disposal Induced Seismicity in the Delaware Basin

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Due to advancements in horizontal drilling and hydraulic fracturing, hydrocarbon production in the Delaware Basin of West Texas and Southeast New Mexico, a subbasin of the Permian Basin, has surged over the past decade and is expected to continue growing in the foreseeable future. As a byproduct, considerable amounts of wastewater brine are produced that require disposal into subsurface reservoirs. Current disposal target formations include siliciclastic rocks of the Delaware Mountain Group above the producing shale

intervals and deeper carbonate rocks of the Ordovician (Ellenburger) through Devonian above the basement. Seismicity in the region, which in places has exceeded M5, has been primarily associated with wastewater disposal. Here, we focus on basement seismicity in Culberson County and model it with a stress-driven 3D geomechanical model based on rate-and-state friction. First, we determine the pore pressure evolution from a flow model using a realistic stratigraphic framework and history match to bottom hole pressure measurements . Next, we estimate Coulomb stress changes on the fault planes where earthquakes are occurring using finite element modeling, including poroelasticity. Then, we relate Coulomb stress changes to the observed declustered seismicity using a stress-driven model based on rate-and-state friction. Our models can be used to test different possible triggering factors such as direct fluid triggering or poroelastic triggering. Our results suggest that induced seismicity in Culberson County is primarily driven by pressure diffusion from deep disposal rather than through poroelastic stress transfer, implying fluid migration to the basement. Curtailment of deep disposal in Texas since 2022 has resulted in a declining trend of induced seismicity. However, impacts from deep injection in New Mexico cannot likely be ignored as a potential factor moving forward.

Managing Induced Earthquake Potential with Deep Graph Neural Networks

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Earthquakes of societal and regulatory concern continue to occur in the unconventional oil fields of the U.S. In 2024 alone, 16 magnitude 4+ earthquake including 3 larger than magnitude 5 occurred in Oklahoma, Texas and New Mexico. Most of these events can be linked to deep injection of oilfield wastewater. Also of note was a M_W 4.6 event in the Eagle Ford of Texas, now the largest frac-induced earthquake in North America. As problematic seismicity continues to occur despite attempts to manage it through reductions in deep disposal, industry and regulators alike have expressed the need for better methods to identify areas with increasing potential for large magnitude earthquakes with sufficient lead time to take actions to mitigate the hazard.

In our study, we focused on employing deep learning techniques to explore the complex, non-linear relationships between injection activities and earthquake hazards in Oklahoma. Our primary aim during model development has been to develop a model that incorporated disposal/production data that outperforms baseline earthquake hazard estimators based solely on seismicity rate. We developed an attention-based graph neural network (GNN) model "*InFormer*" that utilizes two attention mechanisms: one temporal, and one spatial. This architecture allows encoding of both long-term and long-distance context to capture far-reaching relationships. A simple rolling mean of seismic activity is used as a baseline for comparison with training results. Results are encouraging for models trained with a 6-month context and a 3-month forecast horizon. These initial experiments illustrate the potential of deep learning to forecast evolving earthquake hazard by leveraging temporal injection histories. By incorporating deep nonlinearities on the feature set, *InFormer* demonstrates strong temporal generalization, achieving 30% to 40% improvement in model validation over 3-month and 6-month rolling mean baselines. Transfer learning continues to be challenging, as the seismicity response to a given volume of injected wastewater in different areas may deviate significantly.

Modeling and Forecasting Induced Seismicity in the Midland Basin, Texas and Oklahoma

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Earthquakes can be triggered by human activities such as injection or extraction of fluids into or from the subsurface, in particular in relation to oil and gas operations. These earthquakes can result from pore pressure diffusion or stress perturbations due to poroelastic effects. Here, we present a modeling framework which calculates stress changes resulting from various subsurface operations (i.e., wastewater disposal, hydraulic fracturing, conventional and oil and gas unconventional prodcution), and forecasts induced seismicity at large basins scale. The model can be used to infer causal links between seismicity and subsurface operations, as well as to hindcast/ forecast seismicity both temporally and spatially, based on past/future injection/extraction scenarios. We first demonstrate the capability of the framework in the case of seismicity induced by wastewater disposal in Oklahoma. We next focus on induced seismicity within the Midland basin in Texas. Understanding the seismicity at the scale of the Midland basin is challenging due to a variety of subsurface operations, which include hydraulic fracturing, salt water disposal and oil/gas production, as well as the complex geological setting of the basin. We show that in both case studies, the model can be calibrated successfully to the observations assuming that earthquakes are triggered by poroelastic stress changes. The time response of the seismicity depends primarily on the initial strength excess, which can result in the induced seismicity lagging the onset of stress perturbation by many years. It also depends on the earthquake nucleation process which affects the response to stress changes at a short (<1 year) time scale. The modeling framework provides an effective tool to forecast induced seismicity and to investigate the factors that determine the potential of a subsurface operation for triggering earthquakes.

Advanced Deep Learning for Distinguishing the Quarry Blasts from Induced Seismicity

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The signal characteristics of non-seismic events caused by quarry blasts are similar to earthquake events, leading to unreliable and potentially erroneous manual identification, especially in the absence of source location information. In this paper, we propose an advanced deep-learning-based framework to distinguish between earthquakes and quarry blasts. In the data preprocessing stage, we apply the continuous wavelet transform algorithm to the 60-sec three-channel waveforms for time-frequency conversion. The proposed discrimination framework comprises a dilated convolutional transformer (DCT) and a capsule neural network. DCT combines the local perception capability of traditional convolutional neural networks, effectively extracting spatial features from multi-channel scalograms. Additionally, the multi-head self-attention module in the transformer dynamically adjusts feature weights across different positions to adaptively focus on significant features, which is crucial for handling complex background noise and irrelevant information in earthquake and quarry blast signals. Then, the features extracted by DCT are transferred to the capsule neural network for hierarchical feature representation. The dynamic routing mechanism in the capsule neural network allows for flexible and adaptive feature propagation and integration between capsules, enabling precise distinction between earthquakes and quarry blasts. We use an artificial intelligence (AI) earthquake dataset recorded by the Texas Seismological Network (TexNet) to demonstrate the classification performance of the proposed network. Compared to state-of-the-art classification networks, the proposed method has higher reliability and more satisfying performance.

Mitigation and Optimization of Induced Seismicity Using Physics-based Forecasting

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Fluid injection can induce seismicity by altering stresses on pre-existing faults. Here, we investigate minimizing induced earthquake potential by optimizing injection operations in a physics-based forecasting framework. We built a 3D finite element model of the poroelastic crust for the Raton Basin, Central US, and used it to estimate time dependent Coulomb stress changes due to ~25 years of wastewater injection in the region. Our finite element model is complemented by a statistical analysis of the seismogenic index (SI), a proxy for critically stressed faults affected by variations in the pore pressure. Forecasts of seismicity rate from our hybrid physics-based statistical model suggest that induced seismicity in the Raton Basin, from 2001 to 2022, is still driven by wastewater injection despite declining injection rates since 2011. Our model suggests that pore pressure diffusion is the dominant cause of Coulomb stress changes at seismogenic depth, with poroelastic stress changes contributing about 5% to the driving force. Linear programming optimization for the Raton Basin reveals that it is feasible to reduce earthquake potential for a given amount of injected fluid (safety objective) or maximize fluid injection for a prescribed earthquake potential (economic objective). The optimization tends to spread out high-rate injectors and shift them to regions of lower SI. The framework has practical importance as a tool to manage injection rate per unit field area to reduce induced earthquake potential. Our optimization framework is both flexible and adaptable to mitigate induced earthquake potential in other regions and for other types of subsurface fluid injection.

The Prinos CO_2 Storage Site (Greece): Seismotectonic Setting and Monitoring Challenges

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The Prinos CO_2 storage site, located offshore in the seismically active North Aegean Sea, represents a pioneering effort in Carbon Capture and Storage (CCS) technology in Greece. With an annual storage capacity of 2.5–3 million tons of CO_2, the Prinos project demonstrates the feasibility of multimodal CO_2 transport and offshore storage, as part of the EU-funded HORIZON project COREu (grant ID 101136217). This effort addresses key challenges in scalable decarbonization by advancing technologies for transport interoperability, Measurement-Monitoring-Verification (MMV), and the safe, cost-effective design of CCS chains.

The storage site is situated near known active fault systems which include normal and strike-slip faults associated with the North Aegean Trough and adjacent crustal deformation zones. The challenges of seismic monitoring in such a complex tectonic setting are addressed by employing novel technologies—such as wireless subsea sensors (Saipem's) and autonomous underwater vehicles (AUVs) equipped with CO_2 sniffers—it sets a precedent for integrated CCS monitoring systems. Seismic monitoring aims to establish a robust baseline of seismicity using historical records and geophysical data, while assessing the impacts of CO_2 injection at depths of 2700–3000 meters, under ~110 bars of pressure, within the saline aquifer. Real-time observations from subsea acquisition nodes and onshore seismic stations track micro-seismic events during and after injection, correlating spatiotemporal seismicity patterns with plume evolution and injection parameters. Advanced probabilistic and deterministic seismic hazard assessment (SHA) models, evaluate fault activation hazards and stress transfer within the reservoir. Cost-effective solutions, like multi-well DAS vertical seismic profiling, are also explored to ensure long-term seismic monitoring. The Prinos case study advances real-time hazard forecasting methodologies and positions Greece as a leader in CCS innovation, contributing to sustainable industrial practices and the broader goals of European decarbonization.

Transient Rate-dependent Forecast for Induced Earthquakes in Carbon Sequestration

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Carbon Capture and Storage (CCS) operations can induce earthquakes during and aFer the injection operation. Accurate forecasts of induced seismic activity enable operators to assess time-dependent hazards and adjust injection strategies to mitigate risks. While statistical models and data-driven machine learning techniques are commonly used for earthquake forecasting, their reliance on abundant and precise seismic data limits their ability to capture complex geological processes, such as short-term seismicity transients.

Physics-based forecasting methods, such as the coupled Coulomb rate- and state- friction model, provide a robust theoretical framework for incorporating the underlying mechanisms responsible for transient seismicity rate changes associated with earthquake clusters. Our team has developed a framework leveraging these methods to perform fast and reliable forward modeling of space-time earthquake clustering driven by fluid migration. The process begins with identification of spatial-temporal cluster of seismic events, followed by estimation of the static.

Coulomb stress change for each cluster based on an empirical approximation of Okada's solution. Both positive and negative Coulomb stress changes are accounted for with an optimized weighting approach. Transient seismicity rate changes are then evaluated using the rate- and state- earthquake rate model informed by these weighted Coulomb stress changes.

This approach is validated on data collected from the Illinois Basin Decatur Project, a pilot initiative for deep CO2 storage. Results demonstrate that our method effectively models the transient clustering behavior observed in the IBDP catalog. Extension of these methods to produce forecasts over many realizations can establish upper and lower bounds for seismic activity related to injection.

The work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Efficient Physics-based Modelling of Induced Seismicity Decatur CCS Project and Upscaling to the Illinois Basin

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To enable worldwide scalable development of carbon sequestration in saline aquifers, we need to assess (i) the risks of induced faulting and seismicity, (ii) the associated risk of leakage, and (iii) basin-scale interactions between projects. We focus on the Illinois basin which hosted the Decatur CCS project and that will potentially be. hub for commercial scale CCS projects. Seismic activity was reported near the Decatur CCS1 site (first pilot injection site), but corrections to the injection strategy have reduced the earthquake rate for larger injections in the nearby Decatur CCS2 project (second injection site for commercial purposes). We use statistical and physics-based modeling to determine whether these earthquakes were directly caused by the injection process, tectonic loading, or inter-earthquake triggering. Our approach involves a modular, computationally efficient, physics-based, workflow to simulate the effects of fluid injection in subsurface reservoirs, their geomechanical deformation, and seismicity generation. We find a strikingly high spatio-temporal correlation between earthquakes attributed to fluid injection and the Coulomb stress changes from our model. The strength excess in the faults that hosted these earthquakes is remarkably low, indicating that the faults in the basement were critically stressed despite the tectonically quiet setting. We further use our model calibrated with CCS1 to hindcast seismicity in CCS2 and find remarkable agreement with the low observed rates of seismicity, confirming that injections in formations hydraulically separated from the basement will result in low seismicity rates. Finally, we expand our analysis using scenarios for large scale CCS in the Illinois basin (20+ injection wells) and provide potential seismicity scenarios. Overall, our tool for seismicity forecasting can enlighten regulations for CO2 sequestration.

Site-specific Seismic Hazard Analyses in Oklahoma Addressing Both Tectonic and Induced Seismicity

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We have performed site-specific probabilistic seismic hazard analyses of the U.S. Bureau of Reclamation's Altus and Fort Cobb Dams and East and Lugert

Dikes located in southwestern Oklahoma (OK). The structures will be subject to ground motions from both tectonic and induced earthquakes, the latter which has dominated the seismicity in the state since 2009 due to wastewater injection. The Meers fault, which is within 55 km of all four sites, dominates the tectonic hazard in much of Oklahoma. Traditionally, induced seismicity is not included in seismic hazard analyses but the associated ground motions need to be accounted for in the seismic safety of the structures. Inputs into the PSHA include the 2012 EPRI/DOE/NRC CEUS seismic source model updated for the Meers fault and the NGA-East ground motion models (GMMs) adjusted for the bias observed by Ramos-Sepulveda et al. (2024). To account for hazard from induced earthquakes in the PSHA, we included a zone of gridded induced seismicity and induced seismicity GMMs. Altus Dam and the two dikes are located 73 km west of the zone. Fort Cobb Dam is located at the western boundary of the zone. We calculated recurrence for 12 induced seismicity catalogs covering time periods that had a common end date of July 2023 but starting dates that differed by a year (2011, 2012, etc. through 2022). This was done to examine temporal trends in rate due to declining induced seismicity since 2015. In the PSHA, we adopted the recurrence for the period starting in 2019. Altus Dam is located on rock whereas the other three sites are located on alluvium and required site response analyses. The 10,000-year return period hard rock PGA for Altus Dam was 0.42 g and about 0.6 g for the other sites on alluvium. The major contributor to hazard at all four sites was the Meers fault with very little contribution from induced earthquakes including Fort Cobb Dam which is outside the areas of highest seismicity in the zone. For a site in the highly active part of the induced zone and more distant from the Meers fault, the induced seismicity contributes to the PGA hazard up to about 30%.

From Physics to Forecasts: Advancements and Future Directions of Induced Seismicity Research [Poster]

Poster Session • Tuesday 15 April

Conveners: Stanislav Glubokovskikh, Lawrence Berkeley National Laboratory (sglubokovskikh@lbl.gov); Jeremy Gosselin, Natural Resources Canada, Geological Survey of Canada–Pacific (jeremy.gosselin@nrcanrncan.gc.ca); Ian Main, University of Edinburgh (Ian.Main@ed.ac.uk); Alexandros Savvaidis, University of Texas at Austin (alexandros.savvaidis@beg.utexas.edu); Jake Walter, Oklahoma Geological Survey, University of Oklahoma (jwalter@ou.edu)

POSTER 105

Development of a Machine Learning-based Ground Motion Model for Induced Earthquakes in the Central and Eastern United States

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In this study, a Ground Motion Model (GMM) is developed using machine learning regression techniques to predict Peak Ground Acceleration (PGA) and Pseudo-Spectral Acceleration (PSA) values across 17 periods up to 3 seconds. The model utilizes data from 31,000 induced earthquakes in the Central and Eastern United States (CEUS), focusing on small-to-moderate magnitude events with moment magnitudes (M_W) ranging from 3.0 to 5.8, hypocentral distances (R_{hypo}) up to 200 km. Input parameters for the proposed GMM include M_W, R_{hypo}, and the time-averaged shear-wave velocity of the upper 30 m of soil (V_{S30}), while the output variables are PGA and PSA across different periods. Machine learning methods, including Artificial Neural Networks (ANN), Kernel Ridge Regression (KRR), Random Forest Regression (RFR), and Gradient Boosting Regression (GBR) are employed. GBR demonstrates the best performance among the individual models.

An ensemble technique is applied to combine the outputs of individual models, resulting in a robust and smoothed final prediction. The use of machine learning addresses the limitations of traditional GMMs, such as the need for predefined functional forms, and the ensemble approach further enhances model robustness. Comparisons with conventional GMMs show that the proposed method achieves higher accuracy, particularly when sufficient training data are available. The results highlight the potential of machine learning-based GMMs for reliable seismic hazard assessments, especially for small-to-moderate earthquakes in the CEUS region.

POSTER 106

High-Resolution Seismic Monitoring Reveals the State of Stress in the Delaware Basin

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Wastewater injection from unconventional production is regarded as a prime driver of seismicity in the Delaware Basin of West Texas, which started increasing here lagging the stimulation of the reservoirs. Seismic monitoring in the area has grown with public and private arrays deployed to better characterize the earthquake activity. The combination of such arrays has been used to deliver a highly detailed image of the seismic response in this area: over 700,000 events complete to ML0.2 have been detected and located since April 2019; in that period 7,000+ moment tensors for events above ML2 have been inverted using an amplitude-based, first-motion scheme in tandem with a polarity-based algorithm.

Moment tensors complemented with high-precision locations are used to run a robust spatial stress inversion over the area. Critical to running such inversions is the ability to select the fault plane from the auxiliary plane in the moment tensor. The nearest neighbouring hypocenter locations, after refinement through double-differencing, helps with this problem as often they will illuminate the faults on which these larger events nucleate, allowing for identification of the fault on which the larger event with the moment tensor occurs. By running a series of local stress inversions, and (Monte Carlo) perturbing the solutions to only select stress states that appear stable, we resolve an overall trend of a dominantly normal stress state where there is a slow sweep of azimuths of SHmax from NW-SE trending to EW as one travels from SE to NW across the basin. However there are areas where the stress appears to be much more rapidly varying, and the state appears more strike-slip and the orientation of SHmax likewise changes rapidly over relatively short (<10km) scales.

POSTER 108

Seismicity in Sichuan, Southwestern China, 2009-2019: Interaction of Hydraulic Fracturing Induced Earthquakes Characterized by the Nearest-Neighbor Distance Approach

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Earthquake interaction, which is critical to understanding the nucleation and rupture process of induced earthquakes, has not been fully studied. We applied the Nearest-Neighbor Distance clustering approach to the seismicity of the Sichuan Region to investigate the interaction between Hydraulic Fracturing (HF) induced seismicity inside the Sichuan Basin and compare them with the tectonic seismicity in the surrounding regions. Background seismic rate and cluster types are measured after separating the background events and earthquake clusters. We found that seismicity inside the Sichuan Basin shows a high background seismic rate. Many clusters with a mainshock magnitude greater than 4.0 have complex structures with foreshocks referring to a multi-stage rupture process. In addition, many complex clusters have multi-stage foreshocks, which manifest a cascading nucleation process. Three attributes are used to better describe the features of the complex clusters. We find many earthquake clusters inside the Sichuan basin deviated from an aftershock sequence and show swarm-like features. The commonly observed earthquake swarms in induced seismicity regions may result from cascading nucleation and rupture processes on complex fault systems. We conclude that earthquake interaction plays an important role in inducing earthquakes in the Sichuan Basin and should be considered in the future induced earthquake rupture model and risk estimation.

Geophysics in a Changing World: Monitoring Applications from Seismology and Beyond

Oral Session • Tuesday 15 April • 4:30 PM Local

Conveners: Jochen Braunmiller, University of South Florida (jbraunmiller@usf.edu); Seth Carpenter, Kentucky Geological Survey, University of Kentucky (seth.carpenter@uky.edu); Felix Rodriguez Cardozo, University of South Florida (felixr1@usf.edu); Glenn Thompson, University of South Florida (thompsong@usf.edu)

Real-time Detection and Insights From the September 2024 Surprise Glacier, Alaska, Landslide Sequence

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On September 20, 2024, a series of repeat landslides above the terminus of Surprise Glacier in Prince William Sound, Alaska, triggered a small tsunami that was detected in real-time — a first for landslide-generated tsunamis in the region. The landslides were identified using seismic data and later corroborated with satellite imagery, tide gauge readings, and infrasound observations. Although Surprise Glacier has experienced rapid retreat over the past year, analyses done before this landslide sequence did not indicate any evidence of precursory deformation at this location. Even though the retreat has contributed to slope instability, our analysis suggests that an intense period of rainfall immediately preceding the landslides was likely the primary trigger.

We present the detection and interpretation of the Surprise Glacier landslide sequence, focusing on the integration of diverse geophysical data streams collected within hours after the event, as well as detailed modeling performed in the days and months that followed the sequence. An experimental seismic monitoring system successfully triggered detection alerts within three minutes of the main landslide, using stations located 20 to 250 km from the source. Infrasound signals from a nearby array, located 20 km away, corroborated the event's location approximately 30 seconds after the seismic arrival, and the tide gauge 16 km away confirmed a tsunami wave 12 minutes later. A subsequent landslide seismic force inversion and seamless landslide-tsunami simulation, as well as imagery interpretation, provide further insights into the landslide's dynamics, failure sequence, and implications for hazard assessment. This interdisciplinary approach underscores the critical role of seismic monitoring in early warning and hazard response, complemented with strategically placed instrumentation to further mitigate risk in vulnerable regions.

Characterizing Analog Instrument Responses Relevant to Long-term Oceanic Microseism Analyses

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Long-running seismological records of oceanic microseism intensity provide a unique quantitative resource to study historic storm systems and global climate change. However, one challenge in these studies is the accuracy and availability of sufficiently precise instrument responses for early seismic instruments. In this study, long-period Benioff data spanning 1935 to 1940 and digital broadband data from 1988 to present day recorded at the Harvard seismic station (HRV) are used to empirically constrain the analog instrument response of the analog seismometer using global earthquakes at teleseismic distances. The resulting instrument response correction demonstrates the feasibility of more widely using this methodology to recover missing instrument responses, or to correct inaccurate ones; and additionally assists in characterizing non-seismic long period noise for historical data. Applying this response correction at HRV yields preliminary observations of relative North Atlantic storm-associated microseism levels spanning more than 90 years.

Global Frequency-dependent Primary and Secondary Band Microseism Change Since the Late 20th Century

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Extensive digital seismic data archives enable the analysis of the global microseism wavefield across nearly four decades. We examine multi-decade variability in vertical-component (Rayleigh wave-dominated) primary and secondary microseism signals between 1988 and 2024. 73 stations from 82.5° N to 89.9° S latitude from the Global Seismographic, New China Digital, and GEOSCOPE networks are used; all with >20 years of data and >80% data completeness. Acceleration power spectral densities are estimated using 50%-overlapping, 1-hr moving windows integrated in 2-s wide period bands to produce band-passed amplitude time series. We remove nonphysical outliers, earthquake signals, and harmonic seasonal variations (using a fundamental period of T_0 = 365.2422 d). We smooth with a $T_0/6$ moving-median window to emphasize seasonal-scale and secular variability and estimate primary (14–20 s) and secondary (4–10 s) band trends using L1 residual norm-minimizing functions. Increasing microseism amplitude is observed for most of the Earth in both the primary and secondary bands (averages of 0.16 and 0.09 %/yr, respectively). The two microseism secular change rates correlate at R=0.65 and have a regression slope 1.04. However, secondary trends are systematically lower by about 0.05 %/yr, consistent with variable excitation of the secondary source relative to the primary due to its dependence on interfering ocean waves. Primary microseism signal station histories regionally cluster to station separations of 1000's of km and multiyear signal variations reflect the effects of interannual variability (e.g., El Niño–Southern Oscillation) on large-scale storm and ocean wave energy. Microseism intensity histories in 2-s period bands exhibit global to regional correlations that reflect teleconnected ocean swell, Rayleigh wave propagation and attenuation, and the large-scale reach of climate variation. Secular trends as a function of period suggest greater intensification of microseism energy at long periods, consistent with more frequent large-scale storm systems that produce longer-period ocean swell.

Seismic and Gravity Imaging for Dam Design in a Complex Geologic Setting

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Major infrastructure construction typically relies on boreholes to characterize geotechnical properties. In complex geologic settings, however, drilling may be insufficient to capture the full range of subsurface conditions and geohazards. Here we present perspectives from a project to develop a 96,000 acre-foot reservoir with four dams totaling 10,000 linear feet in Colorado's Rocky Mountains. Challenges at the site include dozens of polyphase faults concealed by 100+ meters of local volcaniclastics, gypsum karst sinkholes, nearly 50 different geologic units with differing geotechnical properties, and rich cultural resources that preclude intrusive investigations in much of the area. Proactively building a comprehensive, 3D geologic/geotechnical model by integrating borehole data, geologic mapping, and geophysics has been key to adapting to geologic complexity while optimizing engineering design and construction planning with respect to local geology. Site-wide gravity surveys and 3D gravimetric tomography efficiently initialized the model, guiding dam layout to avoid dissolution-prone and poorly lithified units while taking advantage of antiformal bedrock highs. Boreholes then focused on gathering samples from dam foundations and other key areas. Active-source seismic imaging, including full-waveform, reflection, and 3D tomography, constrained structure between boreholes. In turn, the seamless gravity model plus geologic mapping allowed robust constraints on 3D structure beyond borehole and seismic footprints. The 3D geologic model was then populated with physical parameters determined from lab tests on borehole samples, allowing the subsurface to be treated as an engineering material for dam design. The 3D modeling reduced project cost by allowing design to avoid problematic units, take advantage of favorable structures (e.g., bedrock highs), estimate foundation excavation depths, and identify onsite quarry material. We conclude that comprehensive 3D geotechnical models can optimize planning and design, and that geophysics provides a strong base for these models, even in the most challenging geologic settings.

Optical Detection of Modal Frequencies of Structures

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The experimental assessment of the modal frequencies of engineering structures is a key-step in several seismological applications, such as providing the entry point in seismic response spectra, the calibration and validation of dynamic models, the evaluation of the effect of interventions/retrofitting in the dynamic behavior of existing structures, and more.

Accelerometers are still the preferred motion transducers in this type of application by the engineering community, while the seismological community prefers seismometric transducers (geophones), due to their larger sensitivity at low frequencies and intrinsic lower noise, which makes them more suitable for weak motion analysis and soil applications.

In recent times sensors measuring displacements (based on electromagnetic wave source-to-target travel times or on interferometric approaches) have also started to be used. These have the advantage of being contactless and capable of exploring a larger portion of the structure from a single acquisition point. This is however achieved at the expense of much larger amounts of data to process. Assessing the direction of motion with these methods is more difficult than with the standard acceleration/velocity transducers. These methods also require stable air conditions to not impair the displacement/distance measurements.

Differently from the measurement principles listed above, here we focus on optical (based on visible radiation) approaches, applicable with standard photo cameras, and explore their potential in the assessment of modal frequencies of structures. Optical approaches have been used to study mechanical vibrations, particularly in laboratory experiments, where several variables can be kept under control. Here we apply them to detect the modal frequencies of standard structures under operative conditions. We will explore different workflows, discuss their performance and possible improvements and show that dynamic characterizations of large vibrating structures can also be achieved by means of standard videocameras.

Geophysics in a Changing World: Monitoring Applications from Seismology and Beyond [Poster]

Poster Session • Tuesday 15 April

Conveners: Jochen Braunmiller, University of South Florida (jbraunmiller@usf.edu); Seth Carpenter, Kentucky Geological Survey, University of Kentucky (seth.carpenter@uky.edu); Felix Rodriguez Cardozo, University of South Florida (felixr1@usf.edu); Glenn Thompson, University of South Florida (thompsong@usf.edu)

POSTER 43

Visualizing Cyclical Variations in Seismoacoustic Activity Using Circular Spectrograms

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Environmental and anthropogenic signals are often periodic. For example, wind noise tends to follow diurnal and seasonal patterns whereas human facilities operate on a fixed schedule. These patterns can be difficult to extract and visualize using typical rectilinear time-frequency plots such as Fourier spectrograms. We describe a method to highlight periodic variations in signal power with respect to frequency by constructing a "circular spectrogram." A data set with suspected cyclic variations is identified, and spectra are calculated over a set of time windows. Spectra corresponding to the same point in the cycle (e. g. a certain time of day) are assembled and the median is taken. The ensemble of spectra is plotted as a circular image, with the angular position of each pixel determined by its point in the time cycle and its radial position determined by frequency. When color coded by power, this produces a visualization of repeating variations in the time span of interest. We show how these circular spectrograms are calculated as well as provide examples of power fluctuations highlighted by this method. Initially developed as a data quality assessment method for the Physics Experiment 1 seismoacoustic network, the circular spectrogram shows promise for broader scientific insights across a variety of environments and time spans.

POSTER 44

Cost-effective Groundwater Monitoring Using Nodal Geophones: Updates From a Case Study in the Upper Mississippi Embayment

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The aquifer system of the Upper Mississippi Embayment (UME) supports the water needs of agriculture, industry, and an increasing population in a large five-state region of the central United States. However, increasing demand coupled with unregulated use may threaten the long-term sustainability of this vital resource, highlighting the need for reliable groundwater monitoring across this region. Seismic interferometry offers a promising solution to meet this need by measuring spatiotemporal variations in seismic wave speeds from which changes in groundwater storage can be inferred. We are undertaking a multi-year interferometric investigation of a ~2,000 km^2 area in the Kentucky part of the UME, which hosts multiple aquifers from the surface to depths up to ~600 m. Based on previous studies and preliminary work in the larger UME, the necessary resolution requires both a relatively dense array of seismometers (~10 km spacing or less) and recordings of ambient noise at frequencies ≤0.2 Hz. To satisfy these requirements in our study area, we plan to deploy a dense array of cost-effective nodal instruments (nodes) that can reliably record weak, low-frequency seismic waves. We evaluated the performances of three types of nodal instruments through temporary deployments at two sites in the project area with differing depths to the basal bedrock confining layer (~200 m and ~500 m). Comparisons of waveforms and power spectral densities from the nodal recordings against those from co-located traditional broadband seismometers revealed that two types of nodes record ambient vibrations at frequencies ≤0.2 Hz, establishing that low-cost nodes are suitable for this project. We have also retrieved preliminary inter-station reference Green's Functions from stacked cross-correlograms calculated from station pairs near a deep (>100 m) groundwater monitoring well. We will present an overview of the multi-year project, and results from the nodal geophone assessment and the retrieved Green's Functions.

POSTER 45

Seismic Site Characterization and Basin Depth Estimation Using Seismic Ambient Noises: An Example From the Hetauda Dun Valley, Nepal

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Subsurface geometry, particularly the depth to bedrock, is important for site-specific seismic hazard studies, as basin geometry and local geology plays an important role in the altering and amplification of seismic waves. In this study, we characterize site response within Hetauda Dun Valley by utilizing the seismic ambient noises measured at ninety-two points. The horizontal to vertical spectral ratio (HVSR) and the centerless circular array techniques are used to estimate fundamental frequency and shear wave velocities respectively.

The HVSR data reveal a wide variation on fundamental frequency spanning 0.55 Hz to 7 Hz. The central part of the valley is characterized by low fundamental frequency (<1 Hz), whereas northwestern part of the valley exhibits relatively higher fundamental frequency. The lowest frequency is found in and around Chaughada area, characterized by fine grained sand, silt and clay, where the urbanization is rapidly but haphazardly expanding. In accordance with the guidelines of the National Earthquake Hazard Reduction Program, two site classes, site Class C and site Class D, are identified based on the time-averaged shear wave velocity up to a depth of 30 m. The northeastern part of the valley falls in the site class D and the remaining area lies on site class C. This is consistent with the known response of the northeastern part of the valley, which is comparatively less stiff than the western part, making it more susceptible to damage during an earthquake. The shear wave velocity models indicate variation in basin depth from 11 m to 281 m. The eastern part of the valley, including Chaughada, is deeper than the western part. Two distinct N-S trending troughs of low shear wave velocity are observed, the first east of Chaughada and second through the Hetauda Industrial Area. We hypothesize these are paleo-river channels.

POSTER 46

Using Horizontal-to-vertical Spectral Ratio to Characterize Landslides in Complex Terrain

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The horizontal-to-vertical spectral ratio (HVSR) technique is popular within the earthquake community for site characterization. This method uses the ratio between seismic noise or earthquake recordings on horizontal and vertical components to estimate fundamental frequency, site amplification, and derive sediment thickness using a known shear-wave velocity. The method can also be used for other purposes, such as estimating the depth of landslide slip surfaces where fractured, broken material slides on a generally intact substrate. Community standards for HVSR are mainly established for simple, 1D-varying subsurface compositions. Interpretation is less straightforward in more complex terrain that characterizes many landslide settings. There is a need to better understand how to use and interpret HVSR results in these geologically complex settings because the technique can provide useful information at a lower cost, and in a less invasive way, than other geophysical and geotechnical approaches. In this study, we apply the HVSR technique to characterize landslides of varying structural complexity: the Slumgullion slow-moving landslide near Lake City, Colorado; the Bald Eagle sackung near Leadville, Colorado; and two landslides triggered by the February 6, 2023, Türkiye earthquake sequence. We installed one or more 3-component seismometers at each site and conducted rock drops to roughly estimate shear-wave velocity using direct wave arrival times where pre-existing measurements were unavailable. We find that some sites have a single, high-amplitude HVSR peak, while other sites have more complicated HVSR curves with multiple, lower-amplitude peaks. We compare the HVSR curves at the sites, explore the source of their varying degrees of complexity using simple modeling, and interpret the results of each site in context of other available information to characterize the landslide geometry. Through this work, we aim to better understand the usage of the HVSR technique for landslides and other complex geologic settings.

POSTER 47

Rapid Seismic and Infrasonic Assessment of a Large Landslide in Denali National Park (Alaska) Aided by Aerial and Satellite Imagery and Numerical Flow Modeling

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On September 13, 2023, at 6:06 PM local time, a large rock–ice avalanche occurred in Denali National Park (Alaska). Unlike many remote Alaska landslides, this event was rapidly detected. A tourist flightseeing operator noted a dust cloud in the area, and seismic signals generated by the landslide were detected by real-time earthquake monitoring systems operated by the Alaska Earthquake Center (AEC) and National Earthquake Information Center. An AEC-hosted seismic landslide detection tool provided a location and a preliminary size. The landslide also generated significant infrasound (low-frequency atmospheric sound) waves which were recorded at distances exceeding 250 kilometers. The following morning, park staff — equipped with the initial seismic parameters — flew to the landslide and took aerial photographs.

To determine the failure timeline and dynamics of this landslide, we use long-period seismic signals to infer the time-varying force vector $f(t)$ exerted by the landslide on the Earth. We process infrasound array data to determine the timing and back azimuth of multiple failure signals recorded on four arrays located across Alaska. We reconstruct the failure using the numerical flow model SHALTOP, constraining the model output with $f(t)$ and deposit morphology measured from aerial and satellite imagery. Our analyses reveal that

- two smaller pre-event slides occurred eight and three minutes prior to the primary failure;
- the primary failure consisted of three to six million cubic meters of rock and ice which broke free at a steep angle before traveling to the north-northwest about three kilometers, creating abundant dust; and
- the source region was still producing seismogenic post-event slides eight days after the main failure sequence.

This well-recorded event motivates re-examination of current detection, location, and characterization capabilities for large, rapid, remote landslides. With an eye towards operational monitoring and streamlined event response, we will highlight some "lessons learned"from our multi-institution response which are broadly applicable to this class of remote hazards.

POSTER 48

Joint Inversion of MASW and Ambient-noise HVSR Data for Estimating Shear Wave Velocity Profile in Warm Permafrost: A Case Study at Northway Airport, Alaska

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The study aims to investigate the impacts of permafrost degradation on shear wave velocity and seismic response of warm permafrost sites. A joint dataset, combining Multichannel Analysis of Surface Waves (MASW) and Horizontal-to-Vertical Spectral Ratio (HVSR) analysis of ambient noise acquired at Northway Airport, Alaska, was utilized to delineate the permafrost table and shear wave velocity profiles. MASW data acquisition involved deploying 24-channel vertical geophones (4.5 Hz) spaced 3.0 m apart and connected to a data recorder. Seismic signals were generated using a sledgehammer striking a plate, with five stacked two-second seismograms recorded per location at offsets of 3.0 m and 4.6 m on both sides of the array. Surface wave dispersion characteristics were analyzed to extract phase velocity data in the 5–18 Hz frequency range. In parallel, three hours of ambient noise data were recorded using a three-component broadband velocity sensor. The data were band-pass filtered (3–70 Hz) and segmented into 180 one-minute windows. HVSR values for each segment were computed in the 4–18 Hz frequency range by taking the ratio of the geometric mean of the horizontal components (NS and EW) to the vertical component. Median HVSR and its standard deviations were evaluated assuming a lognormal distribution. Joint inversion was performed using Monte Carlo sampling to integrate the HVSR and MASW datasets. The inversion process utilized an initial 1D layered earth model from previous geotechnical reports, iteratively refining parameters such as layer thickness, shear and compressional wave velocity, density, and Poisson's ratio. The computed HVSR and dispersion curves were compared against their respective observed values during each iteration to minimize the least-squares error between them. The final model from inversion reveals significant insights into the shear wave velocity structure of warm permafrost sites and the impact of permafrost degradation on seismic site responses and provides a robust framework for assessing seismic hazards in the permafrost-affected areas undergoing degradation due to climate change,

POSTER 49

Identification of Cavities in Karst Areas Using Seismic Ambient Noise

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The identification and mapping of underground cavities is of significant importance in the context of urban development and civil engineering projects, as their undetected presence, whether of natural or artificial origin, poses a substantial geotechnical hazard. Also, the cavities produced by underground nuclear explosions (UNE) are of particular interest. The detection and location of a cavity generated by a UNE can serve as important evidence in the framework of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) on-site inspections. In order to enhance the capabilities of the CTBT on-site inspections, a Finite-Interval Spectral Power (FISP) methodology based on the ambient noise analysis has been developed for the detection of a deep underground cavity (*Kristekova et al. 2021*).

Applications of the FISP method included the two CTBTO field tests in the karst areas: a site near Felsőpetenyi in Hungary and the mountainous area in the vicinity of Rotmoos, Styria, Austria. In the first case in Hungary the seismic ambient noise was recorded on a grid of receivers (more favorable configuration) however in the case of the Austrian test data noise was recorded only on two separate receiver profiles, comprising 22 and 19 stations. This limited configuration was due to the difficult terrain in the mountains and hence also limited accessibility. However, the density of receivers along the profiles was higher than during the field test in Hungary. The objective of the Austrian test was to test on-site inspection methods in challenging terrain conditions and to identify cave targets of various sizes within a depth range of approximately 35 to 350 meters in a complex cave system. Six hours of relatively undisturbed noise data across the majority of the receivers were used for the calculation of the FISP values at several frequency bands. We have identified FISP anomalies that could be attributed to the presence of cavities and/or spatial variability of complex local geological conditions. These findings agreed well with the results obtained using electrical conductivity measurements and active seismic surveys.

POSTER 50

Exploring Possible Tornado Seismic Signals From the December 10-11, 2021, Tornado Outbreak in the Central U.S.

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Tornadoes can cause significant structural damage and endanger lives. Although Doppler radar is able to detect storms that can produce tornadoes, it is unable to identify when a tornado has actually touched down. If grounded tornadoes transfer significant amounts of their energy into the earth as seismic vibrations, seismometers could offer a solution by serving as touch-down warning systems. As an initial effort to evaluate this possibility, we analyzed waveform data from permanent broadband seismometers located within 50 km of an EF-4 tornado's 129 km-long track. This tornado touched down in NW Arkansas on December 10, 2021, and was one of several tornados in the December 10–11 outbreak. We also gathered tornado track data, touch-down and lift-off times, and Enhanced Fujita (EF) ratings from the National Weather Service. Our approach to identifying tornado-seismic signals (TSSs) included analyzing seismograms and spectrograms before, during, and after the tornado touched down. Preprocessing the waveform data involved tapering, filtering (passband of 0.005 to 45 Hz), and instrument response removal. Spectrograms were then plotted from two-hours prior to touch down through two hours following the tornado's lift off to isolate any unique signals while the tornado was in contact with the ground. Preliminary results suggest that TSSs have been recorded at two seismic stations, both of which are located within 6 km of this tornado's track. Vertical- and horizontal-component spectrograms reveal a unique band of increased intensity between 30–45 Hz during ground contact. Two other stations that do not show enhanced signals in this frequency band are located at distances of 20 km or greater from the tornado's track, suggesting attenuation reduced higher-frequency signals at these larger distances. Our next steps include analyzing recordings from the other tornados in this outbreak and incorporating nearby short-period seismometers in our analyses. In addition, we will evaluate the thresholds at which TSSs can be recorded based on distance, frequency content, and EF rating.

POSTER 51

High and Low Noise Models for Geophone Deployments: Toward Global Denoising Strategies and Enhanced Global Monitoring Capabilities

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The use of geophones for seismic data acquisition has become more popular in recent research due to their low cost and the ease of conducting large temporary deployments. The current noise models available are mainly developed from global broadband instruments and do not represent the geophone noise levels that are typically encountered for shallow emplacement, given that broadbands are usually well buried or vaulted. The traditional noise models cover the lower frequencies and are outside of the typical range of geophones (0.001–10 Hz), with most of the signals of interest in geophones ranging up to 100 Hz or more. We are developing noise models that will represent geophone deployments across the world and within various geologies and environmental conditions. The comparison of these models will help us establish a quality control for nodal deployments by ensuring that the instruments are providing the data quality needed and meets the minimum threshold for detection. Using the nodal deployment data we have from Puerto Rico, Nevada, and Florida, in addition to other deployments identified on the EarthScope DMC and International Federation of Digital Seismograph Networks, we will contrast the marine and inland environments by analyzing the geological response for noise level variations, revealing possible common patterns in the seismic data, and isolate the High and Low Noise Models that are more representative of these types of deployments. This process will help to understand the noise level variations along diverse geologies and will become an input for seismic data quality enhancement and accurate detection and differentiation of signals of interest. This work was done by Mission Support and Test Services, LLC, under Contract No. DE-NA0003624 with the U.S. Department of Energy, the National Nuclear Security Administration's Office of Defense Nuclear Nonproliferation. DOE/NV/03624--2086.

Improving the State of the Art of Earthquake Forecasting Through Models, Testing and Communication

Oral Session • Tuesday 15 April • 2:00 PM Local

Conveners: José A. Bayona, University of Bristol (jose.bayona@bristol.ac.uk); Kélian Dascher-Cousineau, University of California, Berkeley (kdascher@berkeley.edu); Pablo Iturrieta, GFZ German Research Centre for Geosciences (pciturri@gfz-potsdam.de); Leila Mizrahi, ETH Zurich (leila.mizrahi@sed.ethz.ch); Berman Neri, Tel Aviv University (neriberman@gmail.com); Max Schneider, U.S. Geological Survey (mschneider@usgs.gov)

ETAS With Anisotropy in the Spatial Distribution of Aftershocks

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In the standard Epidemic-Type Aftershock Sequence (ETAS) model, the spatial aftershock density depends on the distance to the triggering event but does not incorporate directional information. However, well-located aftershocks generally exhibit directional patterns, primarily occurring along fault lines. For specific faults, detailed fault geometries and stress patterns have been used to refine aftershock forecasts (Bach and Hainzl, 2012; Field et al., 2017; Savran et al., 2020). However, in contexts where fault-specific information is unavailable or where data spans multiple fault systems, we aim to adopt a purely data-driven approach. We modify the ETAS formulation and the associated parameter inversion algorithm by incorporating an elliptical model that better captures the directional nature of aftershock triggering. In the expectation step of the Expectation-Maximization (EM) procedure, each triggering event is assigned an ellipse that best describes its aftershocks' locations. This adaptation influences the optimized triggering function resulting from each maximization step, as it depends on the evolving properties of the ellipses. Overall, our method yields a self-consistent estimation of ETAS parameters and event-wise aftershock ellipses.

Aiming to improve earthquake forecasting models for Europe, we apply this method to the ESHM20 dataset (Danciu et al., 2021), and compare forecasts, but also parameter trends (e.g. productivity law), to models for the same area which assume an isotropic spatial kernel. Preliminary retrospective tests demonstrate a positive information gain of the elliptical model versus its isotropic counterpart. We further evaluate the model in a pseudoprospective framework and test it across different regions, comparing the results against synthetic best-case scenarios. Our goal is to investigate the best approach to apply this modified aftershock modelling to real-time forecasting, resulting in more precise forecasts of spatial distribution and productivity of events: this is especially important during sequences with large-magnitude mainshocks and potentially destructive impact.

Stress Shadows in Physics-based Forecasts of Aftershock Locations

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The spatial distribution of aftershocks is an important component of earthquake forecasting following a mainshock, and in current operational forecasts an empirical decay with distance from the mainshock is often used. In physical models, in contrast, aftershock triggering is commonly attributed to static Coulomb stress changes from the mainshock, in combination with rate-and-state friction, which produces spatial kernels with multiple lobes of forecasted seismicity rate increase and decrease. However, the static Coulomb stress change kernels usually don't outperform a simple decay with distance in testing. One challenge is that some aftershocks occur in "stress shadows", where a decrease in static Coulomb stress is modeled to suppress earthquake occurrence. We investigate what causes aftershocks in the stress shadows, and how to improve the physics-based spatial kernels.

We examine several hypotheses that reconcile the aftershocks in stress shadows with the static Coulomb stress change model, including inaccuracy in modeling, effects of receiver fault complexity, variability in fault friction, secondary triggering from prior aftershocks or afterslip, and continuing background earthquakes. When tested on standard network catalogs and machine-learning focal mechanism catalogs for the 2016 Kumamoto, Japan, and 2019 Ridgecrest, California, aftershock sequences, none of these hypotheses can explain most of the aftershocks in the stress shadows, and taken together they can explain only about half of these aftershocks.

Alternatively, we consider dynamic stress triggering from the passing seismic waves. We find that the spatial and temporal distribution of aftershocks in the stress shadows are consistent with the expectations of dynamic triggering: the aftershocks mainly occur in a burst over the first few days to weeks, and decay with distance like near-field body waves. We find that a hybrid spatial kernel, combining static Coulomb stress lobes with dynamic-stress decay with distance in the stress shadows, performs better than a static-stress-only kernel in pseudo-prospective testing.

Evaluation of 10 Years of UCERF3-ETAS Next-day Forecasts

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Rigorous evaluation of earthquakes forecasts is a crucial step in understanding and improving the capabilities of earthquakes forecasting models. The UCERF3-ETAS model is currently the most advanced seismicity model combining a long-term seismicity model incorporating hypotheses of fault rupture dynamics and elastic rebounding with an Epidemic-Type Aftershock Sequence (ETAS) model for short-term seismicity. UCERF3-ETAS has also been used on demand for operational earthquake forecasting of important seismic sequences like the 2019 Ridgecrest one. Here, we have evaluated a very large database of UCERF3-ETAS next-day forecasts for California from 1 August 2008 to 31 August 2018. Each next-day forecast is composed of 100,000 synthetic catalogs generated by the model. The synthetic catalogs comprise events with magntiude Mw ≥ 2.5, start at 00:00:00 UTC, last 24 hours, and include all events prior to midnight in the history for generating the next day's forecasts. The 2008-2018 period comprises important seismic sequences, the most relevant being the 2010 7.2 Mw El-Mayor Cucapah sequence, as well as relatively quiet periods. Evaluating this extensive set of forecasts not only provides insights into the model's ability to accurately forecast daily seismicity, but also to understand which components drive the model in active and quiet periods, and the interplay between them. This is particularly evident when analysing the temporal evolution of quantities such as the magnitude or the spatial distribution provided by the forecast and how they change based on the history of the process. We assess the consistency between forecasts and observations using the statistical tests for catalog-based forecasts developed by the Collaboratory Study for Earthquake Predictability (CSEP), as well as Turing-style tests which provide an alternative way to evaluate a forecast visually.

ETAS-positive Parameter Sets for Three Southern California Earthquake Catalogs

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Statistical analysis of seismicity is hindered by incomplete recording of earthquakes. One of the major sources of incompleteness is the overshadowing of smaller earthquakes by larger ones. "Positive" statistics works around this incompleteness by restricting the analysis to intervals between earthquakes where the second is larger than the first (by some margin). The main statistical model used in earthquake forecasting is the Epidemic Type Aftershock Sequence (ETAS), and this model can also be defined without reference to a magnitude of completeness using positive statistics (ETAS+). Here I present parameter sets estimated with ETAS+ for three classical and enhanced earthquake catalogs for Southern California. The catalogs comprise 1) the ANSS Comprehensive Catalog, 2) the Hauksson et al waveform relocated catalog, and 3) the Ross et al QTM catalog. Estimates are made at different minimum magnitude cutoffs and over a range of time intervals to capture temporal variability in the parameters. Results with ETAS+ are compared to classical ETAS estimates. With the classical approach, nearly all the parameters show a dependence on minimum magnitude, consistent with the expected variation with minimum magnitude due to incompleteness. This bias is present but reduced in the QTM enhanced catalog. On the other hand, estimates made with ETAS+ show very little systematic variation with the minimum magnitude. ETAS+ returns both Gutenberg-Richter *b*-values and productivity scaling parameter *alpha* close to one, for all magnitude cutoffs, suggesting self-similar clustering. The Omori *c*-parameter is estimated to be on the order of the smallest interevent times in the catalog, meaning it is likely only an upper bound. For the QTM catalog with a lower magnitude cutoff of M2, the minimum catalog interevent time is quite small, and the *c*-value is constrained to be less than 10 seconds.

Challenges in Hazard and Risk Assessment for Seismicity in Volcanic Regions: Cases for Guadeloupe and Italy

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We all know that volcanoes and seismicity are correlated. Yet, in traditional Probabilistic Seismic Hazard Analysis (PSHA), seismicity in volcanic regions is often not considered, grouped into the regional background model despite clear tectonic differences, or considered at a very simplified level. Assessing the seismic hazard and risk in these tectonically-complex regions certainly has its challenges that we don't pretend to have the answers for; rather, we take a dive into the most impactful aspects of modeling seismicity in volcanic regions: rate modeling, maximum magnitude, scaling relations.

In this study, we highlight examples from Guadeloupe and Italy to explore key issues and pose several questions to the community on how to model such seismicity. (1) How does volcanism impact the maximum magnitude? Volcanoes and associated high heat flow can act as barriers to rupture propagation on crustal faults as well as change the recurrence characteristics of nearby faults. (2) How do we build a recurrence model for a non-stationary process? The variable stressing/loading rates and non-constant material properties in a volcanic region mean the classical approaches of Gutenberg and Richter (1944) and/or Poisson modeling may not be appropriate. The task of balancing the swarm-like behavior of volcanic seismicity with the threat of flank-collapse seismicity is also a challenge. (3) How do simplified approximations of modeling this seismicity compare to more detailed approaches? Is it sufficient to only consider a different scaling relation and ground motion model? Or is modifying the rate model alone sufficient? Can we get "close enough" by only changing one or two aspects of a model, or do we truly need more detailed models for volcanic regions?

We consider these issues and give examples in Guadeloupe and Italy where we have observed variations in the hazard and risk, depending on how this seismicity is handled.

Improving the State of the Art of Earthquake Forecasting Through Models, Testing and Communication [Poster]

Poster Session • Tuesday 15 April

Conveners: José A. Bayona, University of Bristol (jose.bayona@bristol.ac.uk); Kélian Dascher-Cousineau, University of California, Berkeley (kdascher@berkeley.edu); Pablo Iturrieta, GFZ German Research Centre for Geosciences (pciturri@gfz-potsdam.de); Leila Mizrahi, ETH Zurich (leila.mizrahi@sed.ethz.ch); Berman Neri, Tel Aviv University (neriberman@gmail.com); Max Schneider, U.S. Geological Survey (mschneider@usgs.gov)

POSTER 132

Forecasting Ground Motion Intensity Time Series with a Generative Pre-trained Transformer

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Typically, earthquake forecasts project the expected rate or number of earthquakes in the hours to weeks following a large earthquake. While grounded in the statistics and physics of seismogenesis, earthquake forecasts inherently do not include the complexities of ground motion physics. Here, we develop a ground motion-based approach to earthquake forecasting, which we call ground motion forecasting. Rather than forecast the rate or number of earthquakes and apply a ground motion model, we directly forecast future ground motion at a particular location from recorded ground motion. To do so, we introduce the Generate Unsupervised Aftershock Velocity Amplitudes (GUAVA) model. GUAVA is a generative pre-trained transformer with ~100 million model parameters that generates time series of ground motion intensity autoregressively at 10 Hz sampling rate with recorded ground motion time series as input. We train GUAVA on all continuous ground motion intensity time series (~225 stations) recorded by the Southern California Seismic Network within 2 degrees of the epicenter of 2019 M7.1 Ridgecrest, CA earthquake sequence from July 1-10, 2019. The GUAVA training is designed to maximize the log-likelihood of the next ground motion amplitude A(t+1) given the previous 8,192 (2^13) ground motion samples (A(t), A(t-1), .., A(t-8192) – effectively the last 819.2 seconds of data at 10 Hz) using stochastic gradient descent. When given a new ground motion time series as input, GUAVA generates suites of aftershock ground motion time series – complete with body, surface, and coda waves. We evaluate GUAVA's performance using the Kullback–Leibler divergence between the predicted and true distribution of future ground motion intensities on the December 5, 2024, M 7.0 Offshore Cape Mendocino earthquake. We suggest that GUAVA could be run in real-time using streaming seismic data to forecast ground motion from seconds to minutes after intense shaking occurs, as a type of Earthquake Early Warning for aftershock ground motion.

POSTER 133

A Deep Learning Application to Model the Full Distribution of Higher-order Aftershock Numbers in the ETAS Framework

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The Epidemic-Type Aftershock Sequence (ETAS) model is the state-of-the-art framework used for operational earthquake forecasting worldwide. It models earthquake occurrence as a stochastic point process, where earthquakes trigger cascades of aftershocks according to a set of empirical laws governing the timing, location, and quantity of direct aftershocks, as well as the magnitude distribution. These laws are described analytically and depend on several region-specific parameters that characterize the triggering relationships between earthquakes and their direct aftershocks. However, due to the stochastic nature of the cascading process, the distribution of indirect aftershocks has traditionally been obtained only through extensive simulations—a process that is both time- and resource-intensive.

In our recent study (Mizrahi and Jozinović, 2024), we demonstrated that the mean number of expected indirect aftershocks, given the parameters governing the direct aftershock distribution, can be accurately estimated using a simple deep-learning model. The main advantage of our approach compared to the simulation-based approach is the significant speed-up of the calculations, with the ML model taking only 813 µs on average, without a loss in accuracy. Here, we extend this approach to estimate not only the mean but the full distribution of higher-order aftershock numbers, modeling it as a negative binomial distribution. While estimating the full distribution is more challenging than estimating the mean, it is a crucial step toward enabling the faster machine-learning-based approach to replace simulations without sacrificing valuable information about forecast uncertainty. We demonstrate that this extended model can infer the full distribution of higher-order aftershock numbers accurately orders of magnitude faster than the classical simulation-based approach.

POSTER 134

Towards Operational Earthquake Forecasting in Switzerland

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Seismic risk is among the most significant natural hazard threats to society in Switzerland, as well as in many other European and global contexts. While earthquakes cannot be prevented or predicted, improving our understanding of the probability of damaging events can play a critical role in preparedness and risk mitigation efforts.

To date, only a handful of countries, including Italy, New Zealand, and the United States, operate authoritative operational earthquake forecasting (OEF) systems. The recent review by Mizrahi et al. (2024a) examines these systems in detail, highlighting key similarities and differences in their models, testing methodologies, and communication strategies. Moreover, the review incorporates insights from an expert elicitation process, shedding light on areas of consensus and ongoing debate within the earthquake forecasting community.

Building on these findings, the Swiss Seismological Service (SED) is now advancing efforts to develop an operational earthquake forecasting system for Switzerland. This presentation will provide an overview of our progress to date, including the development and testing of a forecasting model calibrated on the Swiss earthquake catalog (Mizrahi et al., 2024b). I will also discuss plans for the system's implementation, covering aspects such as computational workflows, forecast visualization, and strategies for integrating automated testing frameworks. Together, these efforts mark a significant step toward operationalizing earthquake forecasting in Switzerland and enhancing societal resilience to seismic risk.

POSTER 135

The Influence of Magnitude Determinations on b-Values

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The b-value describes the relative frequency of small versus large earthquakes in the Gutenberg-Richter relation. It has been found to vary between different regions and can also change spatially and temporally on relatively small scales. Such variations are of great interest to the scientific community because the b-value is considered to directly describe the expected size of future earthquakes. However, not all b-value variations and observations are necessarily meaningful.

When the sample sizes used to calculate b-values are small, statistical errors can lead to apparent variations, even in the absence of true underlying differences. Furthermore, even in large datasets, statistical, technical, and procedural factors unrelated to the physical characteristics of earthquake-size distributions can influence b-values.

In this study, we specifically examine the effects of magnitude determinations on b-values. Differences in magnitude definitions across regions may partly explain inter-regional variations, while network-specific factors, such as station errors or corrections, could introduce systematic spatial biases within a single region. We aim to quantify the influence of magnitude determinations on b-value variations and distinguish how much of the observed variability can be attributed to physical processes versus methodological or instrumental factors.

POSTER 136

Evaluating the Forecasting Performance of U.S. Geological Survey Aftershock Forecasts

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The U.S. Geological Survey (USGS) releases public aftershock forecasts following earthquakes with magnitudes 5 or larger in the U.S. and related territories. This system provides forecasts for specific durations (next day, week, month, year) and magnitude thresholds (M3+, M4+, …, M7+). We release the forecasted distribution for the number of aftershocks in each duration-magnitude bin, represented by a fine grid of quantiles. Forecasts are produced soon (20 minutes) after the mainshock and get updated regularly in intervals that increase with time. We are prototyping a forecasting system that uses the temporal Epidemic-Type Aftershock Sequence (ETAS) model and also accounts for short-term aftershock incompleteness using a parametric model. Early in the sequence, ETAS parameters are drawn from generic distributions of values that have fit previous aftershock sequences in that tectonic region, and as the sequence develops, parameter distributions are updated in a Bayesian manner to fit the sequence specifically. In this work, we evaluate the performance of this proposed aftershock forecasting system, by comparing the forecasted distribution of aftershock counts in each forecast bin to the observed count, using the USGS's Comprehensive Catalog. We employ a battery of forecast metrics designed for such probabilistic comparisons and that are meaningful for the forecasts' end-users. In specific, we consider metrics that can reveal (1) the scale of misprediction of the forecasted distribution, (2) the precision of the forecasted distribution and (3) the tendency of the forecasted distribution to over- or under-predict. We consider whether and how to account for aftershock incompleteness and whether and how to perform sequence-specific parameter estimation for different ETAS parameters and the effects of these decisions on forecast performance. We also examine forecast performance across the forecasts' dimensions: forecast duration, magnitude threshold, and time since mainshock. We present first findings of our evaluation strategy applied to simulated aftershock forecasts made under this proposed system.

Innovative Applications of Seismic Nodal Technology for Hazard Mitigation and Earth System Monitoring

Oral Session • Tuesday 15 April • 2:00 PM Local

Conveners: Andy Barbour, U.S. Geological Survey (abarbour@usgs.gov); Paul Bodin, University of Washington (bodin@uw.edu); Nahomy Campos, Volcanological and Seismological Observatory of Costa Rica (nahomy.campos.salas@est.una.ac.cr); Esteban J. Chaves, Volcanological and Seismological Observatory of Costa Rica (esteban.j.chaves@una.ac.cr); Joan Gomberg, U.S. Geological Survey (gomberg@usgs.gov); Sonia Hajaji, Volcanological and Seismological Observatory of Costa Rica (soniahajaji@gmail.com); Marino Protti, Volcanological and Seismological Observatory of Costa Rica (marino.protti.quesada@una.cr)

Probing the Seismicity and Magmatic Plumbing System of Erebus Volcano Using Machine Learning Techniques and a Dense Near Summit Seismic Array

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Nodal-style deployments have great utility for studies of active volcanoes. Mount Erebus, Antarctica, the southernmost active volcano in the world, has been continuously active since its discovery in 1841. For the past decades the volcano has produced frequent Strombolian explosions originating from a lava lake within its summit crater. The seismic activity at Mt. Erebus has been monitored by the Mount Erebus Volcano Observatory (MEVO). Eruptions from the lava lake and icequakes from the highly glaciated volcano dominate seismicity catalogues from Erebus. This contrasts with other active volcanoes which typically exhibit a wide range of internal seismicity, including volcano-tectonic earthquakes, (deep) long-period events, and hybrid events.

In this study, we focus on detecting and interpreting multiple types of seismicity at Erebus volcano using artificial intelligence techniques. To accomplish this, we apply multiple machine learning phase pickers (EQTransformer and PhaseNet), trained with different data sets that include waveforms from tectonic and volcanic observatories, to approximately two months of seismic data from an array of over 100 three component short-period stations, augmented by a small number of broadband stations, that were deployed during the austral summer of 2008. We associate picks into events using PyOcto, a high-throughput seismic phase associator. This procedure detects thousands of events within the two months of data, with the greatest number of events being detected by EQTransformer trained on a volcanic dataset. We obtain hypocenter locations using a solver that employs the fast marching method and accommodates topography. We characterize and cluster the seismic events based on dynamic time warping distances, frequency indices, and hypocentral locations. Our objective is to develop a concise but high-resolution seismic event catalog for Mount Erebus to explore its internal and near-surface seismicity for further insight into its magmatic plumbing system.

Nodal Deployment and Characterization of Microseismicity and Structure at Cape Modern Geothermal Field, Utah

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Microseismicity during stimulation and production related to enhanced geothermal systems (EGS) contains rich information of reservoirs including fracture locations, its orientations, fluid migration, and permeability. The Cape Modern Geothermal Field in Utah has been monitored by multiple types of seismic instrument including shallow-borehole seismometers, surface nodal arrays with and without data telemetry, and borehole distributed acoustic sensing (DAS). We apply comprehensive analyses to observed seismic data using both numerical and artificial-intelligence (AI)-aided methods for detection, location, focal mechanisms, and stress characterization to understand the evolution of seismicity and reservoir changes. Multiple fractures are revealed by the location and focal mechanisms of small events. The nodal deployment can enhance the aperture coverage for accurate estimation of focal mechanisms, although the distance from the reservoir to surface suppresses high frequency wavefields, which makes the corner frequency analysis difficult. The continuous measurements can contain rich information of ambient noise, which provides near-surface structure model to understand the geology and ground motion. Because of the frequency band of the ambient noise, the tomography is mainly sensitive to 100-500 m depth from the surface and reveals the NE-SW structures. We also compare the quality of datasets recorded by different instrument to make a recommendation of optimal network for seismic monitoring.

Nodal Arrays for Improved Tomography Imaging of the Ecuadorian Forearc and Insights Into Slip Behavior Controlling Process

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Large subduction earthquakes (Mw > 7.7) often occur along the Ecuadorian subduction zone where the Nazca plate converges towards the South American plate. In 2016, the Pedernales megathrust earthquake (Mw 7.8) led to nearly 60 temporary stations being deployed. Data from this international response and the permanent network run by IG-EPN showed that subducted seafloor topography, accreted terranes, and inherited structures control the slip behavior along the margin. However, the role of fluids in the stress build-up and the influence of a large rupture on the distribution of fluids remain open questions. For that reason, nodal arrays were installed in the northern Ecuadorian forearc in 2020 and 2022, overlapping with the rupture area of the Pedernales earthquake. The second array overlaps with 60 broadband stations deployed from 2021 to 2022 from the foothill of the Andes to the coast. Using Deep-Learning phase picking on continuous recordings, we derived a seismicity catalog of over 3,000 earthquakes made of 300,000 P and S arrivals. Both P and S-wave velocity models were derived from a 3D travel time tomography inversion. The models were then used to infer fluid saturation and crack density.

The velocity model derived from the nodal arrays shows higher resolution features than tomography inversion, which used broadband stations only. We identified a slower and narrower velocity area overlaying with the rupture extent of the 2016 Pedernales earthquake and more focused high-velocity and high Vp/Vs structures. The velocity model shows structures associated with higher amplitude peaks in the over-thickened oceanic crust of the downgoing plate. The nodal arrays offer insights into the controls of slip behavior around the plate interface. The subducting plate appears more cracked and saturated with fluids than the overriding plate. The plate interface is highly fractured which suggests that cracks may consist of fluid migration pathways. The fluid circulation may cause seismicity on subducting faults while the seepage on the plate interface could trigger subduction earthquakes.

High-resolution Imaging of Fault Damage Zones Based on Multiple Ultra-dense Arrays in the Aftershock Zone of the 2023 Kahramanmaras Earthquake Sequence in Southern Türkiye

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The 2023 Kahramanmaras earthquake sequence included two events of magnitude 7.5 and 7.8 only nine hours apart causing significant damage and loss of life in southern Turkey and northern Syria. To capture the ongoing aftershock sequence and image fault zone structures in greater detail, we deployed an array of up to 200 5-Hz Smartsolo nodal stations and 16 broadband/strong motion stations across the rupture zone for ~100 days beginning in May 2023 which we termed the "Eastern Anatolian Seismic Temporary" (EAST) array. We also deployed an ultra-dense fault zone profile across the Pazarcık segment of the East Anatolian Fault (EAF) and the Sakçagöz-Narlı Fault (SNF) where the M7.8 mainshock initiated. In Fall 2024, we deployed four additional dense fault zone profiles across and along the Pazarcık segment of the EAF where the M7.8 mainshock likely ruptured at a supershear speed. In this study, we present preliminary results from the analysis of fault zone waves recorded by these ultra-dense fault zone profiles. Specifically, we selected local earthquakes from a new high-resolution earthquake catalog built using our nodal recordings. Next, we use both visual inspection and automatic methods to detect fault zone trapped waves (FZTWs) that are recorded by stations close to the surface rupture zones. We examine the moveout of the FZTWs associated with both hypocentral depth and source-receiver geometry to better understand the depth extent and asymmetric properties of the fault damage zones. We also attempt to detect fault zone head waves (FZHWs) that refract along the bi-material fault interface to better quantify the velocity contrasts across multiple fault segments. Our preliminary results suggest the presence of an asymmetric damage zone further to the east across the Pazarcık segment of the EAF, which is consistent with the preferred damage zone along a bi-material rupture zone. Future work will examine other fault-zone profiles and combine waveform modeling of fault zone waves and body-wave tomography to better understand the relationship between fault zone properties and earthquake rupture behaviors.

Fault Geometry in the 2023-05-11 Mw 5.5 Lake Almanor, California, Earthquake Sequence, Revealed by Precise Aftershock Locations and Focal Mechanisms From a Nodal Deployment

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The 2023-05-11 M_w 5.5 Lake Almanor earthquake, and a M_w 5.2 aftershock ~11 hours later, ruptured normal faults in a sparsely instrumented region in Northern California, with only one strong-motion seismic station within 10 km and two broadband stations within 25 km epicentral distance. Previously, the 2013-05-24 M_w 5.7 Canyondam earthquake and its aftershocks had occurred ~5 km southeast of the May 2023 earthquakes (Chapman et al., 2016). The presence of several nearby dam facilities within 15 km motivates a detailed study of the causative fault structure(s) and geometry at depth, to inform site-specific seismic hazard.

Within two days of the mainshock, the U.S. Geological Survey (USGS) deployed 34 nodal seismometers for ~2 months, from 2023-05-13 to 2023-07-27, to record the Lake Almanor aftershocks at close (<5-10 km) epicentral distances with dense azimuthal coverage. These nodal seismometers, spaced ~3 km apart, recorded three-component continuous waveforms sampled at 200 Hz. For over 100 ComCat M 1.0 to 4.1 earthquakes between 2023-05-13 and 2023-07-24 (USGS, 2017), contributed by Northern California Seismic Network, we use nodal waveforms to improve event locations and focal mechanism estimates. Automatic P and S picks on 15-second nodal event waveforms, made by the PhaseNet deep-learning model (Zhu and Beroza, 2019), result in hypocenters that are 2-5 km deeper than ComCat. Subsequent double-difference relocation illuminates northeast-dipping fault geometry with changing dip along the fault strike. Additional first-motion P-wave polarities and S/P amplitude ratios from the nodal data reduce the uncertainty in focal mechanism orientation by ~25°. We find that the 2023 M_w 5.5 sequence locates northwest of the 2013 M_w 5.7 sequence without spatial overlap, and occurred on a large underlying fault structure with potential for a M6+ earthquake.

Innovative Applications of Seismic Nodal Technology for Hazard Mitigation and Earth System Monitoring [Poster]

Poster Session • Tuesday 15 April

Conveners: Andy Barbour, U.S. Geological Survey (abarbour@usgs.gov); Paul Bodin, University of Washington (bodin@uw.edu); Nahomy Campos, Volcanological and Seismological Observatory of Costa Rica (nahomy.campos.salas@est.una.ac.cr); Esteban J. Chaves, Volcanological and Seismological Observatory of Costa Rica (esteban.j.chaves@una.ac.cr); Joan Gomberg, U.S. Geological Survey (gomberg@usgs.gov); Sonia Hajaji, Volcanological and Seismological Observatory of Costa Rica (soniahajaji@gmail.com); Marino Protti, Volcanological and Seismological Observatory of Costa Rica (marino.protti.quesada@una.cr)

POSTER 8

Guralp Artius: A Revolutionary Broadband Node to Further Enable Passive Seismology

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The Artius broadband node represents a transformative innovation in seismic instrumentation, designed to bridge the gap between traditional broadband seismometers and popular nodal systems. While broadband seismometers offer unparalleled sensitivity and frequency range, their cost and complexity often limit large-scale and dense deployments. Conversely, geophones provide cost-effective solutions for high-frequency applications but lack sensitivity to low-frequency seismic signals, which are critical for many research and monitoring purposes. Artius provides a cost-effective compromise, delivering increased sensitivity and a true broadband frequency range at an economic price point.

Designed by Güralp Systems, Artius integrates a compact, highly sensitive broadband seismometer with an environmentally sealed anodized aluminium enclosure, ensuring optimal performance and robustness across diverse geophysical applications. Boasting a response of 30 seconds to 200 Hz, Artius greatly outperforms geophone-based systems while still being perfectly suited to rapid temporary deployments where it can be either pushed or staked into the ground and connected to an external power supply. Artius pushes the limits of versatility, facilitating real time data monitoring, as well as passive data collection. Artius has an onboard SEEDlink server, compatible with all standard seismological monitoring techniques, truly setting it apart from anything on the current market.

Artius is designed to be docked into an eight-node capacity docking station for data validation and mass data download. The docking station also serves as a 'huddle' system for configuration and testing prior to deployment, ensuring each node is performing optimally prior to deployment. The Artius nodes are intended to be deployed in large arrays, perfect for passive seismology, ambient noise studies and earthquake studies.

POSTER 9

Using Nodal Arrays for Fluvial Seismology Applications: Tracking Flow Fronts, Rockfalls and Bedload Transport

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Seismic instrumentation along river systems have produced useful observations of a variety of fluvial processes, including signals from water turbulence and bedload transport, although many early studies focused on data from one or a few seismic stations. More recent efforts in fluvial seismology have deployed many more stations in various array geometries to better characterize the fluvial signals. Here we describe multi-year seismic nodal array deployments in the Arroyo de los Pinos ephemeral tributary of the Rio Grande in central New Mexico, USA used to characterize signals associated with monsoonal flash floods and resulting bedload transport. Over the five years of deployment, we have placed nearly 250 nodes (average ~50 per summer season) along the channel banks, where they have recorded signals from over 18 floods ranging in flow depths of few cm to ~1.4 m. These nodal arrays also captured signals associated with channel bank collapse and rockfalls during high flows; in some cases the nodes were involved in the bank collapse. In addition, we describe flood signals recorded on a seismic node buried within the channel itself, providing unique observations of flow and transport signals directly below the active flow, suggesting much higher frequency energy than recorded at nodes several meters away on the channel banks. We also discuss deployment strategies to reduce effects of other local noise sources on the fluvial signals of interest.

POSTER 10

Apparent Large Seismic Velocity Variations Across the East Anatolian Fault, Turkiye

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We use aftershocks of the 6 February 2023 Mw 7.8 and Mw 7.6 Kahramanmaras (Turkiye) earthquake sequence that were and data recorded on nodal seismometers to develop 2D tomographic Vp and Vs models of the upper 12 km of the crust across the East Anatolian Fault (EAF) near Malatya, Turkiye. Nodal seismometers were deployed along an ~8-km-long, N-S-oriented profile, centered on the EAF, with nominal 0.5-km spacing. We used eight aftershocks (M2.1 to M2.9) that were aligned with the nodal array, and we developed velocity models using first-arrival P- and S-waves and local-network-based hypocenters. The resulting models show wide-ranging velocities (Vp = 5 to 7.5 km/s; Vs = 3.1 to 4.7 km/s) across the EAF in the upper 12 km of the crust, with higher velocities (Vp ~6 km/s to 7.5 km/s; Vs = 3.6 km/s to 4.7 km/s) north of the EAF and lower velocities (Vp ~5 km/s to 5.5 km/s; Vs ~3.1 km/s to 3.5 km/s) south of the EAF. Vp/Vs ratios are highest (1.8) directly beneath the fault at 7 to 11 km depth. Such large velocity variations make it difficult to accurately locate earthquakes using the network's regional 1D velocity model. In addition, our velocity models are affected by the local network-determined hypocenters. As a result, we develop more detailed velocity models and earthquake locations using a combination of regional nodal seismometer data and network data.

POSTER 11

Revealing 3D Subsurface Structure of Paliki Peninsula, Kefalonia, Greece

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Paliki Peninsula, the western end of Kefalonia Island, has been repeatedly hit by moderate to large earthquakes and is located in one of the most active seismotectonic regions of the Mediterranean Sea, to the east of the major Kefalonia-Lefkada transform fault. In 1953, an Mw 7.0 earthquake, preceded by two Mw 5.9 and Mw 6.6 foreshocks, produced extensive damage in Kefalonia. More recently, in 2014, a sequence with two main shocks (~ Mw 6.0) within eight days caused considerable damage and ground failure in the Paliki Peninsula. To develop a new 3D subsurface model for understanding site effects and to compute a more detailed velocity model for accurately locating earthquakes, a joint geophysical field campaign was organized in September 2024. During this campaign, we installed eight cross-profiles and one array through the Paliki Peninsula, using 24 SmartSolo IGU-16HR 3C nodes, three SmartSolo IGU-BD3C-5LC broadband devices and two Tromino instruments. Ambient noise measurements were carried out at 220 locations, resulting in 3225 hours of recorded ambient noise data, including recordings of tens of small earthquakes. Array- and cross-correlation techniques, and Horizontal to Vertical Spectral Ratios (HVSR) were applied to model the shallow sedimentary cover and variation in bedrock depth, for better understanding the impact of earthquakes on this area. Preliminary results show increasing thickness of Miocene marls deposits from west to east, overlaying a bedrock of Eocene limestones deeping towards the eastern shoreline of the peninsula, with a steeper attitude in the north. To our knowledge, this is the first time that such large-scale fieldwork has been performed on the Ionian Islands and the recorded data will stimulate new research studies, contributing significantly to more precise earthquake locations, and more accurate local hazard assessments and risks evaluations.

POSTER 12

Urban Seismology in Cartago, Costa Rica Using Seismic Nodal Arrays to Uncover Faults

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Analyzing seismic signals to find faults in tropical areas presents unique challenges, due to intense weathering, dense vegetation, varying climate, thick soil layers, and extensive human infrastructure. Despite these obstacles, the risks associated with natural disasters, such as earthquakes and volcanic eruptions remain significant. A notable example in Costa Rica is the city of Cartago, where a magnitude 6.2 earthquake destroyed much of the area in 1910. The specific local fault or faults responsible for this and previous events remain unknown.

To address this knowledge gap, we deployed 70 Smart Solo Nodes across a 20 km x 16 km area in Cartago to try to identify and map the faults. These sensors were strategically placed every 2 km next to houses, farms, businesses, and public lands. We aim to better constrain the earthquake hazard by providing detailed insights into the 3-D structures and mechanics of this fault zone. This temporal array will be removed at the end of April 2025.

This project is a collaborative effort between the Observatorio Vulcanológico y Sismológico de Costa Rica, Universidad Nacional (OVSICORI-UNA), and the U.S. Geological Survey, with major support from the U.S. Bureau of Humanitarian Assistance's Earthquake Disaster Assistance Team (EDAT) program. We conduct monthly service runs to collect data, amounting to 6 GB per day, while employing both hand-picking techniques and machine learning for phase identification and earthquake localization.

Our preliminary results indicate the presence of microseismicity associated with swarm activities in both the western quadrant, and the southeast quadrant, the latter corresponding to the northwest end of the Talamanca mountain range. Our ongoing efforts will continue to refine hazard mitigation strategies, ultimately improving community resilience and knowledge about natural disasters.

POSTER 13

Unsupervised Spectral Clustering and Spectral Ratio Analysis of Earthquakes in Cushing, Oklahoma

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Oklahoma has been at the center stage for the increase in midcontinent seismic activity during the last 15 years due to the production of oil and gas and the associated injection of fracking fluids and wastewater disposal. While there were notable large earthquakes, such as the M5 Cushing and Pawnee events, there are a vast number of smaller events; the spectral characterizing of these events can provide valuable insight into faulting mechanisms, which can lead to a better understanding of how fluid injection impacts the evolution of the subsurface. Two hundred fifty small earthquakes were detected using a combination of machine learning and beamforming algorithms with a dense nodal array composed of 130 three-component stations deployed in Cushing, Oklahoma, from November 5th, 2019, to December 15th, 2019. Here, we use SpecUFEx to perform the unsupervised spectral clustering of these earthquakes to investigate their spectral content's spatial and temporal variations. SpecUFEx uses non-negative matrix factorization and hidden Markov modeling to create a fingerprint of an earthquake's normalized spectral content; these fingerprints are then used as features to perform k-means clustering of the events.

Analysis of the spectral content centered around the P-wave arrival on the vertical component of all stations in the array using SpecUFEx identified two spectral clusters. One cluster is enriched in energy across a higher and broader frequency band; the other cluster appears narrow-banded. The main Cushing fault exhibits events only in the broad cluster enriched in high-frequency content, while two faults outside the array are almost entirely narrow-banded. The clustering results suggest that the spectral content recorded at the array stations may be sensitive to the hosting fault structure or the event's path to the array. To determine the path effect on the clustering results obtained from SpecUFEx, we will perform further analysis by exploring the spectral ratio of the events in each cluster and calculating the empirical Green's function to obtain the corner frequency and stress drop.

POSTER 14

The Antics Large-N Seismic Deployment in Albania

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Despite being an earthquake prone country with one of the highest seismic hazard in Europe, the velocity structure and seismogenic sources of Albania remain poorly resolved in detail. Attempting to tackle this issue we conceived the project ANTICS (AlbaniaN TectonIcs of Continental Subduction), including a dense deployment of 382 seismic stations covering about 60% of the country from east to west, with an average inter-station spacing of 6 km. This network remained in place between September 2022 and May 2023, after which it was reconfigured into a 4-line array for receiver function analysis until April 2024, when the whole network was dismantled. Additionally, the ANTICS deployment was built upon our previous experiment in the region, concerning the aftershock seismicity of the 2019 Mw=6.4 Durrës earthquake.

Some of the goals of the ANTICS project are (1) detection and characterization of local seismicity using AI-based methods for detection and association of earthquake phases, (2) full characterization of the 3-D velocity structure using LET, FWI and seismic noise correlations, and (3) receiver function analysis for deeper structure. Here we present the network deployment and its goals, along with some of the results obtained so far. We also delve into the dataset recovery and overall quality, highlighting the challenges of deploying, processing and archiving such large temporary dataset. Finally, we expand on our future plans for the area, including the further deployment of stations towards the south, in the bordering region between Albania and northern Greece.

POSTER 15

An Initial Dense Seismic Array Study of Magmatic System Structure and Seismicity of the Three Sisters Volcanic Complex

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The Three Sisters volcanic complex of central Oregon is classified as a Very High Threat system, with geodetic evidence for ongoing multi-decadal surface deformation, lava flows as young as ~1600 years, and Holocene eruptions of compositions ranging from basaltic andesite to rhyolite. Yet, there is little knowledge of the 3-D distribution of middle to upper crustal magma storage and microseismicity beneath this multi-vent volcanic complex located within the High Cascades graben. Observational seismology has been limited by the need for minimal impact in a large federal Wilderness. An array of about 240 low-impact three-component nodal seismometers from Summer 2024 is providing the first local imaging and microseismicity perspectives on the Three Sisters magmatic system. Ambient noise surface wave tomography of shear velocity in the middle-to-upper crust, local seismicity detected by deep learning models, and teleseismic receiver function results will be presented. Seismicity and structure identified in the study will be compared with swarm activity detected by the regional network in 2001 and available geodetic constraints. Based on erupted compositions and geodesy we hypothesize that upper crustal magma storage is more likely in the southern portion of the complex, near South Sister volcano. The results will also serve as a case study on the potential of a low-impact nodal array deployed largely on foot in Wilderness for an initial evaluation of modern seismic structure and activity at an understudied high threat volcanic system.

POSTER 16

Volcanic Tsunami and Its Prediction for Early Warning

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Volcanic tsunamis pose serious threats to nearby coastal communities. Our study of the 2022 Tonga volcanic event revealed that the erupted air-pressure wave was a precursor to the tsunami. Contrary to previous theories, our findings indicate that the eruption process drives both the air-pressure wave and tsunami dynamics through a coupled atmosphere-ocean source mechanism. This insight offers a new approach for incorporating air-pressure sensors into early warning systems. Related publication: Nature's *Communications Earth & Environment*, *https://doi.org/10.1038/s43247-024-01694-z* .

The Landscape Record of Earthquakes and Faulting

Oral Session • Wednesday 16 April • 8:00 AM Local

Conveners: Solène Antoine, California Institute of Technology (santoine@caltech.edu); Sean Bemis, Virginia Tech (sbemis@vt.edu); Ron Counts, University of Mississippi (rcounts@olemiss.edu); Hanna Elston, Smith College (helston@smith.edu); Nadine Reitman, U.S. Geological Survey (nreitman@usgs.gov); Jessica Thompson Jobe, U.S. Geological Survey (jjobe@usgs.gov)

Quantifying the Erasure of Earthquakes From Desert Landscapes: Implications for Interpreting the Geomorphic Record of Faulting in Hazard Assessment

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Seismic hazard analysis relies on knowledge of the timing of past earthquakes, the length and segmentation of faults, the distribution of slip, and the par-

titioning of that slip between primary and distributed fractures. This information is recorded in the landscape coseismically and erased over time by surface processes. The surface process clock starts ticking immediately after the earthquake so that the time elapsed since the most recent event and surface process vigor dictates the level of detail available for mapping the fault. We use landscape evolution models (transport-limited 2D linear diffusion) to quantify the information loss due to surface processes from the record of surface-rupturing earthquakes in desert landscapes. For the original landforms, we rely on lidar topography collected following the surface ruptures from the 2019 Ridgecrest (California) and 2010 El Mayor-Cucapah (Baja California) earthquakes. We sample a range of rupture styles and rock types. We simulate the effect of surface processes over a 10,000 year time series since the scarp-forming event, mapping the discernible fault traces at five time steps within this series. We rely on two metrics to characterize the information loss associated with surface processes: the change in mappable fault trace length over time and a degradation coefficient that quantifies the evolution of topographic slopes. Only 20-70% of the original fault trace length remains mappable at 10k years. This variability and the rate at which information is lost is primarily controlled by the geometry of the original surface rupture structure. Our findings provide quantitative constraints on the loss of information that can be incorporated into probabilistic displacement hazard assessment.

Rock, River, Record: Reading the Geomorphic Record of Seismic Cycles Through Bayesian Inversion of River-incised Landscapes

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Earth's topography is a complex recorder of tectonic processes due to its continuous reshaping by surface processes. Deciphering the interplay between tectonic forces and surface processes is essential for extracting quantitative information about tectonics. Successfully retrieving tectonic forcing from landscape is particularly appealing in light of recent observations showing that seismic cycle deformation leaves a distinct spatial footprint in the long-term (~100+ kyrs) morpho-structure of forearcs, suggesting that subduction landscapes could provide valuable insights into the long-term behavior of seismic cycles (Oryan et al., 2024).

Here we present a method to invert river incised landscapes for geological uplift pattern shaping the terrain. We rely on the fact that rivers incise topography at rates strongly dependent on local slope, making them well-suited to encode information about long-term vertical displacements. We leverage the normalized slope-area analysis of rivers (χ-analysis) to constrain the spatially-varying, long-term uplift function that has shaped a mountainous region using a Gauss-Newton inversion algorithm that best linearizes river elevation in χ-space. We demonstrate the resilience of our inversion method by retrieving uplift patterns from synthetic landscapes that incorporate complexities beyond those described by our stream power model. Subsequently, we apply our inversion to five natural landscapes shaped by normal faults (half-grabens) and to a 200-km-wide region of the Himalayas. We show that our inversion extracts uplift fields consistent with patterns expected from upper crustal flexure and previous estimates derived from geomorphological markers. The success of our method highlights its potential application to subduction landscapes, where it can shed light on the intricate behavior of seismic cycles over timescales far longer than those covered by current seismo-geodetic observations.

Using Mapped Tectonic Faults as a Record of Past Earthquakes to Predict Future Surface Rupture Location

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In surface-rupturing earthquakes, fault displacement can damage infrastructure that crosses fault zones. Geologists often predict future fault rupture locations from faults mapped based on landforms interpreted from remote sensing datasets like lidar topography and imagery. The effective use of fault maps for this purpose requires the following: Past earthquakes must create a persistent record in the landscape's geology and/or geomorphology. For example, earthquakes may create landforms such as fault scarps and triangular facets that are not significantly obscured by erosion. Geologists must accurately identify surface features, understand how tectonic and surface processes modify the landscape, and integrate these interpretations into the fault map. The record of past earthquakes must serve as a dependable predictor of future earthquakes, requiring that earthquakes largely rupture pre-existing faults.

We evaluated the accuracy of regional-scale fault maps in predicting the location of surface ruptures during the subsequent earthquake. Based on seven earthquakes with varying slip sense and in different climates, we found that the mapped faults predicted 12%- 68% of the principal ruptures with 15-30 m median separation distances between the predicted ruptures and well-mapped faults. We also investigated how tectonic landform type and surficial lithologic age influence fault location uncertainty. Certain tectonic landforms such as fault scarps and range fronts mapped prior to the earthquakes showed lower location error, while faults cutting Holocene units exhibited larger errors. Our work to quantify uncertainty in fault location mapping will improve engineering assessments, risk management and the definition of fault study and exclusion zones.

Lacustrine and Terrestrial Paleoseismic Records of the Twin Lakes Fault Near Mt Hood, Oregon, USA

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The Oregon Coast block, located in the Cascadia Subduction Zone forearc, has been translating north and rotating clockwise relative to North America for much of late Cenozoic time. Proposed extension along faults may partially relieve intra-plate strain at the trailing edge of this block. Bare earth lidar topography reveals a series of N- and NNW- trending extensional and oblique faults across the modern High Cascade volcanic arc. Previous paleoseismic investigations have characterized several of these faults as Holocene-active. Immediately south of Mt Hood, the N-S trending, west-dipping Twin Lakes fault impounds a series of small drainages. Scarps up to at least 12 m high and depositional basins on the down-dropped fault block suggest a history of repeated surface-rupturing earthquakes.

In summer 2024, we extracted a series of lake sediment cores from two fault-dammed basins, Frog Lake and Lower Twin Lake. Stratigraphy at Lower Twin includes silt laminae, ash beds, and a wedge of massive coarse sediment that thins away from the subaqueous fault scarp. Preliminary stratigraphic interpretations correlate the coarse wedge to existing post-LGM timing constraints for the penultimate earthquake on the Twin Lakes fault. New multi-beam seismic surveys produce high-resolution bathymetry and sub-bottom profiles of both lakes, revealing a bathymetric low and stratigraphic on-lapping at the Twin Lakes fault scarp. New geologic mapping shows glacial deposits offset at the scarps damming both lakes, with paleo-lacustrine deposits on the uplifted footwall east of Frog Lake. We also excavated a hand-dug paleoseismic trench across a 1.5 m-high, uphill-facing scarp between the two lakes. The trench revealed evidence for a surface-rupturing earthquake that produced 0.7 m vertical offset in glacial deposits across a 2.5 m-wide zone of faults and fissures, capped by an unfaulted ash we interpret as the Old Maid eruptive tephra (1781-1790s C.E.). This new lacustrine and terrestrial evidence suggests the Twin Lakes fault has produced multiple late-Quaternary surface ruptures, designating it a local seismic hazard.

Constraining Past Earthquakes in the NMSZ Using Sediment Records of Three Separate Lakes

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The New Madrid Seismic Zone (NMSZ) is an enigmatic source of large intraplate earthquakes that poses hazard to the central U.S. Given the earthquake history and source location of the NMSZ is poorly understood, we use lacustrine paleoseismology techniques to improve estimates of recurrence and proximity of large earthquake events. Here, we present a continuous record of large earthquakes from sediment cores collected from three lakes spanning the NMSZ: Swan Pond, KY (northeast), Reelfoot Lake, TN (central), and Wapanocca Lake, AR (southwest). Computed tomography (CT) scanning and bulk gamma density reveal high-density beds and convoluted bedding that indicate major depositional disturbances at these sites in the past. Bayesian modeling of radioisotopic ages indicate these events roughly coincide with previously documented past earthquakes. The historic earthquakes and aftershocks in 1811-1812 CE are distinct in all three lake records, and magnetic susceptibility peaks resolve three discrete events within Wapanocca Lake sediments. Wapanocca Lake sediments also preserve evidence of seismic disturbances from three older periods that overlap with regional evidence of liquefaction and sackungen ~1450 CE, ~900 CE, and at the base of the record at ~560 CE. Another period of sediment disturbance is distinct in deeper Swan Pond sediments, coinciding with evidence of liquefaction in the central and northern NMSZ ~900 CE. Clear evidence of seismicity is lacking from all three Swan Pond sediment cores ~1450 CE, when liquefaction features were concentrated in the central and southern NMSZ. The sediments in Reelfoot Lake abruptly shifted from a river floodplain to a lacustrine environment following the 1811-1812 earthquakes; the sediment record extends to the mid-1700's with no evidence of earthquake disturbance prior to 1811-1812. Evidence of ground motion recorded in three basins in conjunction with liquefaction and sackungen features provide a rich dataset to constrain the timing and frequency of large earthquakes in the NMSZ and expands the paleoseismology toolkit to include small, shallow-sloping lakes in the central U.S.

Geodetic Imaging of Strain Partitioning Between the Megathrust and Crustal Faults in Cascadia

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Strain accumulates in the Cascadia subduction zone region over interseismic periods and is released via large magnitude earthquakes and slow-slip events (SSE). The spatial distribution of strain accumulation can vary due to megathrust geometry, extent of interplate coupling, upper-plate fault configuration, and the degree of forearc segmentation. Here, we use interseismic GNSS surface velocities to constrain elastic block models and evaluate a suite of possible block configurations that are primarily based on the Cascadia Region Earthquake Science Center Community Fault Model. In addition, we include several sets of offshore faults that trend sub-perpendicular to the trench and a network of dip- and strike-slip faults in southern Cascadia to test possible segmentation of the forearc. Because several models fit the inverted GNSS velocities equally well, we compare modeled fault slip rates to geologic estimates and uplift rates to leveling and tidal gauge data in order to delineate between models. Segmented forearc models fit independent uplift rates better than continuous forearc models, and in some cases, the addition of segments improves the model fit of crustal fault slip rates to geologic rates. However, the slip rates on the trench-perpendicular faults that segment the megathrust do not agree with previously published slip rates. Most models estimate shallow megathrust coupling that is stronger offshore Washington (46-48°N latitude) and northern California (40.5-42°N) than it is offshore Oregon. The coupling distribution on the megathrust is sensitive to fault segmentation, and the greatest differences among models arise in southern Cascadia and offshore Vancouver Island. Slip deficit accumulated on the megathrust can be released via SSEs, impacting the net spatial distribution of coupling over longer time periods. As a consequence, coupling on the megathrust varies temporally. Constraining the spatial distribution of interseismic coupling and its temporal variations that may arise from SSEs can improve our understanding of the seismic hazard in the Cascadia subduction zone.

Insights From 3D DEM Models Into Along-strike Variability of Ground Surface Ruptures Observed in Thrust and Reverse Fault Earthquakes

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We explore how source characteristics and geological site parameters affect along-strike variability in ground surface deformation patterns commonly associated with thrust and reverse fault earthquakes. Building on the 2D analysis by Chiama et al. (2024), which identified relationships between geological parameters (such as sediment depth, density, and fault dip) and surface rupture patterns using a suite of 3,434 2D distinct element method (DEM) models, we extend the investigation into 3D DEM models.

Our 3D models successfully reproduce major fault scarp types – monoclinal, pressure ridge, and simple – aligning with ground rupture characteristics previously identified in 2D modeling. For 3D models with homogeneous sediment strengths and constant fault dip along-strike, scarps tend to form cylindrical styles of deformation. In contrast, variability in these parameters along-strike results in diverse scarp styles, widths, and dips, as well as variable patterns of secondary fracturing. Notably, 3D scarps often display secondary conjugate fractures that facilitate hanging wall collapse and may influence long-term denudation of these features. Furthermore, we examine the effect of oblique slip which yields transitional fault scarps from thrust and reverse fault morphologies to strike-slip patterns of deformation with narrower scarp widths. These DEM models replicate surface fault rupture patterns observed in events such as 1999 Chi-Chi, 2008 Wenchuan, and the 2024 Wushi aftershock. Finally, we show that DEM models can effectively reproduce patterns of multiple rupture cycles, including erosion and sediment deposition, captured in paleoseismic trench observations. We propose that these 3D DEM models support and further augment the quantitative relationships between fault characteristics (slip, dip) and sediment strengths and thicknesses derived from the 2D DEM results of Chiama et al. (2024). Together, these results can be used to forecast along-strike patterns of ground surface deformation from thrust or reverse fault earthquakes based on specific fault characteristics and geological site conditions.

Constraints on Geometry of the San Joaquin Hills Blind Thrust Fault, Orange County California U.S.A, From Quaternary Geology and Recent Earthquakes

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The landscape record of earthquakes on blind faults can be subtle. An active blind fault beneath Los Angeles (USA) was famously discovered on January 17, 1994 when it generated the M_w6.7 Northridge earthquake. In hindsight, geomorphic and subsurface evidence of the fault was recognized and geologists set about to find other potentially active blind faults in the region. The San Joaquin Hills in coastal Orange County, CA, are underlain by complexly faulted Miocene marine rocks that are uplifted and exposed at the southern margin of the Los Angeles basin. A suite of gently folded uplifted Quaternary marine terraces, an emergent Holocene shoreline and uplifted Holocene fluvial deposits have previously been mapped and interpreted as evidence of an active blind thrust fault dipping SW 20-30 degrees beneath an anticline subparallel to the Newport-Inglewood fault zone, with partitioned slip on the San Joaquin Hills thrust and strike-slip Newport-Inglewood faults. Published and unpublished models of the San Joaquin Hills blind fault differ in geometry, Quaternary uplift rate and fault slip rate. The Quaternary Fault and Fold Database of the USGS and the Community Fault Model of the Statewide California Earthquake Center include models of the San Joaquin Hills thrust. Better constraint on fault geometry is desirable for seismic hazard assessment. In June 2024 a sequence of M2.8, M3.6, M3.4 earthquakes occurred at a depth of 12-13km beneath Newport Mesa near where the axis of the anticline is exposed in upper Newport Bay. USGS focal mechanisms from all 3 events include nodal planes that dip 48-56 degrees SW with nearly pure thrust or right oblique thrust. Seismicity in combination with Quaternary geology of the San Joaquin Hills suggests that a moderately (~50 deg) SW dipping fault with nearly pure thrust motion is the best model for the poorly constrained blind fault.

Unearthing Slickenlines on the 2016 Rupture of the Kekerengu Fault and Paleosurface Ruptures of the Alpine Fault, New Zealand: Testing the Veracity and Utility of the Rupture-propagation-direction / Curved-slickenline Hypothesis

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Earthquake rupture direction is known to influence the distribution of strong ground shaking in large earthquakes. A recent theory put forward by Kearse et al. (2019; *Geology* v 49, n 9) - based on spontaneous dynamic rupture modelling and grounded in geological field observations - links patterns of curvature of slip striations (slickenlines) on fault surfaces to the direction of rupture propagation. We test this theory by un-earthing slickenlines on a fault (the dextral Kekerengu Fault) that had a known rupture propagation direction (northeastward) during the 2016 Kaikōura earthquake, New Zealand. Slickenlines that were exhumed from 1-4 m below the ground surface record the same sense of convexity as those observed on surface scarps immediately following the 2016 rupture. The slickenlines had a convex-up sense of convexity when viewed looking southeast onto the northwest-facing fault plane. This indicates a northeastwardly propagating rupture.

On the Alpine Fault, the dominant structure in New Zealand's ~30 mm/yr continental transform plate boundary, we observed on natural and hand-excavated exposures of the fault plane many curved slickenlines that formed during paleosurface ruptures. These were studied at three sites that span a region known to variably halt or allow passage of past earthquakes (an "earthquake gate"). Our field data reveal directions of paleo rupture propagation that complement and enhance the fault's spatiotemporally rich paleoseismic record. At Hokuri Creek and Martyr River, we observed both convex-up and convex-down curved slickenlines on and adjacent to principal slip surfaces, indicating past ruptures from both northeast and southwest of the proposed "earthquake gate". At Martyr River, relationships suggest that the most recent event (inferred to correlate to 1717 CE) ruptured from the southwest. Our results both here, and on the Kekerengu Fault, demonstrate the utility of curved slickenlines as a valuable new paleoseismological tool for determining past rupture directions, applicable to surface-rupturing faults globally.

Shear Wave Velocity Measurements in Fine Grained Soils With Muted Surface Fault Displacement Following the February 2023 Kahramanmaraş, Türkiye Earthquake

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Surface fault rupture causes significant damage to built infrastructure, such as pipelines, making understanding its behavior important for engineering design. Engineers and geologists need to perform remote observations and field measurements of fault rupture following large earthquakes to drive this understanding. The 2023 Mw 7.8 Kahramanmaraş earthquake in south-central Türkiye provided a unique opportunity for such studies. Following the first phase of fieldwork aimed at measuring surface fault rupture near the intersection of the East Anatolian (EAF) and Narlı faults, the second phase focused on shear wave velocity measurements along and across both fault ruptures for a variety of different geologic and subsurface soil/rock conditions. We focused on one such area on the EAF where the surface fault rupture was not easily visible aerially (i.e., muted). The results of the shear wave velocity measurements in this region revealed that the surficial units of fine grained lacustrine sediment have very low shear wave velocities (< 50 m/s), leading us to hypothesize that the muted expression of surface fault rupture in this area was due to the damping effects of these weak surficial units. These soft sediments are approximately 3 to 5 m thick and likely dispersed the faulting effects broadly, leading to a lack of any concentrated surface expressions of displacement as viewed both northeast and southwest of this area. This observation has important implications for the validity of surface fault rupture models, particularly in areas with soft, low-velocity soils where fault displacement may be less visible despite significant underlying deformation.

The Landscape Record of Earthquakes and Faulting [Poster]

Poster Session • Wednesday 16 April

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POSTER 1

Landscape Response to Deformation in the Northern Ecuadorian Forearc

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In the northern Ecuadorian forearc, subduction of the Nazca Plate and Carnegie Ridge beneath South America uplifts the Coastal Cordillera and activates faulting. This region has experienced multiple historic Mw 7.7–8.8 megathrust earthquakes, including the Mw 7.8 Pedernales earthquake in 2016, along with smaller (~M 5) crustal fault earthquakes. We use geomorphic metrics to analyze landscape response to long-term deformation and examine relationships with seismicity, slip behavior, and structure. Using the ALOS World 30m DEM dataset, we delineate drainage basins, generate long profiles to identify knickpoints, and calculate Normalized Steepness Index (Ksn), Hypsometric Integral, and Chi Analysis. We integrate these geomorphic metrics with earthquake locations and subsurface structure from a 3D tomographic inversion using local earthquake data recorded by dense broadband and nodal deployments. In the northern forearc, we delineate 89 drainage basins. Larger, older basins are inland, while smaller, younger basins are near the coast. Older drainages feature well-developed dendritic rivers, while younger basins do not, which reflects recent coastal uplift. Some rivers divert parallel to the coast before reaching the ocean. High Ksn values are noted along the Coastal Cordillera and main faults. The northern and southern segments of the Coastal Cordillera show westward drainage divide migration, while the central segment exhibits westward migration in the west and eastward migration in the east, connecting it to the southern segment. The seismicity has been plotted against the KSN values in our study area. Crustal seismicity of the Esmeraldas swarm has been previously correlated with an active fault. Knickpoints and high KSN values are found in the adjacent areas of the fault. The Rio Verde River intersects the Businga Dome, cored by mafic oceanic basalts. Changes in river sinuosity correlate with a crustal fault exhibiting slow-slip and earthquake swarms. We observe knickpoints associated with high KSN values on the surface above deep seismicity at the northeast downdip termination of the Pedernales rupture.

POSTER 2

A Multi-scale Look Utilizing Seismic Reflection Profiles and Paleoseismic Trenching Across Quaternary Active Faults in the Kittitas Valley, Washington, USA

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The Kittitas Valley, located in central Washington State, USA, is a low-relief basin within the northwest corner of the Yakima fold province, a region of active NNE-SSW shortening in the backarc of the Cascadia subduction zone. Our study focuses on the Dead Coyote and Craigs Hill faults, two en echelon faults that transect the valley and parallel the prominent and active fault-cored anticlinal ridges to the south. To understand the subsurface geometries, relative timing, and rate of deformation of these individual structures in the Kittitas Valley, we combine observations from multi-scale seismic reflection datasets, including legacy industry profiles (~4.5 km depth) and ~7.5 km of new high-resolution profiles (<1.5 km depth), with tectonic geomorphic mapping and paleoseismic trenching. The seismic data reveal shallow north-vergent anticlinal folding beneath an east-west trending set of fluvially incised knolls that define the queried Craigs Hill fault trace in the middle of the valley. Conversely, south-vergent folding is observed below the Dead Coyote fault scarp, located ~6 km to the north. Stratigraphic and structural relationships of late Pleistocene glacial drift deposits and Quaternary colluvial deposits within two trench exposures across the Dead Coyote fault scarp indicate multiple episodes of late Quaternary surface faulting above a south-verging thrust fault. Optically stimulated luminescence dating results, supported by pedogenic characteristics of buried soils developed on scarp-derived colluvial wedges, indicate long recurrence intervals of rupture with the most recent earthquake occurring at <5.3 ka and the penultimate earthquake occurring at <60.3 ka. Our findings suggest that these seismogenic faults within the populated Kittitas Valley accommodate and transfer transpressional regional strain westward across the Cascade Mountains.

POSTER 3

Near-fault-observation in a Seismic Gap Area: The Case of Mt. Morrone-Maiella Fault System (Central Italy)

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In May 2022, some INGV researchers launched an ongoing passive seismic experiment as part of the PON-GRINT project in the Mt. Morrone area of the Central Apennines, Abruzzo, Italy. The Mt. Morrone fault is known to be geologically active based on geological and paleoseismological studies. However, despite this, the past 40 years have shown low seismic activity, with only a few low-magnitude events detected. The experiment aims to monitor microseismicity in the study area, including any seismic events related to the Mt. Morrone Fault that permanent networks may not have detected.

The Apennine chain, formed by thrust and fold systems, has experienced significant tectonic activity due to the westward subduction of the Adriatic lithosphere. This has caused extensive uplift and extensional faults, forming intermountain basins, such as those at Fucino, Sulmona, and L'Aquila, filled with Plio-Quaternary continental deposits.

In this study, the Apennine sector under investigation is in the southeastern part of the Abruzzo region, has been affected by several significant historical earthquakes, including the 1706 (M_w = 6.6) and 1933 (M_w = 5.7) events, as well as the 1349 and 1456 seismic sequences (M_w = 6.6 and 7.0). The literature available also indicates that the 1456, 1706 and 1933 earthquakes originated in this area.

Between May and October 2022, twenty-three temporary seismic stations were deployed across a ~250 km² area stretching from the Sulmona-Pratola Peligna basin to Mt. Morrone. Preliminary analysis of the first 12 months of data shows sparse seismicity, mainly located beneath the Popoli-Sulmona basin. These events appear to be linked to the Mt. Morrone fault, with hypocentral depths consistent with the fault geometry. The seismicity forms two clusters: one on the northwest side of Mt. Morrone and another between Mt. Morrone and Maiella, likely related to the Caramanico fault along the western flank of the Maiella anticline.

POSTER 4

Lidar Analysis of an Elevated Marine Terrace Along the Olympic Peninsula, Washington State, USA

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Lidar reveals subtle geomorphic features in regions of dense vegetation, making it particularly useful along the forested coastlines of the Pacific Northwest. We use a bare-earth surface model derived from lidar to analyze a prominent terrace along the coastal extent of the Cascadia subduction margin in the western and northern Olympic Peninsula, Washington State, USA. The terrace extends discontinuously for ~150 km from Queets to the southern shoreline of the straits of Juan de Fuca. The geomorphic expression of the terrace is clear, displaying an even and undissected surface, a prominent front edge forming the modern rapidly eroding seacliff, and a backedge inset into high landslide-dominated bluffs. In most places, the bluffs mark the eroded edge of an extensive glacial till plain, with glacial flutes extending to within a few meters of modern sea level. Terrace geomorphic backedge elevations derived from lidar and confirmed by GNSS RTK measurements vary from ~4-8 m NAVD (North American Vertical Datum 88). Outcrop observations and test pits near Point Alava establish the marine origin of the deposits forming the terrace, which is underlain by an elevated marine abrasion platform capped by cobble grading into well sorted beach sand. The location, sedimentology, and geomorphology of the terrace are most simply explained as an elevated and abandoned beach complex. The lack of more than one conspicuous terrace surface suggests that terrace abandonment happened suddenly, consistent with a tectonic rather than glacio-isostatic origin. Future work will include testing predictions of fault deformation models against the distribution of terrace uplift values to discriminate between subduction and upper plate sources.

POSTER 5

Geophysical Investigation of a Quaternary Fault Beneath the National Mall and Memorial Parks in Washington DC

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The Adams Mill fault (AMF) is a high-angle reverse fault that thrust crystalline bedrock over an unconsolidated Potomac River gravel near the original entrance of the Smithsonian National Zoological Park (SNZP) in Washington, D.C. Two luminescence ages, ~451 ka and ~338 ka, indicate the gravel, and therefore the fault, are Quaternary. USGS geologic maps published in 1994 and 2017 show the AMF trends ~165° from the SNZP to a fault exposed at 18th and California Streets (in a 1931 trench), and to Lafayette Park north of the White House, where USGS drilling identified a fault. The 1994 map terminates the AMF in Lafayette Park. The 2017 map shows the fault continues southward under the White House, across the Washington Monument (WM) grounds, and into the Dumfries Fault Zone near the Thomas Jefferson Memorial.

Geophysical profiles using electrical resistivity (ER) and refraction microtremor (ReMi) were acquired on the WM grounds to try to image and verify the fault. Two parallel ER profiles show the bedrock elevation abruptly drops ~150 m west of the WM, which is consistent with the presence of a fault. Similarly, the ReMi data showed a significant change in shear wave velocity across the same position ~150 m west of the WM. Unfortunately, the two ER profiles were not spaced far enough apart, and two possible fault orientations best fit the ER data. One possible orientation is ~055°, which is roughly parallel to the Dumfries fault system on the 2017 map. This trend crosses through Arlington National Cemetery and lies ~500 m north of the Pentagon. The other possible fault orientation is 001°. A southward projection of this trend aligns well with a very straight, 20 km long section of the Potomac River, which suggests this channel section may be fault controlled. Displaced reflectors in an unpublished seismic reflection profile from East Potomac Park tenuously supports this possibility. Whether the fault at the WM is kinematically linked to the AMF is uncertain, but the presence of a Quaternary fault in an aseismic region is notable and provides new insight into the long-term paleoseismic history of the D.C. region.

POSTER 6

Left-lateral Faulting Beneath the Monte Cristo Range, West-central Nevada

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Earthquakes of M6.5 or smaller are challenging to interpret in the geomorphic record because of subdued coseismic surface rupture that can be obscured through time. We investigated one such earthquake, the 15 May 2020 M6.5 Monte Cristo Range (MCR) earthquake of west-central Nevada, a left-lateral rupture. Small coseismic surface breaks with horizontal displacement <20 cm were documented west of the MCR immediately following the earthquake. The eastern portion of the rupture, where the earthquake nucleated within the MCR, had no documented surface rupture. We further investigated the apparent lack of pre-existing or coseismic faulting through the MCR using additional field reconnaissance mapping, lidar review, and optical pixel tracking. None of these investigations revealed apparent surface faulting through the MCR in the eastern rupture domain, despite InSAR and aftershock observations indicating that an east-west trending, left-lateral fault ruptured at depth. While optical pixel tracking revealed a broad fault zone across the eastern portion of the rupture, this method showed a ~5km long surface rupture co-located with field observed surface rupture in the western domain. These surface rupture features have appreciably degraded over the four years since the earthquake. We completed two return trips to the rupture area to document the evolution of 2020 rupture features. Sites with vertical displacement (<10 cm) were better preserved than sites with primarily horizontal displacement. Taken together, our observations highlight the limited preservation of a moderate magnitude strike-slip earthquake, similar to observations made following the 1968 M6.6 Borrego Mountain earthquake. In probabilistic seismic hazard analyses, an event like this is unlikely to be captured in a geologic compilation of fault geometries (in the eastern domain) or with a geologic slip rate due to a lack of consistent long-term preservation of displacement along strike (in the western domain). Rather, this rupture represents a classic 'background' earthquake and would be captured by gridded seismicity.

POSTER 7

Paleoseismic Trenching Reveals Multiple Recent Earthquakes on the Great Southern Puerto Rico Fault Zone

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The Puerto Rico-Virgin Islands (PRVI) microplate is located within the broad deformation zone of the North Caribbean Plate Boundary. Active faults onshore Puerto Rico are accommodating northeastward PRVI motion, including the Great Southern Puerto Rico fault zone (GSPRFZ). On the southern coastal plain, the GSPRFZ is an active right-lateral normal northwest-trending fault. Quaternary landforms record ~4–8 m of oblique displacement on the GSPRFZ, but the number and timing of individual surface-rupturing earthquakes remains unconstrained. To address this, we excavated a paleoseismic trench across the GSPRFZ at a site where a single, ~1.5-m-tall south-side-down scarp crosses a Quaternary alluvial fan surface ~200 m along strike from an exposure of a bedrock fault zone. In the trench exposure, we documented faulted fluvial and colluvial deposits, two generations of fissure fill, and un-faulted colluvium. The primary fault in the trench was sub-vertical and branched into a ~0.5–2.5-m-wide zone of faults and fissures near the surface. The fault geometries and juxtaposition of different deposits across the fault zone suggest a significant component of strike slip, consistent with the geomorphic expression. Based on the trench observations and correlations with regional deposit ages, we interpret that the GSPRFZ has hosted at least two surface-rupturing earthquakes in the latest Pleistocene to Holocene, pending numerical chronology data (radiocarbon and luminescence dating). This dated exposure, along with existing data from prior paleoseismic trenches on the GSPRFZ and Salinas faults, will provide the first numerical constraints on GSPRFZ rupture history.

POSTER 8

Geomorphic Characterization of Fault Creep in the San Francisco Bay Area, California

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Creep has been observed along many seismogenic faults globally but is particularly common in the San Francisco Bay Area where the San Andreas Fault System distributes slip across several sup-parallel fault strands. Identification and characterization of creeping faults is a critical component of earthquake hazard assessment as creep can influence fault loading and stress transfer. Geomorphic evidence of creep in the landscape can be difficult to distinguish from seismogenic rupture. Observations of fault creep typically require long-term measurements through geodetic and satellite data and local deformation features, such as the opening of cracks and deformation of anthropogenic structures.

We focus on the Calaveras Fault in the San Francisco Bay Area which is both rapidly creeping and known to produce large (≥M6) earthquakes in the last century, providing the ideal natural laboratory to distinguish between active creep and seismogenic deformation in the landscape. Geomorphic fault mapping has not been updated in public databases since the availability of new lidar-based DEMs in Northern California. We aim to create a geomorphic framework for recognizing and delineating the subtle surface expression of slow or transiently creeping faults that can be used as a template for future creep characterization. Using high-resolution lidar data augmented with field observations along the Calaveras Fault, we refine fault stand locations in the actively creeping Morgan Hill section of the fault and document geomorphic indicators of faulting.

POSTER 9

Preliminary Insight Into Volcanic and Tectonic Controls on Crustal Deformation Near Ljósufjöll, Snæfellsnes Peninsula, West Iceland

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The interplay between volcanoes and tectonics are critical for understanding crustal dynamics and the ongoing Reykjanes Peninsula (RP), Iceland eruptions (2021-present) and graben forming events there provide key insight to this. The Snæfellsnes Volcanic Zone (SVZ) is off-rift and ~100 km to the north of the RP. Although the geochemistry and petrography of the SVZ is known, little is known about the structural framework or tectonic setting. We used a combination of remote sensing, combined with fit-for-purpose drone photography that we modelled using structure from motion (SfM) techniques to develop high resolution (~10 cm) digital elevation models (DEMs) there were a base for geological, geomorphic, and structural mapping, combined with field observations. We identified a major transtensional strike slip fault, striking N135°E and down to the Northeast with a major vertical component (from 4 to 12 m). There is evidence of significant strike-slip displacements including rivers, gulleys and lava flows. We observed recently active extensional fissures showing mode one opening and these fissures end at a "young" late-Holocene cone which shows a structural control of the volcanism here.

SVZ seismic activity in the last few decades was negligible. However since 2021 a greater number of small earthquakes (up to Mw 3.4) occurred along the southern section of the SVZ. Seismicity is up to 20 km. While this is not a sign of an impending eruption, it is an indicator that the SVZ is perhaps being influenced by new magma movement, that shallows over time, which is likely an indication of a future eruption, thus by the time of SSA 2025, it would not be surprising if an eruption had started there. Because of the large fault area and deep seismogenic zone, potentially large earthquakes up to Mw 7+ could be possible based on the preliminary results we show here. These findings contribute to a better understanding of the interaction between volcanic and tectonic processes on SVZ, offering useful insights into crustal deformation mechanisms in oblique rift zones and associated seismic and volcanic hazards.

POSTER 10

Expression of the Creeping San Andreas Fault at the Topo Creek Site

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The 150-km-long creeping section of the San Andreas Fault separates two sections that are mostly or entirely interseismically locked and known to host large M7+ earthquakes, notably in 1906 and 1857. The creeping section moves gradually at nearly the long-term fault slip rate (~35 mm/yr) and has no historical seismicity greater than M6 except in the vicinity of Parkfield in the southern transition zone. Whether or not large ruptures could propagate through the creeping section, potentially activating the northern and southern sections in a single M8+ earthquake, is a subject of ongoing debate and has significant implications for earthquake forecasts such as in the National Seismic Hazard Model. We report results from the Topo Creek site, near the middle of the creeping section, where we excavated trenches to search for evidence either for or against past large seismic ruptures. In the trenches, the fault is expressed in well-bedded alluvial sediment. The fault zone is about 10 m wide and includes a 2-m-wide zone of more intense deformation. The broader zone is characterized by a pervasive penetrative shear fabric with few well-defined individual shear planes. The apparent offset of units and intensity of shearing gradually decreases towards the surface without any clear upward terminations of faults or abrupt contrasts in degree of deformation that would indicate earthquake horizons. Even within the zone of concentrated deformation, we did not observe features indicative of sudden brittle rupture or strong shaking, such as sand blows, filled fissures, colluvial wedges, or broken blocks. All the deformation observed at this site is consistent with gradual creep and does not require high-speed frictional slip. The 2-m-wide zone of more intense deformation is the only area with features potentially consistent with large coseismic surface ruptures. We consider it unlikely that multiple such ruptures occurred during the time period represented by the exposed stratigraphy without broadening the intense deformation zone or leaving behind any unequivocal evidence.

POSTER 11

30 Years of Landscape Response Following the 1992 Landers, CA, Earthquake

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The landscape record of earthquakes is a primary tool to interpret the location, displacement, and recency of active faulting. Landscapes evolve after earthquake rupture from both natural and anthropogenic causes (e.g., precipitation, gravity, dirt bikes), causing erosion and modification of vertical fault scarps and laterally offset features. The 1992 M7.3 Landers, California, earthquake offers an opportunity to quantify the degradation of lateral and vertical displacements that were well documented post-earthquake (Arrowsmith & Rhodes 1994, McGill & Rubin 1999). We focus on an ~500-m-long section of the Emerson fault scarp near Galway Lake Road that had up to 5 m right-lateral and 1.75 m vertical displacement with areas of localized and distributed deformation. We document landscape change over 30 years using fault-parallel and fault-normal trenches and vertical differencing of topography derived from 1992 USGS aerial photographs taken two days after the earthquake and 2022 drone photogrammetry. The 1992 colluvial wedge in the fault-normal trench is 30-50 cm thick at the base of the vertical scarp, diminishing to 10-15 cm, 1.5 m down-trench from the base of the scarp. This wedge overlies a basal rock line, interpreted to be the ground surface prior to the 1992 earthquake, followed by chaotic debris deposits, and topped with finely bedded slope wash, burying ~1/3 of the original free face. The fault-parallel trench exposes a new channel incised since 1992, a channel offset in the 1992 earthquake, and a broad wash containing a thalweg possibly offset in the penultimate event. Vertical differencing and field observations document extensive rills across the scarp (some with apparent left-lateral offset due to flow patterns), headward-eroding channels deeply incised into what were broad washes in 1992, and the formation of post-1992 channels on the downthrown block. Evidence of most distributed deformation (cracks and minor faults) is erased in 30 years. The results of this work will inform how landscapes are interpreted for evidence of active faults, with implications for fault displacement hazard models.

POSTER 13

Evidence for Dextral-transpressional Quaternary-active Faults in the Northern Central Valley, California

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The northern Central Valley, California, has a long-lived history of faulting, but the locations and kinematics of active faults remains unknown. Regional tectonic models, largely based on geodetic data, suggest the region could accommodate transpression in a broad left-step as dextral shear is transferred westward from the Walker Lane across the northern Sierra Nevada microplate toward the southern Cascadia subduction zone. To better understand the locations and kinematics of the cryptic, low-rate deformation in the northern Central Valley, we integrated neotectonic mapping on historical aerial images and 1-m lidar-derived topography with 8 reprocessed seismic reflection profiles and InSAR. Neotectonic mapping of subtle fault-related features and apparently diverted channels shows evidence for at least 5 potentially active oblique-dextral faults that strike N50º-80ºE. Collectively, we call these faults the northern Sacramento Valley fault system, including the Dry Creek, South Cow Creek, Bear Creek, Battle Creek, and Red Bluff faults, from north to south. Juxtapositions and discontinuities of strata on the seismic reflection data are interpreted as ~20 subsurface faults that primarily offset Cretaceous and older strata, but at least 5 faults that extend upward into Pliocene (Tehama-Tuscan Fm) and Quaternary (Red Bluff Fm) strata. Several of the faults mapped in the subsurface data align with the neotectonic lineaments. A mismatch in stratal thickness across faults and broad zones of warped and folded strata, interspersed with multiple closely spaced faults with variable sense of slip, together suggests the faults may comprise transpressional flower structures, also consistent with the neotectonic mapping. Finally, discrete changes in northward interseismic strain accumulation that align with the mapped neotectonic features indicates these faults accommodate regional strain. Together, these data identify two new potentially active faults and support the presence of a distributed, low-rate dextral-transpressional N50º-80ºE-trending fault system at the northern end of the Central Valley.

Late-breaking on Recent and Future Large Earthquakes

Oral Session • Tuesday 15 April • 10:30 AM Local

Conveners: Aitaro Kato, Earthquake Research Institute, the University of Tokyo, (akato@eri.u-tokyo.ac.jp); Shengji Wei, Nanyang Technological University Singapore, (shjwei@ntu.edu.sg); Hongfeng Yang, The Chinese University of Hong Kong, (hyang@cuhk.edu.hk)

The Multi-segment Complexity of the 2024 Mw 7.5 Noto Peninsula Earthquake Governs Tsunami Generation

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The 1 January 2024, Mw 7.5 Noto Peninsula (Noto-Hanto) earthquake ruptured in complex ways across an active near-shore fault system, causing strong ground shaking, ionospheric disturbances, and a large tsunami within the Sea of Japan. We unravel the complex rupture dynamics and tsunami generation of the Noto Peninsula earthquake using a 6-subevent centroid moment tensor (CMT) model that we obtain from a Bayesian inversion of teleseismic and strong motion data. For the inversion, we use a Markov Chain Monte Carlo method with a Metropolis–Hasting accept-reject criterion, where the number of subevents is not prescribed but iteratively updated based on reducing the seismic waveform misfit. We observe a bilateral rupture propagation with two distinct rupture episodes: an initial, onshore rupture toward the southwest followed by a subsequent, partly offshore rupture toward the northeast, which re-nucleates at the earthquake's hypocenter after a 20 s delay and causes significant seafloor uplift. Such re-nucleation may have been aided by upward fluid migration due to fault valving, allowing high pore-fluid pressure to effectively weaken the fault, offering a physics-based explanation of this effect. This second rupture episode with substantial moment release toward the northeast (40%), that is, offshore, may be necessary not only for improving the fit to seismic waveforms but also for more accurate tsunami generation. Here, we map the subevent model to seafloor deformation to construct a complex multi-fault uplift model, validated against geodetic observations, that aligns with known fault system geometries and informs tsunami simulations. The model can explain tsunami wave amplitude, timing, and polarity of the leading wave, which are crucial for tsunami early warning. Upon comparison with alternative source models and analysis of 2000 multi-CMT ensemble solutions, we highlight the importance of incorporating complex source effects for realistic tsunami simulations.

Analysis of the Magnitude 5.7 Parker Butte Earthquake Near Yerington Nevada, Using High Precision Relocation, InSAR, GPS, and Strong Motion Data

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On Monday December 9th, 2024, at about 3:08PM local time, a moment magnitude 5.7 earthquake shook northwestern Nevada. The epicenter was about 24 km NNE of Yerington, Nevada where moderate shaking was felt. Light shaking was reported in Reno, NV, Carson City, NV and felt as far away as Sacramento CA. Following the earthquake, the Nevada Seismological Laboratory (NSL) and Nevada Geodetic Laboratory (NGL) in the Nevada Bureau of Mines and Geology (NBMG) initiated a coordinated response to gather perishable geologic observations and seismic and geodetic data. We deployed 5 temporary seismometers to monitor the ongoing seismicity and reoccupied several dozen stations in the Mobile Array of GPS for Nevada Transtension (MAGNET). In the 60 days after the mainshock, we've located over 1000 aftershocks including five events from local magnitudes 3.5 to 4.2. Preliminary coseismic displacement from geodetic observations were ~1 cm at the GPS stations nearest the epicenter (~13 km). This sequence has provided an opportunity to apply high precision location, InSAR and GPS analysis, and strong motion data to examine the fault structure, rupture patterns and ground motions of this area. We will be presenting our preliminary analyses using these methods and our initial interpretations. This knowledge is valuable for exploring the unique rupture characteristics, subsequent ground motions, and associated seismic hazards of earthquakes in the north-central Walker Lane Shear Zone.

The 2025 Ms6.8 (Mw 7.1) Dingri Earthquake Sequence and Seismogenic Structure

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The 2025 Ms6.8 (Mw7.1) earthquake was a typical north-south normal faulting event within the Tethyan Himalaya of the Tibetan Plateau. Using a back-projection method, we analyzed the rupture process of the mainshock, which primarily propagated northward from the epicenter. The rupture extended approximately 50 km and lasted around 25 seconds. Additionally, China University of Geosciences (Wuhan) deployed a dense seismic array after the earthquake, capturing extensive seismic records. Based on this high-density dataset, we applied a AI method (PhaseNet) to automatically detect P- and S-wave phases. After phase association and precise event location, we obtained a high-resolution aftershock catalog that clearly delineates the spatial distribution of the earthquake sequence's fault plane.

The spatial distribution of aftershocks not only outlines the mainshock rupture plane but also reveals activity along subsidiary faults. For example, near Changsuo Village, a NNW-trending fault branches off from the main rupture, which is identified as an antithetic fault based on spatial patterns. Another interesting feature is that south of the epicenter, the aftershock-defined fault plane dips northeast, whereas north of the epicenter, it dips westward. These two fault planes intersect near the epicenter. Preliminary focal mechanism solutions further highlight the complexity of this earthquake sequence, with the NNW-trending fault at Changsuo Village exhibiting a normal faulting component with right-lateral strike-slip motion, while an SSW-trending fault south of the epicenter appears to have a left-lateral strike-slip component. A detailed study of source parameters based on dense seismic array data will provide deeper insights into the fault geometry and local stress conditions.

Sampling the Earthquake Cycle in a Graben System: Insights from the 2025 Mw7.1 Dingri Earthquake in the Southern Tibetan Plateau

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Earthquakes result from complex spatial and temporal interactions between fault slip and tectonic loading through seismic cycles. However, high-quality deformation and fault slip observations spanning the entire earthquake cycle are rare, limiting our understanding of fundamental earthquake physics. Here, we integrate geodetic and seismic observations to analyze the inter-, co-, and post-seismic deformation and fault slip associated with the 2025 Mw7.1 Dingri earthquake that occurred along the Ama Drime Graben (ADG) in southern Tibet. Our result shows that the mainshock ruptured unilaterally towards north with a maximum rupture speed of ~3 km/s, primarily on the twisted, branching fault segments along the eastern edge of the graben. The strongest high frequency seismic waves were radiated from the transition of deep to shallow slip to the north of the epicenter. The dynamic waves from early rupture triggered the rupture at 3-5 km depth on a fault segment along the western edge of the graben, which is part of the ~200 km long fault that has shallow creep at a rate of ~1.5 mm/year during inter-seismic period. Shallow post-seismic slip was promoted on this fault segment, with slip complementary to its co-seismic rupture. Fault segments have the largest coseismic slip triggered afterslip on nearby secondary faults, as well as deep afterslip and viscoelastic relaxation. A wide range of fault friction properties and complex fault geometry is needed to reconcile these observations, mapping them is critical to identify potential rupture zones for future damaging earthquakes.

Two Days, Three Earthquakes, Three Provinces

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More than a dozen earthquakes are recorded daily in Canada. Widely felt earthquakes attracting media attention are less frequent. The occurrence of three such earthquakes in three distinct regions of the country in less than thirty-six hours is unusual. The action began with a magnitude (MW) 4.7 earthquake near Grand Prairie, Alberta at 15:41 UT on 20 February 2025 in a region of known wastewater injection and previous industry induced events. In the weeks preceding this event there were several small, both suspected and confirmed, industry induced events in the epicentral area and neighboring British Columbia (BC). As of 25 February, it has not been confirmed whether this event was induced. It was felt up to 200 km away in Edmonton and Prince George; reports indicate weak-to-light shaking near the epicenter. Due to the potential links to hydraulic fracturing, there was broad interest in the event. Thirty hours later, a magnitude (Mw) 4.7 earthquake occurred 75 km north of Vancouver, near Sechelt, BC, at 13:27 local time (21:26 UT 21 February). More than 7000 people submitted felt reports via the Natural Resources Canada "Did You Feel It" page, making this the most reported event in our database. Interest was high as this event resulted in the first Earthquake Early Warning (EEW) alert in southwestern BC. Vancouver City Hall was evacuated, and one BC Ferries terminal was closed for a short time. The EEW system functioned properly but there was considerable misunderstanding among the public as to who should have received the alert. More than 50 media interviews have been conducted, many explaining EEW, how the public should expect to be alerted and how they should respond. This was a valuable test for the EEW system and public education in the region. Finally, a small (MW 2.5) earthquake occurred near Chatham, Ontario, at 22:40 UT on 21 February. Although small, the event attracted media attention because it occurred in a populated region where felt earthquakes are rare. Its occurrence shortly after the Sechelt earthquake meant that staff were temporarily responding to both earthquakes simultaneously.

Late-breaking on Recent and Future Large Earthquakes [Poster]

Poster Session • Tuesday 15 April •

Conveners: Aitaro Kato, Earthquake Research Institute, the University of Tokyo, (akato@eri.u-tokyo.ac.jp); Shengji Wei, Nanyang Technological University Singapore, (shjwei@ntu.edu.sg); Hongfeng Yang, The Chinese University of Hong Kong, (hyang@cuhk.edu.hk)

POSTER 141

Sequence Analysis of the M7.1 South Halmahera Earthquake on July 14, 2019: Hypocenter Relocation, Moment Tensor and Static Stress Changes

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The M7.1 South Halmahera earthquake, which occurred on July 14, 2019, was a strike-slip event preceded by a foreshock three days earlier and followed by a series of aftershocks. This study investigates the triggering dynamics of this earthquake using precise hypocenter relocation with the Double-Difference method, moment tensor analysis to explore deformation patterns, and Coulomb stress modeling to evaluate static stress changes. The results indicate that the mainshock triggered aftershocks primarily to the west-northwest and southeast of the epicenter, consistent with static stress redistribution patterns. In the southwest of the mainshock, particularly in the eastern part of Bacan Island, normal-faulting earthquakes were identified in proximity to a hydrothermal zone. While tectonic processes remain the dominant factor in triggering seismicity, the presence of the hydrothermal system suggests a potential secondary influence in promoting localized earthquake activity in this area. This study provides valuable insights into the interplay between tectonic processes and localized factors, such as hydrothermal activity, in earthquake triggering. The findings contribute to a better understanding of seismic hazards in South Halmahera, particularly in regions influenced by complex geological settings.

POSTER 142

Local Magnitude (Ml) Calibration and Seismic Attenuation in the Ethiopian Rift Valley: Implications for the 2024–2025 Earthquake Swarm

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This study investigates seismic attenuation in the Ethiopian Rift Valley during the 2024–2025 earthquake swarm and concurrent diking episode, demonstrating that attenuation functions developed for Southern California (Richter, 1958; Hutton and Boore, 1987) are not directly applicable to this tectono-magmatic setting. Using zero-to-peak acceleration derived from synthetic Wood-Anderson seismograms, we calibrate a region-specific attenuation function through multiple linear regression analysis. The best-fit solution for the Ethiopian Rift valley is:

log(A0)= (1.05 +or- 0.1)log(r/100)+(0.0022 + or - 0.0003)(r - 100) + 3

where r is the hypocentral distance in kilometers and = is the reference distance. Comparative analysis shows Southern California has the highest attenuation at), reflecting strong crustal absorption. The Ethiopian Rift (2024/25 Swarm) exhibits higher attenuation at than the 2006 model likely due to magma intrusion and faulting. Tanzania and Danakil show lower attenuation and , indicating less energy loss. The Ethiopian Rift's attenuation (α=1.05, β=0.0022) suggests enhanced wave propagation, driven by magma-tectonic interactions. These findings highlight the need for region-specific models to improve seismic hazard assessment in active rift systems and provide insights into stress accumulation and volcanic-seismic risks.

POSTER 143

Detailed Analysis of the February 21, 2025 Sechelt Mw 4.7 Earthquake

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Within Southwest British Columbia (SWBC), the Sunshine Coast , extending from the northern boundary of Vancouver to the northern extent of the Georgia Strait, historically has a lower level of seismicity compared to the rest of SWBC, with no known earthquakes exceeding magnitude 4. On February 21, 2025, at 1: 26pm local time, SWBC was rattled by a rare M_w 4.7 (M_L 5.4) crustal earthquake that occurred at the tip of Salmon Inlet, 75 km northwest of Vancouver, BC. Due to the relatively low density of seismic monitoring and limited historical seismicity in the area, during the immediate response to the event there was significant uncertainty regarding the depth and focal mechanism. Detailed examination of earthquake depth, source mechanism analysis, and aftershock distribution indicate that the depth of this event is in fact deeper than the 1.5 km originally reported by Natural Resources Canada. Although peak ground accelerations exceeding 5% g were reported within 50 km of the epicenter, these levels of shaking are not reflected in reported intensities. Additional ground motion analysis and insights gained from remote sensing techniques will complement the analysis of this event and provide a better understanding of the seismic hazard in this region.

POSTER 144

Satellite Geodetic Measurement of the Coseismic and Postseismic Displacements from the January 2025 Mw 7.1 South Tibet Earthquake

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We analyzed synthetic aperture radar (SAR) images from the Copernicus Sentinel-1A satellite operated by the European Space Agency for the coseismic displacements of magnitude (USGS Mww) 7.1 earthquake in southern Tibet. We use SAR interferometry (InSAR) measurements of displacements in the radar line-of-sight directions and pixel offset tracking to measure both the large displacements close to the rupture and the smaller displacements at larger distances. The InSAR coherence with Sentinel-1 radar (6 cm wavelength) is good in the dry Tibetan Plateau north of the High Himalaya. We combine InSAR data from different radar look directions to estimate two components of the surface displacement, and we concentrate on the east and vertical components. The north-south component of slip is measured by the along-track pixel offsets of the Sentinel-1 SAR images but with much coarser accuracy than the slant-range or across-track pixel offsets and InSAR. The large-scale deformation due to slip at depth is dominated by vertical downward motion of about 2 meters just west of our interpreted fault, accompanied by westward motion on the west side and eastward motion on the east side, all consistent with normal fault slip on a north-northeast-striking and west-dipping fault plane. The along-track pixel offsets indicate a probable significant oblique left-lateral slip component of the rupture. The main fault rupture likely reached the surface with close to 1 meter of dip-slip displacement and the surface rupture appears to have small but noticeable variations in strike with a 5-10 km wavelength. This earthquake occurred in an area of substantial interseismic strain identified in our time-series analysis of ten years of Sentinel-1 InSAR data under a related project.

POSTER 145

Remote Observations of Surface Rupture and Fault Kinematics in the January 7, 2025, Southern Tibet Plateau Earthquake

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On January 7, 2025, an Mw 7.1 earthquake occurred in the south-central Tibetan Plateau (USGS event us6000pi9w) as a result of predominately normal faulting in the shallow crust. The earthquake was felt >500 km away

and caused violent shaking (MMI IX) near the epicenter causing at least 126 casualties and >$1 billion estimated economic loss. USGS moment-tensors derived from global seismic observations indicate an approximately north-south oriented fault plane (187° or 349°) dipping moderately east (49°) or west (42°). Preliminary observations from Sentinel1 InSAR and visual and sub-pixel correlation analysis of PlanetScope (3 m/pixel) and WorldView (0.5 m/pixel) optical images are consistent with the west-dipping fault plane. However, these observations also indicate a more complex rupture that may include a listric primary fault, an antithetic secondary fault, and possibly a component of lateral tectonic motion not indicated by most focal mechanisms. WorldView images show widespread liquefaction and lateral spreading features in valleys and near lakes, as well as discontinuous dip-slip scarps that extend for at least 30–35 km near the Lhagoi Kangri dome that mostly coincide with pre-existing fault scarps. Sentinel1-derived interferograms reveal a broad zone of decorrelation primarily west of the mapped surface rupture indicative of diffuse deformation and a secondary lobe of deformation ~15–20 km west of the mapped surface rupture, possibly implying a smaller antithetic fault. Preliminary sub-pixel correlation of WorldView and PlanetScope images show localized deformation coincident with the mapped discontinuous rupture overprinting a broader, primarily east-west extensional signal. Initial finite-fault modeling indicates that a single planar fault cannot account for both seismic and satellite observations; instead, the data require that fault dip shallows with depth, consistent with listric faulting. Together, these observations are consistent with the regional pattern and long history of east-west oriented extension in the shallow crust of the Southern Tibet Plateau.

POSTER 146

The 2024 M7.0 Offshore Cape Mendocino Sequence: Insights from Enhanced Catalogs of Earthquake Locations, Focal Mechanisms and Repeating Events

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On Dec. 5, 2024, a magnitude 7.0 earthquake occurred west of the Mendocino Triple Junction (MTJ) along the transform Mendocino Fault Zone (MFZ). To better delineate the seismogenic fault structures and their slip behaviors during this sequence, we implemented a deep-learning-based workflow to build high-resolution catalogs of earthquake locations and focal mechanisms. The relocated aftershocks mainly concentrated along the MFZ, where we also detected ~20 newly emerged sequences of repeating earthquakes following the mainshock, suggesting an episode of aseismic slip. To the north of the MFZ in the Gorda plate, we observed several clusters of aftershocks, which may correspond to smaller fault segments activated by stress transfer. We have improved both onshore and offshore focal mechanisms. Combined with the estimated moment tensor solutions of the mainshock and its aftershocks (M>3.5), our results suggest a diverse range of faulting mechanisms in this sequence. Our findings indicate the potential fault interactions during this offshore earthquake sequence and emphasize the complex tectonic environment around the MTJ.

POSTER 147

Sequence Characteristics and Seismogenic Structure of the 2025 Xizang Dingri M6.8 Earthquake

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In this study we use continuous waveform data and seismic phase reports from the China Earthquake Networks Center to detect and supplement the sequence of the January 7, 2025, M 6.8 Xizang Dingri earthquake using deep learning methods. After relocating the entire sequence by the double-difference relocation method, we find that the sequence occurred on the Dengmocuo Fault, located in the Shenzha-Dingjie Rift. The sequence extends in a north-south direction, with an aftershock zone approximately 100 km long and 40 km wide. The depth of the earthquakes mainly ranges from 3 to 30 km, gradually becoming shallower from north to south, while the fault plane is nearly vertical, slightly inclined to the northwest. The foreshock sequence started ten days before the mainshock and showed a migration pattern towards the mainshock epicenter, with the migration speed accelerating to about 3 km/h one hour before the mainshock. It is hypothesized that the foreshock sequence have occurred on a blind minor conjugate fault, triggering the mainshock. We have also calculated focal mechanism solutions using polarity data (M3-4), local seismic waveform fitting (M>4) and W phases (mainshock). The dominant solutions are normal faulting, consistent with the tectonic setting.

The rapid reported magnitude of the mainshock was M6.8, lower than the moment magnitude 7.1, presenting a rare case for earthquakes in Chinese mainland. We compare the Ms and Mw for 260 earthquakes since 2013 and find a clear linear relationship.There displays a regional distribution of the difference between surface-wave and moment magnitude. Most earthquakes within the Qinghai-Xizang plateau have larger Ms than Mw, while some earthquakes along the margin of plateau and the Tarim basin show the opposite relationship. Our study provide scientific insights into the earthquake preparation process and mechanism of the 2025 Dingri earthquake, and offer valuable references for understanding the deformation mechanism and seismic hazard of the Qinghai-Xizang Plateau.

POSTER 148

Source and Impact Characterization of the M7.3 2024 Port Vila, Vanuatu, Earthquake

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On December 17, 2024, a magnitude 7.3 earthquake occurred 30 km offshore of Vanuatu's capital, Port Vila. The rapid source characterization by the U.S. Geological Survey (USGS) estimated that the earthquake had an oblique normal faulting mechanism with a depth of 57 km, indicating that it was an intraslab rupture within the subducting Australian plate. Despite being relatively deep and located offshore, the earthquake caused extensive damage and destruction to the housing and infrastructure. The earthquake caused the collapse of nearly a dozen buildings in Port Vila, leading to at least 14 fatalities and over 265 injuries, including a notable partial collapse of the building that housed the U.S. Embassy. The shaking from the event also triggered numerous landslides, lateral spreads, and landslide dams.

We present rapid response products produced by the USGS and GNS Science and show their insights into the seismotectonic framework of the region. We also use rupture kinematics and aftershocks to identify the causative fault plane. We compare impact products to post-event observations, emphasizing how these events evolve as we gain further insight into source properties. While large earthquakes are common along the New Hebrides trench, many hazards associated with these events are linked to their potential for tsunamis, as they largely occur offshore. This event reminds us that ground shaking and coseismic landslides can be significant hazards on islands along active subduction zones. Such hazards can persist for many years post-earthquake due to an increase in the frequency of aftershocks and the increased susceptibility of the earthquake-damaged slopes to post-earthquake rainfall-induced landslides. For example, many of the coseismic landslide dams breached within the first few weeks post-formation, resulting in debris flows and floods and affecting people living downstream who had been evacuated in anticipation of such hazards. Robust monitoring and source characterization is critical to ensure a comprehensive understanding of seismic hazards and the cascading hazards they can cause in the region.

Macroseismic Intensity: Past, Present and Future

Oral Session • Thursday 17 April • 2:00 PM Local

Conveners: Ayse Hortacsu, Applied Technology Council (ayse@atcouncil.org); Susan E. Hough, U.S. Geological Survey (hough@usgs.gov); Jessie Saunders, California Institute of Technology (jsaunder@caltech.edu); Paola Sbarra, National Institute of Geophysics and Volcanology (paola.sbarra@ingv.it); David J. Wald, U.S. Geological Survey (wald@usgs.gov)

Making the Case for Implementing the International Macroseismic Scale (IMS) in the United States

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Macroseismology plays a crucial role in earthquake analysis, tying occurrences and impacts from the past with those of the present and future while continuing to serve a valuable role in earthquake response and mitigation. Here, we report on efforts to facilitate the uptake of the International Macroseismic Scale (IMS) framework in the United States (US), superseding the Modified Mercalli Intensity (MMI) scale. European countries, long accustomed to the European Macroseismic Scale (EMS-98), will have few updates to consider with IMS. However, the US and others will require additional considerations, none insurmountable. The elegance of IMS over MMI is its consistent approach to structural vulnerabilities, damage grades, and quantitative intensity assignments, which are essential for characterizing damaging intensity levels. Lower intensities can continue via crowdsourcing without modification. Conversely, there is a greater role for engineering expertise at higher intensities, requiring practitioners to collect building damage data systematically. We aim to use current inspection and survey protocols already in use for post-earthquake safety, reconnaissance, and insurance and add the capability to assign intensities by employing consistent building taxonomies and damage grades. Working with the Applied Technology Council, Global Earthquake Model Foundation, and California Office of Emergency Services, we intend to modify existing inspection forms, such as ATC-20, to use building damage data for their primary safety tagging purposes, yet also allow aggregation into sharable datasets for IMS assignments and more. Lastly, just as "Richter Scale" magnitudes are now referred to simply as "magnitudes," MMI values could be referred to as macroseismic "intensity" values, allowing seamless IMS adoption among the scientific and public domains given their practical equivalent. As with magnitudes, the underlying metadata must reflect the scale employed. In the long run, utilizing the IMS will lead to better characterization of damage and risks in the US and compatibility with the macroseismic and damage datasets worldwide.

The U.S. Contribution to the International Macroseismic Scale

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The International Macroseismic Scale (IMS) working group seeks to extend the European Macroseismic Scale (EMS-98) globally. To better reflect United States (US) structure types, we have parameterized three components for the US contribution to the IMS: (1) the national building taxonomy, (2) the system to assign vulnerability classes, and (3) damage grades. We chose from commonly used US taxonomies: FEMA P-154, ATC-20, ATC-38, Hazus, and ASCE/SEI 41. We judged each option by nine desirable seismic features and whether maintenance and data-collection training programs for them exist. FEMA P-154 best satisfies our desiderata. Of particular value: its built-in fragility model helps assign vulnerability classes. A significant challenge was how to describe damage grades consistent with the IMS. A suitable system must assign a damaged building one of five damage grades. We adapted the three-level ATC-20 green-yellow-red post-earthquake safety tagging system by subdividing red (unsafe) tags into two grades depending on whether collapse occurred, and yellow (restricted use) tags into two grades depending on the extent of damage. ATC-20 rapid evaluation forms—the de facto global standard for evaluating earthquake building damage—provide all the necessary data to assign these grades. Using ATC-20 leverages an existing evaluation system to provide abundant, free, spatially located post-earthquake damage data and, thus, robust IMS intensity assignments. These country-specific details will be catalogued in a national annex to the IMS. The benefits flow both ways: loss modelers will likely estimate shaking intensity (and therefore damage) before field observations can be made. Doing so will provide US emergency managers, officials, and the public with estimates of safety and functionality of the building stock within minutes of damaging earthquakes. Using ATC-20 protocols, inspectors can help refine these intensity estimates during post-earthquake inspections. As a further benefit, similarities between US and Canadian building data and inspection systems could facilitate the extension of the US IMS contribution to Canada.

Towards the Integration of Field and Web-based Macroseismic Surveys in Italy

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Macroseismology is the only source of data on the effects of earthquakes before the instrumental era, thus being an essential tool for comparing historical and modern earthquakes. This discipline has recently benefitted from citizens' contribution to receiving near real-time information on the effects of present earthquakes through the web. However, traditional macroseismic surveys, conducted by specialised personnel to assess the severity of damage to buildings on site, remain the most viable approach for assessing high intensities. For these reasons, field surveys mostly cover the near-field and are less comprehensive for intensities driven by transient effects. In contrast, web-based, citizen-contributed surveys mainly collect information on low intensities based on transient effects.

Currently, Italy is one of the few countries in the world where state-of-the-art macroseismic data of damaging earthquakes are collected with both field and web-based surveys. To date, the integration of the datasets derived from the two methods to get a comprehensive picture of the macroseismic effects for both the near- and far-field has never been attempted. This study analyses the earthquakes with both types of intensity datasets to identify the criticalities related to their overlapping areas, which generally occur in the range of intensities from 4 to 7 on the European Macroseismic Scale (EMS-98). To compare the two methodologies, the data were spatially homogenized because macroseismic questionnaires are aggregated according to Italian municipalities, whereas field surveys are conducted at the scale of individual populated places, many of which can belong to the same municipality. The integration of the two methodologies for future events will mutually compensate for their respective limitations, to obtain a complete and robust macroseismic intensity distribution.

Exploring the Capabilities of Llms for Earthquake Science: A Case Study on Macroseismic Intensity Measurement

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Generative AI and Large Language Models (LLMs) have recently emerged as transformative technologies, revolutionizing various fields with their ability to generate complex outputs across diverse modalities. While these models have driven significant advancements in areas like natural language processing and computer vision, their potential for scientific applications remains largely unexplored. This study investigates the capabilities of LLMs to advance seismological research and enhance societal resilience to natural disasters. Using Gemini, Google's most capable LLM, we estimate earthquake ground shaking intensity from multimodal social media posts and show how these estimates align with independent observational data. We demonstrate how Gemini can contribute to a deeper understanding of earthquake impacts, improve natural disaster mitigation strategies, and potentially aid in rapid earthquake response and damage assessment. Through this example application, we aim to showcase the power and potential of generative AI and LLMs for applications in seismology and earthquake science.

A New Intensity Data Set and Intensity Prediction Equation for Crustal Earthquakes in the Western United States

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A new data set for macro intensity from crustal earthquakes in the Western US was developed combining the Did you feel it (DYFI) data set from the USGS with the historical intensity data set. Rupture distances were estimated for all events with magnitudes greater than 6. The site conditions are parameterized by the proxy-based VS30 and by the surface geology. The full data set includes 696,000 intensity observations from 5561 earthquakes. In addition to the intensity values, the data set includes the peak acceleration and peak velocity from the NGA-W3 data set for intensity observations near seismic stations. The data set is dominated by the DYFI observations with 96% of the intensity values and 98% of the earthquakes. For magnitudes of 6 or larger at distances less than 30 km, the historical intensity data accounts for 20% of the intensity values. To avoid the impact of censoring on lower MMI values, we establish (1) an Rmax distance based on the distance at which the minus two standard deviation level below the median from a non-parametric fit, and (2) all intensity values less than 2.1 were excluded. This reduced the data set used to develop the intensity prediction equation (IPE) to 358,000 recordings from 3642 earthquakes. The IPE is developed using model forms and regression methods commonly used in modern ground-motion models. In particular, we use a mixed-effects regression and include a magnitude-dependent finite-fault term and a site term, which are not included in the IPEs currently used for the Western US. The new IPE has much stronger saturation in magnitude scaling above M7 at shorter distances and a weaker magnitude dependence M5 at longer distances when compared to currently used IPEs for the western US (e.g., Atkinson et al. 2014). Although the intensity data is correlated to the peak velocity, the site term in the IPE is weak with a ln(VS30) coefficient of only -0.1 compared to -0.67 for peak velocity.

Macroseismic Intensity: Past, Present and Future [Poster]

Poster Session • Thursday 17 April

Conveners: Ayse Hortacsu, Applied Technology Council (ayse@atcouncil.org); Susan E. Hough, U.S. Geological Survey (hough@usgs.gov); Jessie Saunders, California Institute of Technology (jsaunder@caltech.edu); Paola Sbarra, National Institute of Geophysics and Volcanology (paola.sbarra@ingv.it); David J. Wald, U.S. Geological Survey (wald@usgs.gov)

POSTER 17

The Scientific Value of Internet Macroseismic Data in Operational Seismology

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The advent of the internet has had a profound impact on the field of macroseismology, with the EMSC now routinely collecting thousands of felt reports following a widely felt earthquake. In 2023, its LastQuake multi-component system (websites, app, social media & messaging app bots) amassed 470k felt reports (8.5 min median time). After a decade of operation, three principal conclusions can be drawn. Firstly, a data collection system is effective if it also functions as an information system that meets the information needs of witnesses in the immediate aftermath of an earthquake and if it is deployed on multiple platforms. Secondly, in the absence of dense real-time accelerometric networks, a reliable and rapid assessment of the impact of global earthquakes cannot be achieved without the integration of macroseismic data. Finally, for operational seismology, this data represents an effective and affordable complement to dense accelerometric data, particularly in urban areas where the density of crowdsourced data is highest and where the risk is increasingly concentrated as a result of global urbanisation.

In order to illustrate these conclusions, a number of cases are presented. For example, the joint analysis of seismic and crowdsourced data enabled the precise location of the M4.8 New Jersey earthquake to be determined, (within 2km of USGS one). The public was promptly informed, and a total of 3,000 felt reports were crowdsourced in just 20 min in a region where LastQuake was previously unknown. Furthermore, the incorporation of felt reports into ShakeMaps serves to mitigate the inherent uncertainties associated with such models. Even when employed in isolation, without the requisite earthquake parameters, they can effectively identify destructive global earthquakes. In the case of large-magnitude earthquakes, felt reports can be used to rapidly (10 min) determine a line source model. When integrated into the ShakeMap of the M7.8 Turkey 2023 earthquake, the combination of felt reports and the line model provides a reliable estimate of the human impact within 10 min when using the PAGER method (USGS).

POSTER 18

A Proposed Canadian National Annex to the International Macroseismic Scale

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The International Macroseismic Scale (IMS) seeks to improve upon the collection of macroseismic data by detailing and standardizing the process used to assign earthquake intensity values globally. While IMS is intended to be representative of building classes around the world, countries may create their own Annex document. National Annexes are meant to account for the nuances of building types not otherwise captured in the central document, differing vulnerability classes and damage grades of those buildings, and national or regional post-earthquake building code and damage assessment practices that are likely to be mined for macroseismic data.

Canada intends to create a National Annex to the IMS guidelines, leveraging the existing "Did You Feel It?" system from Natural Resources Canada and the related macroseismic evolution ongoing in the United States and New Zealand. This synergy is possible due to the many shared building characteristics and post-event reporting strategies between all three countries. For example, the draft United States Annex (Hortacsu et al., 2024) recommends using a building taxonomy and corresponding vulnerability classes from the Federal Emergency Management Agency's FEMA P-154, combined with damage classifications from the Applied Technology Center's ATC-20. Canadian equivalents from the first-generation Canadian Seismic Risk Model and British Columbia's Post Disaster Building Assessment program will be evaluated using criteria similar to those applied in the United States and abroad to arrive at a concept of implementation. We will present our preliminary Canadian IMS Annex to facilitate input from the Canadian community of earthquake engineers and seismologists.

POSTER 19

To Intensity and Beyond: On the Limits of the Conventional Macroseismic Intensity Scale

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Observed earthquake shaking is increasingly well-characterized with instrumental recordings and systematically interpreted macroseismic data. Ground motion models are determined for not only peak ground acceleration but also peak ground velocity and longer period spectral ordinates. Visualization, however, still commonly relies on the conventional intensity scale, which provides an intuitive way to depict shaking severity. Intensity-based characterizations are moreover used for applications ranging from assessment of early warning performance to estimation of earthquake losses. It has been noted that intensity values ≥ 8 are rare in compilations of both traditional and internet-based intensities. Among the compilation of Did You Feel It? (DYFI) intensities for California earthquakes since 1999, for example, out of over 700,000 intensities estimated by DYFI, intensities ≥ 8 number in the 100s (Chauffer et al., 2025). Theories have been advanced to explain the paucity of observations, including a doughnut effect whereby reports are not submitted from areas where damage was severe (Bossu et al., 2018), and the inability of the DYFI questionnaire to capture sufficiently detailed information to evaluate structural damage. Considering the aftermath of recent damaging earthquakes including 2015

Gorkha, Nepal, and 2019 Ridgecrest, California, events, I suggest that intensity values ≥ 8 are limited in part because population centers tend to cluster in areas underlain by sediments, where pervasive nonlinear sediment response deamplifies shaking at frequences that would be damaging to vernacular small (1-2 story) structures. Strong long-period shaking can damage taller structures, break buried pipelines, and throw people to the ground, but such effects may not correlate well with conventional macroseismic effects. The challenge for characterizing strong ground motion may not only be to better estimate high intensities, but to move away from the conventional intensity scale, which fails to capture shaking effects that are strongly frequency-dependent at frequencies of engineering concern.

POSTER 20

Using "Did You Feel It?" Data to Map Spatially Variable Site Amplification in the Central and Eastern United States: Lessons From the 2024 M 4.8 Tewksbury, New Jersey, Earthquake

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Seismic hazard is strongly influenced by site-specific geologic conditions. In the Central and Eastern United States (CEUS), strong impedance contrasts (with sediments overlying hard intact bedrock) can lead to significant amplifications of ground motions. The inclusion of site effects in ground-motion models (GMMs) requires residual analysis to examine trends in the residuals with site-specific variables, such as the time-averaged shear-wave velocity in the upper 30 m (V_{S30}), sediment thickness, and basin terms such as $Z_{1.0}$ (the depth to shear-wave velocity of 1 km/s). This residual analysis is particularly challenging in the CEUS, where station coverage is sparse and many stations are situated on bedrock, leading to minimal observations of true sediment amplification. Macroseismic intensity data, such as the U.S. Geological Survey "Did You Feel It?" (DYFI) program, can be used to provide much denser spatial coverage of earthquake ground motions in the CEUS than from seismic recording stations alone. The 2024 M 4.8 earthquake in Tewksbury, New Jersey, had the highest number of DYFI reports of any earthquake in history, because of the dense population centers near the epicenter and the lower rates of attenuation seen in the CEUS. This work uses over 180,000 DYFI responses from the 2024 M 4.8 New Jersey earthquake to examine site effects in the CEUS. We use the Atkinson et al. (2014) intensity prediction equation to predict Modified Mercalli Intensity (MMI) for each 1-km grid square using the New Jersey earthquake, and compute residuals between the observed and predicted MMI. These event-specific residuals are compared with residuals from strong motion recordings from the earthquake and examined to search for high-resolution spatial trends in site and basin terms at a 1-km resolution. We hypothesize that the broad spatial coverage of DYFI data can be used to better understand site and basin effects at a higher resolution in the CEUS.

POSTER 21

Guidelines on Using (Uncertain) Macroseismic Data in ShakeMap

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The U.S. Geological Survey (USGS) collects macroseismic intensity (MI) data from users worldwide through the "Did You Feel It?" (DYFI) system. DYFI is a primary MI source for USGS ShakeMap, which combines ground motion data with rupture parameters, site conditions, and ground motion models (GMMs) to estimate the spatial distribution of ground shaking. Despite their utility in ShakeMap, the potential for outliers and larger uncertainties makes it challenging to include crowdsourced MI data operationally. We report here on guidelines for incorporating crowdsourced MI data into ShakeMap. We analyzed MI residuals compared to ShakeMaps that were well-constrained by strong-motion data to understand trends with the number of responses per cell (Nresp) and the MI level. We present these trends, which we have adopted for weighting DYFI "stations" in ShakeMap. Crowdsourced MIs are consistent at lower intensities, so we can readily use them automatically. Higher intensities, particularly with few entries per locale, are more uncertain and require further downweighing with respect to other shaking observations. In short, fewer than three responses result in intensities with larger uncertainties and are bias high; with more and more responses, they trend towards unbiased and have lower uncertainties. Higher intensities are more variable, given the same Nresp. Before this, based on heuristics, we only allowed ShakeMaps to employ DYFI stations with Nresp of three or more; our DYFI uncertainty analyses now quantitatively support that assumption. Moreover, based on requests from financial decision-makers who employ DYFI-informed ShakeMaps for insurance, contingency loans, and catastrophe bonds, we aim to generate DYFI-free ShakeMaps for significant events, deliver them online, and store them permanently in USGS' ComCat archive for escrow purposes. The authoritative maps will continue to use DYFI data because these data significantly reduce the uncertainty in nearly all circumstances, and our new station weighting in ShakeMap more quantitively accounts for DYFI uncertainties as a function of Nresp and the estimated intensity.

POSTER 22

The Effect of Structural Damage on Shakemap

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ShakeMap provides ground shaking intensity estimation in the region hit by a seismic event. It is built based on a conditional Gaussian random field (GRF) model, where the mean and covariance matrix are from a ground motion model and the recordings from seismic monitoring stations. On the other hand, it has been recently shown that information about the ground shaking intensity can be also obtained indirectly from observed damage to the built environment. The object of this study is to present how much damage information reduces the uncertainty in ground motion estimates if compared to the original ShakeMap, and how it tends to more clearly identify, in comparison with the original ShakeMap, the actual shaking intensity at the sites where damage is surveyed. To update ShakeMap a probabilistically-consistent procedure, based on sequential Monte-Carlo method, was employed. The algorithm distinguishes between surveyed and unsurveyed sites. At damage-surveyed sites, it results that the conditional random field of ground accelerations is not a GRF anymore. In contrast, at unsurveyed sites, the conditional random field of ground accelerations remains a GRF. The case study of the 2009 L'Aquila earthquake in central Italy is considered to illustrate this approach and its effect on ShakeMap. In fact, for this seismic event, extensive damage data were collected from thousands of surveyed buildings. Based on these data, a series of illustrative cases were set up changing the number of sites and buildings surveyed at each site.

POSTER 23

Twenty Years of EMS-98 Practice in Italy: A Successful Experience

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Macroseismic intensity originated with the purpose of measuring the strength of an earthquake observing the effects caused on buildings, people, and objects. From this perspective, buildings can be considered seismic sensors that permanently record the shaking. During the last century the residential building stock in Italy has undergone a radical change. Masonry, predominant until the 1960s, was superseded by reinforced concrete. At the beginning of the 21st century a new building code was enforced and important changes in the structural design of buildings were adopted. However, the Italian building stock is still extremely heterogeneous, with areas with widespread high vulnerability buildings, often reconstructed or restored after destructive seismic events. The heterogeneity of building typologies results in a variability in earthquake resistance. The use of the EMS-98, which consider the vulnerability of the buildings as a parameter for the intensity assessment, has become necessary to keep up macroseismic practice with the development of constructive technologies and the application of the building code.

For about twenty years, the QUick Earthquake Survey Team (QUEST), INGV's rapid response group for post-earthquake macroseismic surveys, has been conducting surveys after damaging earthquakes using the EMS-98. In this period about 40 macroseismic campaigns have been carried out, including those following the 2009 L'Aquila (Mw 6.3) and the 2016-2017 Central Italy seismic events (Mw 6.5). On the two occasions, over 20.000 buildings were inspected. During these years, the QUEST group had to tackle the assessment of macroseismic intensity in a wide range of situations, from very light damage to total destruction. For the first time, after more than a century, intensity 11 has been assigned after the 2016-2017 Central Italy earthquakes. This paper describes the main activity of QUEST and provides considerations about the application of the EMS-98 to earthquakes in Italy, highlighting the advantages and criticalities of this scale in the Italian macroseismic practice.

POSTER 24

Constraints of the Non-ergodic Path Effects for Short Distances in GMMs using the Modified Mercalli Intensity Data

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The new Modified Mercalli Intensity (MMI) dataset for the western United States, developed by Fathian-Sabet et al. (2025), has much denser spatial sampling than the empirical ground-motion data sets. As a result, the MMI data may be able to provide better spatial resolution for non-ergodic path effects than the empirical ground-motion data. In this study, we utilize MMI and NGAW3 ground-motion data from California crustal earthquakes to compare the path effects derived from both datasets, with the objective of assessing if the MMI data can yield valuable constraints for non-ergodic path effects that can be used to test or constrain updated non-ergodic ground-motion models (GMMs) for California. The non-ergodic path effects for both data sets are estimated using the methodology established by Sung et al. (2023), which quantifies path effects related to the 3-D velocity structure. We find a significant correlation between path terms for lower MMI values and short-period spectral accelerations. Conversely, for higher MMI values, the correlation of the path effects is strongest for the long-period ground motions (greater than 2 seconds). For the sparse empirical data, the epistemic uncertainty for the path effects is often large. The non-ergodic path terms derived from the MMI data are found to be within the epistemic uncertainty range of the path terms obtained from NGAW3 empirical data. This suggests that incorporating MMI results into the ground-motion model could enhance the accuracy of path effects in areas with limited empirical data, particularly at shorter distances. We also discuss the implications of using nonergodic GMMs with path effects based on the MMI data for the evaluation of probabilistic hazard curves.

Mechanistic Insights into Fluid-induced Earthquakes from the Laboratory to the Field

Oral Session • Tuesday 15 April • 2:00 PM Local

Conveners: David Chas Bolton, University of Texas at Austin (chasbolton19@gmail.com); Xiaowei Chen, Texas A&M University (xiaowei.chen@exchange.tamu.edu); Thomas H. Goebel, University of Memphis (thgoebel@memphis.edu); Congcong Yuan, Cornell University (cy547@cornell.edu)

Injection-induced Slow Slip Events in the Canadian Rockies

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Using satellite-based ground monitoring (InSAR), we show that hydraulic fracturing treatments of the Montney Formation released locked-in stresses near the subsurface deformation front of the Rocky Mountain Fold and Thrust Belt, thereby causing 12 bedding-plane-parallel slow-slip events with magnitudes Mw 4.71 to 5.06 at depths between 1640 and 2410 m. Conversely, human-induced ordinary seismicity concentrates westward. The cumulative seismic moment released by the 12 detected slow slip events between 2017 and 2023 is orders of magnitude larger than that released by the approximately 1800 ordinary earthquakes ML ≥ 1.5 observed between 2005 and 2023. Furthermore, slow slip may occur in the absence of small-to-moderate size ordinary seismicity. Our observations demonstrate the existence of intracontinental slow-slip events within a foreland sedimentary basin on a regional scale. Slip occurs most likely on detachment zones related to marine bioclastic sediments deposited between the fair-weather and storm wave levels, producing alternating competent and incompetent layering. The thin competent layers are load bearing, able to maintain locked-in stresses over geologic time frames; upon their failure, the incompetent layers enable aseismic slow slip. Our findings indicate slow slip may have contributed significantly in the past to the eastward progression of the belt's subsurface deformation front. Counterintuitively, these hydraulic fracturing treatments may have reduced seismic hazard to surface infrastructure, given the amount of tectonic strain energy released by the slow slip events. Our results also provide insights into geologic and geomechanical factors that could enable the occurrence of aseismic slip within other foreland sedimentary sequences and, plausibly, accretionary wedges near subduction zones.

Insights Into Fault Behavior in Southern Kansas From Stress Evolution Modeling of Multiple Induced Earthquake Sequences

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Southern Kansas has experienced an increase in seismicity largely associated with wastewater disposal in the last decade, with earthquake rates being the highest in 2013-2017, including a Mw 4.8 earthquake near Milan, Kansas on 12 November 2014. Detailed studies of seismicity in the area identified a collection of planar fault structures on which earthquakes concentrated, representing both normal and strike-slip faults (Shoenball and Ellsworth, 2017). We used a machine-learning enhanced seismic catalog developed by Park et al. (2022) to perform simple stress modeling for multiple sequences of induced earthquakes in southern Kansas. Our objective is to explore the mechanisms responsible for driving those sequences. These sequences contain many earthquakes that are consistent with earthquake-to-earthquake triggering, suggesting static stress changes have an important role in their evolution. However, each sequence also includes significant numbers of earthquakes that re-rupture areas where previous earthquakes happened and where the driving stresses should be reduced. Assuming a characteristic stress drop for all earthquakes of 3 MPa, between one quarter and one third of earthquakes in each sequence occurred in areas of the fault that had stress changes from previous earthquakes <-1 MPa. This suggests that aseismic slip or continued fault weakening from ongoing pore pressure increase. Our results indicate that multiple processes likely play a role in driving the evolution of earthquakes during induced earthquake sequences in southern Kansas.

Importance of In-situ Stress Estimation in the Understanding of Induced Seismicity

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In this study, we investigate slip potentials of variously oriented major faults in the North Montney Trend (NMT) and the Kiskatinaw Seismic Monitoring and Mitigation Area (KSMMA) in the Western Canada Sedimentary Basin (WCSB). The KSMMA and NMT are seismic monitoring areas implemented by the British Columbia Energy Regulator in 2018 following the concerns about the increasing number of felt seismic events during hydraulic fracture treatments within the Montney Play. The largest recorded M_W=4.6 event occurred on August 17, 2015, in the NMT, and another three events (M_L=3.6~4.3) occurred on November 30, 2018, near the southern margin of the Fort St. John Graben (FSJG) in KSMMA. Our objective is to explain the observed seismicity from a geomechanics point of view. We first estimate full in-situ stresses for the Montney Formation. Magnitude estimation of the maximum horizontal stress is subject to a large uncertainty. We therefore estimate a range of probable values based on the poroelastic stress model, combined with strain corrections inversely proportional to the distance from the Rocky Mountain Fold and Thrust Belt (FTB), as well as commonly used constraints from the borehole measurements and the possibility of a critical stress state. Finally, we estimate the likelihood of slip given known fault orientations in the area.

It is observed that the stress regimes transition from reverse to transpressional to strike-slip in the NMT, and from strike-slip to transtensional/normal faulting in the KSMMA. We found from more than 7000 recorded seismicity locations (magnitude of 1.5 or higher, British Columbia Energy Regulator, 2024) that seismicity does not necessarily occur in areas with the highest pore pressures. Most recorded seismicity occurred close to locations where two principal stresses are close in magnitudes because in these cases fault reactivation can occur on multiple planes. Our findings help explain the range of observed source mechanisms of induced earthquakes in both areas.

Geomechanical Insights Into the Recent Mw 5+ Earthquakes in the Delaware Basin, West Texas

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The northern Delaware Basin (NDB) in West Texas has undergone decades of shallow and deep wastewater injection by 1200+ wells. Meanwhile, seismicity in the area started proliferating in 2019, with > 300k detected earthquakes so far, including three M_w 5+ ones. Injection-induced pore pressure diffusion and poroelastic stressing are two common mechanisms driving seismicity. In the NDB, however, their relative importance remains unknown, partly due to difficulties in modeling the complicated injection system. Also, unraveling the contributions of the two injection zones to seismicity is an open question specific to the area. Here, relying on our latest hydro-geomechanical modeling method, we offer insights into these two questions via targeted analysis of the three M_w 5+ earthquakes. Both hydraulic diffusivity and focal depth are crucial but poorly constrained. We thus address the uncertainties by sampling various shallow and deep diffusivities and tracking the Coulomb stress (CS) from the epicenters down to 12 km deep to cover a wide focal range. We disaggregate the CS by mechanism into pore pressure and poroelastic components and by source into shallow injection- and deep injection-induced components. By mechanism, we find that in-zone far-field and out-of-zone poroelastic stress far exceeded in-zone pore pressure in driving all three events, with the poroelastic component always making up > 80% of the CS at their origin time, irrespective of diffusivity and focal depth, and nearing 100% at their reported depths. By source, shallow and deep injection respectively dominated the CS at shallower and deeper depths, as expected; surprisingly, within the basement between 6 and 7+ km deep, there exists a crossover depth below which shallow injection outweighs the deep injection again. This crossover depth increases with deep diffusivity but is less sensitive to shallow diffusivity. Based on our modeling and the reported depths, all three events were likely mainly driven by shallow injection. However, considering uncertainties in focal depths, we cannot rule out deep injection as the main driver of these events.

Probing Frictional Properties of Delaware Basin Formations: Insights From Laboratory Experiments

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The Delaware Basin in west Texas/SE New Mexico, is one of the most hydrocarbon productive and tectonically complex basins in the US. This intraplate region has experienced a dramatic increase in seismic rates since 2016, a phenomenon linked to waste-water disposal and hydraulic fracturing into shallow and deep formations. However, details of the connection between industry practices and seismicity are unclear. In the central basin, earthquakes are small-to-moderate magnitude and confined at shallow depths (2-3 km) corresponding to injection layers, suggesting a causal relationship. To the north, seismicity is characterized by larger magnitudes (up to Mw=5) involving deeper formations down to the crystalline basement (average depth ~6.5 km), despite most of the fluid disposal volume being injected into shallow formations. Seismological studies integrated with InSAR information reveal that seismicity accounts for no more than 5% of the total deformation, suggesting that the remainder is accommodated aseismically.

To investigate the control of lithology on the distribution of seismicity, we tested the frictional properties of 11 lithologies of the Delaware Basin from the crystalline basement to the Delaware Mountain Group. We characterized the steady-state friction and velocity dependence of friction using a biaxial apparatus in a double direct shear configuration, at normal stresses of 20, 40 and 60 MPa. The friction coefficient μ ranges between 0.33 and 0.66, with phyllosilicate content controlling the weakness of the fault. Frictional stability increases with phyllosilicate content. In general, the rate parameter (a-b) shows good agreement with seismicity depth distribution. We suggest that phyllosilicate-rich formations—where sufficiently thick—act as a seal to fluids and a barrier to earthquake propagation. Where these are absent or thinned, seismic instabilities can extend deeper, reactivating basement faults. Together, these results demonstrate how the lithological architecture of the basin, combined with its structural and mechanical properties control the depth and magnitude of induced seismicity.

Studying Fluid-induced Earthquakes in the Bedretto Lab

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The Bedretto Underground Laboratory for Geosciences and Geoenergies, located beneath the Swiss Alps, offers a unique environment for advancing geoscientific research and energy-related innovations. Situated at a depth of approximately 1.5 km, BedrettoLab provides a controlled setting for investigating deep subsurface processes, particularly those related to geothermal energy, fault mechanics, and fluid-induced seismicity. The laboratory's infrastructure supports a range of experimental studies, including in-situ monitoring of fluid-rock interactions, reservoir stimulation, fault re-activation and stress testing of geological formations. By integrating advanced sensing technologies, continuous monitoring systems, and a multidisciplinary modelling approach, BedrettoLab enables high-resolution observation and analysis of phenomena critical to the safe and efficient use of geo-energies and data-driven, real-time risk mitigation strategies.

This presentation will briefly highlight the laboratory's unique capabilities and then focus on recent findings from ongoing experiments that were executed in the framework of the ERC project FEAR during 2024. During three dedicated experiments, we observed combined more than 100´000 events with magnitudes ranging from -5 to -0.3 with numerous multi-disciplinary sensors. Combining seismicity observations, stress, strain, pore pressure and geochemical measurements, and structural information will allow us to test different hypotheses related to natural and induced earthquakes.

Aftershocks and Ongoing Evolution of Seismicity Surrounding the Damaging 2024 M5.1 Prague Earthquake in Oklahoma

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In February 2024, a M5.1 earthquake occurred near the epicenter of the 2011 M5.7 Prague earthquake, approximately 75 km east of Oklahoma City. The 2024 Prague event had several homes reporting significant damage to chimneys and other minor structural damage. Shortly after the event, the Oklahoma Geological Survey deployed a dense array of USGS-supplied accelerometers and University-owned nodes around the Prague area to monitor aftershocks. This rapid response effort aims to investigate the aftershock sequence and assess the role of deep wastewater disposal in changing the subsurface pressure state.

We will present the latest results on the aftershock evolution of this sequence, which has already culminated in over 5,000 aftershocks, and evolving pressure state of the subsurface. Notably, the area near the 2011 and 2024 events has exhibited relatively persistent seismicity throughout the last decade, with interruptions only by months-long periods of quiescence since initiation of activity. These damaging events, amidst declining injection trends, have important implications for understanding long-lived hazards in areas affected by human-induced seismicity. We will show our preliminary findings from our deployment and discuss their implications for understanding long-term seismic risk and pressure dynamics in induced seismicity zones.

Across Oklahoma, seismicity peaked in 2015 when there were ~900 M3.0+ earthquakes, a dramatic increase from a tectonic background rate of just 1-2 M3.0+ earthquakes per year prior to 2009. Many of those events are now understood to have been induced by wastewater disposal with some events causing moderate, localized damage to rural communities. While the earthquake rate has significantly declined, such that there were 18 and 24 M3.0+ earthquakes in 2023 and 2024, respectively, seismicity across the state remains several times higher than the rate of pre-2009 levels.

On the Link Between Glacial Ablation in the Gongga Mountain, Southeastern Tibetan Plateau and the Aftershocks of the 2022 Moxi Earthquake (M6.8)

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On September 5, 2022, an M6.8 earthquake struck the Moxi segment of the strike-slip Xianshuihe Fault in the southeastern Tibetan Plateau. The aftershocks included a seismic cluster at the foothills of the Gongga Mountain (7,556 m), where the co-seismic Coulomb stress change (ΔCFS) was negative. We propose that this cluster of aftershocks is linked to pore-pressure diffusion, driven by elevated background pore pressure in the foothills due to significant glacial ablation over recent decades in the Gongga Mountain. To investigate this, we developed a poroelastic finite element model that incorporates the region's initial pore-pressure variations. The model simulated both co-seismic and post-seismic changes in pore pressure and Coulomb stress. Our findings reveal that the co-seismic slip of the mainshock initially caused a drop in Coulomb stress at the foothills of the Gongga Mountain. However, this was followed by a gradual increase in stress due to pore-pressure diffusion. The ΔCFS eventually became positive, coinciding with the occurrence of a cluster of aftershocks, including two M≥5.0 normal faulting events, at the mountain's foothills. These results suggest that variations in initial pore pressure - strongly influenced by glacial ablation - played a key role in the aftershock sequence of the Moxi earthquake. This highlights the potential impact of global warming-induced glacial ablation on seismic activity, particularly in tectonically active regions.

Geological CO2 Storage in Swiss Saline Aquifers: Numerical Simulations at Triemli and Insights From the Citru Pilot Project

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Switzerland will have by 2025 to sequester or export about 7 million tons of hard-to-abate CO2 per year. This study investigates the feasibility of CO2 storage in deep saline aquifers in Switzerland, with a focus on the Triemli site in Zurich and the broader Swiss Molasse Basin and Folded Jura. Detailed numerical simulations at Triemli model the injection and migration of CO2, capturing key processes such as pore-pressure evolution, buoyant migration, and long-term trapping mechanisms. These simulations assess the interplay between reservoir properties, fluid behavior, and operational strategies, providing insights into optimizing storage efficiency while ensuring reservoir stability. They also allow us to define a Measurement, Monitoring and Verification strategy and analyse risks. Key risks for CCS in Swiss aquifers are public acceptance, induced seismicity and CO2 leakage. Complementing this numerical study, the CITru pilot project at Trüllikon (www.citru.ethz.ch) plans a test injection of up to 10´000 tons of CO2 into the upper Muschelkalk aquifer. CITru would generate critical data to validate and refine the predictive models developed for CO2 storage capacity in Switzerland and test our models of induced seismicity and fault reactivation potential during CO2 injections.

Mechanical and Acoustic Response of Laboratory Fault-valve Media to Fluid Injections

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The underlying mechanism of fluid-solid interactions remains elusive in the fault-valve systems. Here, we design a new experimental apparatus that enables us to both visualize and listen to the fluid transport and its interplay with granular assemblies within artificial fault-valve media. This setup, featuring regions of alternating permeability, allows us to explore compaction and dilation behaviors that emerge under fluid injection flow. Our research seeks to unravel two primary questions: 1) how does fluid flow interact with porous media and barriers? 2) how to reveal those interactions from acoustic and pressure measurements? Our investigations suggest the following findings: 1) hydraulic transient is observed after/during compaction, which accelerates dilation and is regulated by barrier opening; 2) active acoustic measurements are capable of detecting changes associated with compaction and dilation processes; 3) passive acoustic measurements, conducted at varying injection rates, indicate that the occurrence rate of acoustic emissions is influenced by changes in pore fluid pressure. These direct observations offer a deeper understanding of fluid dynamics in fault zones and their potential to trigger seismic activities.

Mechanistic Insights into Fluid-induced Earthquakes from the Laboratory to the Field [Poster]

Poster Session • Tuesday 15 April

Conveners: David Chas Bolton, University of Texas at Austin (chasbolton19@gmail.com); Xiaowei Chen, Texas A&M University (xiaowei.chen@exchange.tamu.edu); Thomas H. Goebel, University of Memphis (thgoebel@memphis.edu); Congcong Yuan, Cornell University (cy547@cornell.edu)

POSTER 92

Factors That Can Influence the Fault Activation Process: Examples From Wastewater-induced Sequences in Oklahoma and Geothermal Fields in Utah

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Earthquake rupture physics and sequence evolution exhibit varied spatiotemporal patterns. The increased seismicity associated with energy exploration in recent years provides us with an opportunity to further probe the factors that influence the these patterns. In this study, we hope to synthetize new and published observations of earthquake and stress evolution from wastewater injection induced sequences in Oklahoma and induced seismicity at Enhanced Geothermal sites to better understand the interactions among stress, fault geometry and earthquakes. Qin et al. 2022 used focal mechanisms to reveal differences in the temporal evolutions of earthquake clusters with respect to fault architecture and orientation to the stress field. Optimally oriented, near-vertical, narrow faults lead to more burst-like behaviors with larger events, while more complex, mesh-like fault geometries lead to more swarm-like behavior with more extended sequence duration. Directivity analysis on two contrasting sequences confirms simpler fault structures for the more optimally oriented fault. Directivity also finds that the nodal plane more well aligned with stress field tends to be the fault plane rupture during the earthquake for both cases. Extending the focal mechanism and stress field analysis work to Enhanced Geothermal Site in Utah found distinct structures with different spatiotemporal evolution and activation timeline from stimulation, that are influenced by stress field and structure orientation. Further quantitative comparison among different sequences will be updated.

POSTER 93

Reassessing the North Texas Earthquake Catalog Using Machine Learning

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Machine learning (ML) phase detection and association has altered the landscape for the rapid creation of earthquake catalogs. Many rapid deployments in urban areas use a mix of accelerometers and velocity sensors and have a complicated metadata history, creating scenarios the push the limits of available training datasets. The North Texas Earth Study (NTXES) in the Fort Worth Basin consists of rapidly deployed 1- and 3-component short-period, strong-motion, broadband, and nodal sensors in a large metropolitan area with changing configuration as seismicity evolved from 2008 to present. The NTXES catalog, with over 3000 earthquakes, was originally built using automated detection with manual review (Quinones et al., 2019). While the catalog provided fundamentally important data to understand physical mechanisms of induced seismicity in the basin, original efforts to constrain time variation in b-values, conduct nearest neighbor determinations, etc. were limited by incompleteness at both the high and low magnitude end of the catalog. Preliminary work using EQTransformer (Mousavi et al., 2020) to grow the catalog indicated mixed results for picking accuracy and lowering detection magnitudes below the manual review and poor detection results for accelerometers. Here, I compare PhaseNet (Zhu and Beroza, 2018) arrival time detections with the manual catalog, seeing improved results on velocity sensors. The resulting catalog will be used to calculated time-variation in b-value using the b-positive method (van der Elst, 2021) and assess foreshock-mainshock-aftershock and earthquake swarm behavior using nearest neighbor determination (Zaliapin and Ben Zion, 2020). Preliminary work using Texas earthquake catalogs indicate that statistical approaches, and resulting interpretations, can be sensitive to biases in time and space, especially depth, inherent in both automated and relative relocation catalogs, as will be discussed.

POSTER 94

Relocating Induced Seismic Events to Evaluate the 2022 Hydraulic Stimulation Stages at Utah FORGE

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The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) is a unique facility dedicated to advancing enhanced geothermal systems (EGS). It provides a controlled environment for studying induced seismicity and its implications for subsurface reservoir dynamics. In 2022, Utah FORGE conducted hydraulic stimulations in the deviated 16A-32 borehole, divided into three stages. The seismicity induced during these stimulations was originally intended to be monitored by a network of three deep borehole geophone strings positioned azimuthally around the stimulation zone. Due to technical challenges from extreme temperatures, only Stage 3 was monitored with geophones in all three boreholes. Stage 1 relied on a single borehole, while Stage 2 utilized geophones in two boreholes. For each stage, Geo-Energie Suisse (GES) analyzed available data to generate seismicity catalogs. The Stage 3 catalog achieves high precision, with absolute location errors estimated at less than 10 meters, while the Stage 1 and 2 catalogs have lower precision due to reduced network coverage. These differences limit the ability to infer subsurface structures and reservoir dynamics. To address these limitations, this study focuses on relocating seismic events from all three stages using the double-difference algorithm HypoDD. By replicating the original station configurations for each stage, the goal is to evaluate the impact of network geometry on resolution and structural interpretation. Stage 3 will serve as a baseline for assessing resolution loss and structural features in Stages 1 and 2. Through these efforts, the study intends to refine the relocated seismicity for Stages 1 and 2, revealing potential structural features and fluid pathways within the reservoir. Integrating seismic relocation results with hydraulic data is expected to provide critical insights into the reservoir characteristics at the toe of the Utah FORGE reservoir, contributing to improved reservoir management and advancing geothermal energy technologies.

POSTER 95

A General Probabilistic Trans-dimensional Approach to Estimate Spatiotemporal Variations of Recorded Seismicity

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The parameters of the Gutenberg-Richter relation, particularly the b-value, are used to characterize the source behavior of seismicity given an earthquake catalog. Many studies have considered spatiotemporal variations in the b-value, which are interpreted to be linked to the accumulation of stress near active faults in Earth's crust. The b-value is also a valuable input for earthquake hazard assessment. Most methods for estimating variations in the b-value rely on subjective choices of key parameters, such as the minimum and maximum magnitude values and spatiotemporal windowing, which can significantly affect the results. Recent work has introduced a probabilistic trans-dimensional approach, where windows are self-defined according to the information contained within the earthquake catalog. Existing methods require prior definition of the magnitude of completeness of the earthquake catalog, such that only events above this magnitude threshold are considered in the analysis. Here, we develop a general probabilistic, trans-dimensional approach that uses the entire (incomplete) earthquake catalog to estimate models of the spatiotemporal variations in the b-value as well as catalog incompleteness (i.e., decay of the distribution at high and low magnitudes). We demonstrate our method by analyzing several simulated and real earthquake catalogs, including natural and induced seismicity in northwestern Canada. Our results show that variations in catalog completeness can bias estimates of b-value variations when not accounted for, and vice versa. Our results highlight the effectiveness of a general probabilistic trans-dimensional approach in considering the entire earthquake catalog to obtain robust estimates of spatiotemporal variations in recorded seismicity. This will lead to more reliable assessments of seismic hazards, particularly for regions of frequent induced seismicity, such as in western Canada.

POSTER 97

Improving Our Understanding of Seismogenic Faults and Operations That Have Induced Seismicity in the Eagle Ford Basin, Texas

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Unlike many areas of the central United States where induced seismicity has been caused by wastewater disposal, most of the earthquakes in the Eagle Ford Basin in Texas have been related to hydraulic fracturing (HF) wells (*Fasola et al.*, 2019; *Fasola & Brudzinski*, 2023). This includes some of the largest HF-induced earthquakes in the United States, including a M 4.7 earthquake on February 17, 2024 and five events larger than M 4 since 2018 in Karnes County. The seismicity appears to be associated with the Karnes Trough extensional feature, but the detailed pattern of the seismicity and how it relates to faults and HF operations has not been characterized. This study has sought to take advantage of the ~5 years of continuous recordings from the dense (25 km station spacing) seismic network in the area to better detect and locate the seismicity. We have developed a workflow for streamlining the processing that starts with 1) catalog events and phase picks and then performs 2) multistation template matching with automated correlation threshold determination for each template, 3) phase arrival identification for detected matches using cross correlation with the template and other matches, 4) preliminary location of detected matches using the determined phase arrivals, and 5) double difference relocation of template and matched events using cross-correlation enhanced arrival times and a locally determined 1-D velocity model. This approach reveals more than an order of magnitude increase in the number of detected and located earthquakes. Our preliminary results indicate that the seismicity primarily occurs on a series of steeply dipping northeast-southwest trending faults.

POSTER 98

Dynamic Triggering in the Geysers Geothermal Field by Two Recent Large Earthquakes

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Dynamic triggering is widely recognized and validated around the world, and is especially common in geothermal and volcanic regions with high background seismic activity. Study on the interaction of remote large earthquakes and locally industrial activities (e.g., geothermal production) can provide insights on the earthquake nucleation process, and may also benefit induced earthquake forecasting and associated seismic hazard management. In this work, we investigate dynamic triggering phenomenon in The Geysers geothermal field associated with two recent large earthquakes in California, the 2019 Ridgecrest Mw 7.1 earthquake and the 2024 Mendocino Mw 7.0 earthquake. We use deep learning-based workflows to build the microseismic catalog and further estimate the local magnitudes. Seismicity rates increase immediately after the arrival of S-wave, with β-value reaching 10 and 40 for the 2019 and 2024 earthquakes, respectively, suggesting that dynamically triggered earthquakes occurred widely in the geothermal field. Due to the difference in the origin (e.g., distance and direction) of the large earthquakes, the triggered sequences show different characteristics in seismicity rate variation, spatial distribution, and earthquake magnitude. Notably, the 2024 Mendocino Mw 7.0 event triggered two moderate earthquakes (ML 3.6 and ML 4.3) within 2 minutes in the northwestern part of the geothermal field, which are among the largest earthquakes in this region. A detailed comparison of dynamic triggering by the two different earthquakes reveals distinct triggered earthquake sequences and sheds light on the physical triggering mechanisms behind them.

POSTER 100

Investigating the Influence of Seasonal Groundwater Level Fluctuations on Localized Seismic Activity in Southwestern Taiwan

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Seismic activity is frequent in Taiwan, with most research focusing on the east coast due to its high-magnitude events and devastating impacts. However, smaller-scale seismic activity occurs regularly in southwestern Taiwan. In this study, we investigate these localized seismic events and explore their relationship with seasonal groundwater level fluctuations. Using advanced mathematical and statistical techniques, we develop a predictive model to estimate the probability of seismic events (up to a user-defined magnitude) at specific locations within the next few days, based on refined groundwater level data. This model provides valuable insights for seismological experts, enabling a deeper understanding of how groundwater level changes may influence or trigger seismic activity. This work is conducted in collaboration with my master's student, Mr. Yuan Chang Sun (National Tsing Hua University, Taiwan), and utilizes data provided by the Institute of Earth Sciences, Academia Sinica.

POSTER 101

Linking Spatiotemporal b-Value Evolution to Physical Mechanisms Influencing EGS Induced Seismicity

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The development and operation of Enhanced Geothermal Systems (EGS) can induce earthquakes during fluid injections, posing significant hazards for both local populations and the continued operation of EGS plants. An improved understanding of the interplay between the physical mechanisms affecting geothermal induced seismicity is important for current and future EGS projects. One way to analyze seismicity is with the b-value, which represents the slope of earthquake magnitude frequency distributions. Previous EGS studies suggest a pore-pressure driven induced seismicity model where spatially – the b-value is high near the injection point and temporally – the b-value decreases during later stages of injection.

We evaluate the pore-pressure driven model by comparing the spatiotemporal b-value evolutions of nine different EGS induced seismicity scenarios including Basel and FORGE, along with injections from Soultz-sous-Forêts and Cooper Basin. In our spatiotemporal analyses, we find that a majority of examined sequences have a period where the distal b-value is significantly higher than the b-value near the injection point. These sequences indicate that the pore-pressure driven model is inadequate for describing spatiotemporal b-value evolution, and that additional physical mechanisms, like aseismic slip, could have significant effects on EGS induced seismicity. Further characterization of the b-value in EGS induced seismicity sequences provides an opportunity to better constrain the degrees to which different physical mechanisms influence seismicity.

POSTER 102

Characterization of Shallow Seismic Sources in the Neuquén Province, Argentina

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The Neuquén province in southwest Argentina is a major center of oil exploitation. Since 2014, several companies started hydraulic fracturing to enhance oil production in one of the biggest unconventional shale gas-oil reservoir in the world: the Vacamuerta reservoir. This reservoir covers a region of ~30,000 km^2 and is mainly located in the Neuquén province at 2.5-3.5 km depth. Previously, the province was characterized by low seismic hazard (seismic zones 1 and 2 since the official Seismic Zonation Map of Argentina), with a PGA of 0.04 g and 0.1 g, respectively for a return period of 475 years.

Since 2015, the population of Neuquén has reported unusual seismic activity, mainly close to Sauzal Bonito and Añelo. During January of 2019, more than 20 felt seismic events were reported and a rare Mw 4.9 earthquake occurred two months later. This seismic activity generated a strong social concern about the relative increase in seismicity within the Neuquén province and its possible relation to the anthropic activity. By the end of June of 2019, the National Institute of Seismic Prevention (INPRES) of Argentina and the Seismology Laboratory of the Geosphere and Biosphere Research Center (CIGEOBIO dependent on the National University of San Juan and the National Council for Scientific and Technical Research), installed 2 broadband seismic stations in the Sauzal Bonito and Añelo localities. We will present results from analyzing the respective seismicity which included more than 100 earthquakes with M_L magnitudes from 0.6 up to 3.8 between 2019 and 2020. Due to the sparse network, we located events using a single-station multicomponent algorithm, after applying a time correction for a strong anisotropy effect on the horizontal components. We combine cross-correlation analysis and composite focal mechanism solutions, and resolve more than 4 undocumented active seismic sources near Sauzal Bonito and Añelo. Safe and sustainable oil field operations in Neuquén likely require improved long-term monitoring and seismic hazard mitigation.

POSTER 103

Understanding Rupture Directivity of Injection-induced Earthquakes: A Numerical Study Coupling Poroelastic Model With Rate-and-state Earthquake Cycle Simulator

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Understanding rupture directivity is crucial for assessing induced earthquake hazards, as it significantly influences the resulting ground motions. This study analyzes factors controlling the rupture process of induced events by integrating spatiotemporal fluid-induced pressure and stress perturbations from fully-coupled poroelastic models in COMSOL, into fully-dynamic earthquake cycle simulations based on the boundary integral method and rate-and-state friction law. The COMSOL model features a 2.75-km-long rectangular fault, with an off-fault injection of 10 kg/s lasting for ~8 days. The resulting maximum changes in Coulomb failure stress is ~100 kPa, comparable to perturbation values calculated in a prior study for the Delaware Basin due to shallow injections. On-fault pressure and stress perturbations are recorded for ~112 days post-injection until the perturbation drops by >99%. These data are introduced into a rate-and-state fault model for fully-dynamic simulations, under various injection start times, fault configurations, and background normal stress (2 - 60 MPa).

Results show that rupture directivity of induced events depends on the relative strength of pressure and stress perturbations in relation to background stress. When normal stress is relatively high (20 MPa), no correlation is observed between directivity and the induced pressure/stress gradient. In these cases, the nucleation location and direction of triggered events are primarily governed by the heterogeneous distribution of shear stress on the fault that is shaped by prior seismic and aseismic activities. In contrast, when normal stress is lower (2 MPa), most triggered aseismic transients and subsequent dynamic nucleation tend to occur in regions closer to the injection site with stronger perturbations and ruptures propagate away during the injection period. Overall, our findings emphasize the importance of the relative strength of perturbations to background stress in determining the nucleation patterns of induced seismicity. We will also discuss the role of triggered aseismic transients in constraining future earthquake locations.

POSTER 104

Repeating Earthquake Sequences in Induced Seismicity in West Texas

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Induced seismicity from hydraulic fracturing, oil-gas operations, geothermal systems, and CO2 sequestration are common worldwide. They can lead to moderate seismicity on pre-existing faults and constitute a hazard to surrounding communities. In particular, induced seismicity in the Permian Basin in West Texas has rapidly increased since ~2016, in response to increased fluid injection associated with oil and gas operations. Yet the physical processes relating to fluids, fault motion and fault healing that control induced seismicity are still poorly constrained. Repeating earthquakes, -- earthquakes that repeatedly rupture the same seismic asperity time and time again -- provide a perfect opportunity to understand the recurrence and frictional healing of seismic asperities in-situ. We identified repeating earthquakes in the Permian Basin using a catalog of relocated earthquakes from 2017 - 2020 that contain high-resolution measurements of stress drops derived from Trugman and Savvadis, 2021. We identify repeaters as events that have overlapping rupture areas and high waveform similarity. Preliminary results suggest that there are ~20 sequences with quasi-periodic recurrence intervals, ranging in duration from days to years. The wide range in recurrence intervals provides evidence for a range of driving stresses and healing rates across the region. Using measurements of stress drop and recurrence interval, we aim to measure the in-situ healing rates of the seismic asperities that host the repeaters. Along with the periodic sequences, we also identify closely located events with short recurrence intervals that are likely triggered from static-stressing. This work will provide new and unique insights into the physical processes that drive induced seismicity in the Permian Basin and will be integrated with laboratory-based studies of fluid-induced seismicity.

Modern Waveform Processing and Engineering Datasets - Accessibility, Quality Control, and Metadata

Oral Session • Thursday 17 April • 4:30 PM Local

Conveners: Carlo Cauzzi, Swiss Seismological Service (SED) at ETH Zürich (carlo.cauzzi@sed.ethz.ch); Lijam Hagos, California Geological Survey (Lijam.Hagos@conservation.ca.gov); Olga-Joan Ktenidou, National Observatory of Athens (olga.ktenidou@noa.gr); Albert Kottke, Pacific Gas and Electric (arkk@pge.com); Lucia Luzi, National Institute of Geophysics and Volcanology (lucia.luzi@ingv.it); Lisa S. Schleicher, U. S. Geological Survey (lschleicher@usgs.gov)

Recent Improvements and Lessons Learned From Processing Ground Motions at the U.S. Geological Survey

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At the U.S. Geological Survey, we frequently process and analyze ground motions using the software gmprocess and PRISM (Processing and Review Interface for Strong Motion). In doing so, we identify anomalous results and investigate the underlying causes of potentially problematic records. These efforts have demonstrated the need for more rigorous quality control and consistency checks for station metadata. Examples of new consistency checks that we have implemented include: (1) checking for consistency of the individual response stage gains with the overall instrument sensitivity, (2) explicit tracking of the reported input and output units for each response stage to ensure that the result of all response stages yields physically appropriate units, and (3) more extensive checking of data types, e.g., checking that the data type is an integer when the units are reported as counts. We have also compared the processing steps and results between gmprocess and PRISM. These comparisons have led to the development of new features in gmprocess, including: (1) implementation of PRISM's adaptive baseline correction method, (2) support for velocity and displacement spectra, and (3) full support for all volumes of the Consortium of Organizations for Strong Motion Observation Systems (COSMOS) format. We have recognized the need to track and classify problematic records and metadata. Such a dataset is essential for developing quality control and stress-testing ground motion processing algorithms. To meet this need, we have created a repository to archive problematic records and document the type of problem (e.g., clipping, poor signal-to-noise ratio, incorrectly reported instrument sensitivity, low digitizer resolution). The critical characteristic of the classification system is that each record, whether acceptable or problematic, is manually reviewed.

Exploring the Utility of Earthquake Spectra Collected From Smartphones for Ground-motion Modeling

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The field of ground-motion modeling has been increasingly embracing non-ergodic ground motion models (GMMs) with spatially variable coefficients due to their superior performance in capturing highly spatially variable source, path, and site effects. The estimation of non-ergodic terms in non-ergodic GMMs relies on the availability of as many densely sampled shaking observations as possible. Traditional seismic station data may prove insufficient, creating a need to fill data gaps with unconventional datasets. Acceleration waveforms recorded via the MyShake smartphone app provide one such dataset. MyShake has been delivering ShakeAlert earthquake early warning messages to US West Coast users since October 2019. It also provides triggered waveforms recorded using the onboard accelerometer. Using a database of smartphone waveforms from California, Marcou et al. (2024, BSSA) used residual analysis to show that spatial trends in smartphone peak acceleration amplitudes recorded on smartphones have a significant positive correlation to free-field peak amplitudes, and thus smartphone data has predictive power for free-field ground motion. In this work, we extend their analysis to the spectra recorded by smartphone accelerometers, given that state-of-the-art GMMs now model Fourier Amplitude Spectra (FAS). We uniformly process smartphone FAS to investigate their general characteristics over a wide (0.5 - 25 Hz) frequency band. We compare smartphone FAS to predicted free-field FAS from a modern non-ergodic GMM, as well as to recorded free-field FAS for selected earthquakes. We probe the degree to which the response of the structures in which the smartphones record ground motion affects the recorded spectra and any ability to see site resonances. We finally discuss potential ways forward for ground-motion modeling using the smartphone FAS dataset.

The Next-generation ESM: Generating Reference Earthquake Data Sets from High-quality Semi-automated Waveform Processing

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ORFEUS (Observatories and Research Facilities for European Seismology; https://www.orfeus-eu.org/) promotes the coordinated development of waveform seismology data services in the Euro-Mediterranean region, including the rapid raw strong-motion (RRSM; https://orfeus-eu.org/rrsm/) and the engineering strong-motion (ESM; https://esm-db.eu/) databases and associated web interfaces and webservices.

The ESM system provides event-based waveforms, peak motions, response spectra, and earthquake and site/station metadata for events with a magnitude ≥ 4.0. As the ESM is the reference database for harmonized seismic hazard and risk studies in Europe, the ESM data are presently published online after experts' revision and approval to ensure the highest quality. However, manual revision is becoming unsustainable mainly due to the rapid growth of digital earthquake records from global, regional, and national seismic networks. Consequently, a new framework for waveform data processing is required to enable top-quality, automated processing, limiting human intervention.

To address this need, we introduced ESMpro, a modular Python-based software designed for the updated processing framework of ESM. The software, currently available in a stand-alone Beta version on GitLab (https://shake.mi.ingv.it/esmpro/), is intended to facilitate testing and collaboration within the scientific community. ESMpro automates waveform trimming and filtering, identifies poor-quality data and multiple events, and classifies records into quality categories. This reduces the need for manual revision to a smaller subset of incoming data. Additionally, ESMpro's modular and flexible design allows it to support various processing techniques and file formats, simplifying the integration of new or alternative algorithms. Testing conducted on manually processed ESM waveforms demonstrates a strong alignment between automatic and manual data processing, validating the shift toward fully automated procedures for large-scale data processing.

Australian Ground-motion Records Portal

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We introduce a web portal designed to provide seamless access to consistently processed Australian ground-motion records and key engineering parameters, offering a powerful tool for researchers, and engineers. The portal leverages the USGS *gmprocess* software to consistently process ground-motion data and compute engineering parameters of interest. These processed datasets are then integrated into the database, which supports advanced queries based on earthquake parameters (e.g., magnitude, origin time, depth), ground motion metrics (e.g., peak ground acceleration and velocity, response spectral acceleration), and source-to-site distance metrics (e.g., hypocentral distance). Search results can be downloaded in CSV format, including key earthquake, site condition, and source-to-site distance parameters, along with computed engineering metrics. Additionally, processed waveforms are available for download in the standard COSMOS format.

The portal enhances user experience with interactive visual tools, featuring layers that display earthquake locations, recording stations, Australia's seismic site condition map, neotectonic domains, and national seismic hazard maps (current and legacy). Users can explore photographs of recording stations and gain event-specific insights, such as waveform section plots and user-friendly summaries of earthquake, station, and ground motion parameters. The platform also enables users to compare recorded ground motions with ground-motion models in an interactive and flexible manner. With its user-friendly interface and robust features, this platform can significantly contribute to seismic hazard analysis and earthquake engineering in Australia.

Deep Learning-based Approaches to Assess Waveform Quality for Engineering Applications

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Due to rapid advancement in recording capabilities, the number of recorded waveforms has increased substantially, and this trend is projected to continue in the coming years. However, scaling conventional methods of waveform quality assessment to meet the demand of such datasets presents significant challenges, motivating the development of computationally efficient and scalable solutions. Deep learning (DL)-based approaches provide a promising solution to automate waveforms quality assessment over large databases by extracting the characteristics of high and low-quality waveforms. Despite their potential, limited work has explored the suitability of DL-based approaches for this application, where a significant knowledge gap exists on (1) algorithm selection, (2) efficient training workflows, (3) preparation of labeled data to support model training, and (4) the generalizability of trained model across different databases.

This study investigates the development and performance of various DL-based models for waveform quality classification. Using two waveform databases from New Zealand, the study evaluates the effectiveness and generalizability of convolutional and residual neural networks in this classification task. Additionally, different pre-processing and augmentation techniques, including over-sampling for data imbalance and record rotation for augmentation, were tested to understand the best practices for model training. Results show that a residual neural network-based architecture achieves accuracy and F1 scores exceeding 90%, where the same model retains its accuracy, to a lesser extent, when applied to a different waveform database from the same geographic region. Nevertheless, improving model generalizability and performance requires future efforts to establish a comprehensive training database supporting both DL-based and traditional algorithmic approaches.

Modern Waveform Processing and Engineering Datasets - Accessibility, Quality Control, and Metadata [Poster]

Poster Session • Thursday 17 April

Conveners: Carlo Cauzzi, Swiss Seismological Service (SED) at ETH Zürich (carlo.cauzzi@sed.ethz.ch); Lijam Hagos, California Geological Survey (Lijam.Hagos@conservation.ca.gov); Olga-Joan Ktenidou, National Observatory of Athens (olga.ktenidou@noa.gr); Albert Kottke, Pacific Gas and Electric (arkk@pge.com); Lucia Luzi, National Institute of Geophysics and Volcanology (lucia.luzi@ingv.it); Lisa S. Schleicher, U. S. Geological Survey (lschleicher@usgs.gov)

POSTER 48

A Curated Database of High Quality Microtremor HVSR From U.S. Permanent Seismic Stations

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The horizontal-to-vertical spectral ratio of ambient noise (mHVSR) has been used to develop proxies for site effects for many decades. Recent studies have considered the use of mHVSR as a predictor of site effects and parameters derived from mHVSR (e.g., the frequency corresponding to the peak amplitude) have been implemented into ground motion models for predicting site effects. These advancements create a need for obtaining mHVSR at strong motion recording sites. Recording ambient noise, using temporary broadband seismometers, at each of the strong motion stations would be ideal, but it would require an enormous manual effort. Moreover, studying time-dependent variations in ambient noise requires deployment of the seismometer for an extended duration. Alternatively, continuous noise measurements from the permanent seismic stations can be used for obtaining mHVSR. Using the continuous noise measurements from permanent seismic stations drastically reduces the manual effort in data collection as the noise data are continuously archived for most of the seismic networks. The objective of this research is to compile a database of mHVSR obtained from noise measurements at permanent seismic stations in the United States. In the light of the development of new generation of ground motion models for shallow crustal earthquakes (NGA West 3), the compiled HVSR data could be useful for modeling site response. In this research, we compile the three-component noise recordings from approximately 4,200 permanent seismic stations. Three-hour noise recordings were processed using the open source HVSR processing tool *hvsrpy*. Quality control checks are necessary to identify cases in which the computed HVSR is affected by non-stationary effects or by potential instrument malfunction. However, the quality control checks are difficult to automate, and often requires manual examination. After comprehensive quality control checks, the resulting database containing HVSR curves and noise time series will be published in DesignSafe data repository. It is hoped that the database will aid in the development of robust site response models.

POSTER 49

An Updated Review of Ground Motion Flatfiles in the Chilean Subduction Zone

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The Chilean-Peruvian subduction zone, one of the most seismically active regions globally, requires extensive ground motion datasets to advance seismic hazard assessment and risk mitigation strategies. This work expands upon Bastias and Montalva's 2016 (BM16) flatfile by introducing a significantly larger database with 43,585 records compared to the previous 3,572 (a 12x increase), 6,650events (a 14x increase), and 484 sites (2.7x increase). Additionally, the dataset includes data from a vertical array. The database is organized into three flatfiles for seismic events, site stations, and strong ground motion records, each containing detailed metadata to optimize usability. The dataset incorporates major megathrust earthquakes from the Perú-Chile subduction. The seismic source is defined through the moment tensor and the relative geographic positioning of each event within the subduction slab context. Site characterization employs measured shear wave velocity (Vs) profiles, then we use a proxy-based methodology to estimate average Vs at 30 m depth. In addition to the prior proxies (i.e., topographic and HVSR) used in BM16, this study is complemented with the P-wave estimation, which demonstrates superior predictive performance. Also, kappa estimation is provided for 47 stations.

Ground motion records are processed using a Signal-to-Noise Ratio (SNR > 3) scheme, defining the low-cut frequency at the passband filter and avoiding artifacts in the processed time series. This allows for balancing the noise of the traces on the whole dataset. Theoretical P- and S-wave arrivals are identified through an automated workflow using a new hypocentral distance-based formula and picking techniques. The quality control of traces is based on the residuals within the usable spectral periods and in the definition of the bandwidth (in frequency domain) with SNR higher than 3. The dataset introduces new orientation horizontal spectral measures (RotDXX) and azimuth data for RotD100, providing insights on the path orientation.

POSTER 50

Marsquakes Then and Now: Revisiting Viking With Insight

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The Viking 2 lander, operating in the late 1970s, deployed a seismometer on its deck, but its ability to detect seismic activity was severely limited by wind-induced noise and the lack of direct ground coupling. Over 560 sols, it recorded approximately 2,100 hours of data, yielding only two signatures that could be interpreted as seismic events [1]. In contrast, the InSight mission briefly operated its SEIS instrument on the deck before deploying it on the ground under a wind and thermal shield, significantly improving noise isolation and enabling the detection of numerous seismic events [2].

Using the comodulation method of Charalambous et al. (2021) [3], which effectively validated events and phases in InSight's on-ground data, we revisited the Viking 2 dataset, exploiting the similar wind-noise dependence observed in both missions' deck-mounted operations. We detected no seismic events during InSight's brief on-deck phase; however, our analysis of Viking data uncovered 10 candidate events that could not be attributed to wind or lander noise. We further examined these events for their potential seismic origins by comparing them to seismic signatures of InSight detections of known tectonic and impact sources. These results provide new insights into Martian seismic activity during the Viking era and demonstrate the potential for enhanced on-deck seismic detection using modern instruments and advanced processing techniques.

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POSTER 52

Operational Response Insights from the December 2024 Cape Mendocino, California Earthquake Waveform Data Processing and Quality Review

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The USGS National Strong Motion Project (NSMP) plays a critical role in ensuring the quality, completeness, and accessibility of seismic data collected from significant earthquakes. Through a combination of pre-event preparation, near real-time tools, and post-event analysis workflows, NSMP focuses on delivering reliable data products for both immediate response and long-term seismology research and engineering applications. The December 5, 2024, M7.0 Offshore Cape Mendocino, California earthquake provided an opportunity to evaluate and refine NSMP's waveform data processing and quality control workflows. Using Python-based geographic information system (GIS) tools, NSMP identified data gaps that facilitated field recovery of a non-communicating near-source station at Lost Coast Ranch and multi-channel building arrays in the San Francisco Bay region and broader western U.S. for proactive quality review. These tools helped detect metadata inconsistencies and address operational challenges, improving response workflows. Here we aim to highlight the NSMP's current core workflows, including planned developments and improvements to our signal processing pipelines, metadata validation tools, and data dissemination strategies through the Center for Engineering Strong Motion Data Center (CESMD), ShakeMap, and the Northern California Earthquake Data Center (NCEDC). We'll showcase how these workflows were applied in a recent earthquake response, share lessons learned, and offer guidance on effectively accessing and utilizing NSMP waveform datasets and station information, including available site characterization data. These insights are broadly applicable to seismic data users and responders following future significant earthquakes, as waveform datasets evolve from preliminary to more complete versions throughout the event sequence.

POSTER 53

Ground Motion Dataset Verification and Validation, Insights Into Unexpected Sources of Uncertainties Associated to Ground Motion Modeling

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During the last years, the collection of weak motions and the implementation of local ground motion datasets has grown in popularity in low-to-moderate seismicity regions. Such ground motion datasets are then used, for example, to adjust existing Ground Motion Models (GMMs) developed in active regions of the world to the local context, to develop specific non-ergodic GMM or to perform Generalized Inversions (GIT) and assess seismological models.

Regardless of the final application, careful Verification and Validation (V&V) of the collected and processed data are essential to ensure the quality of the dataset and therefore the robustness of the following analyses.

In low-to-moderate seismicity regions as continental France, available ground motion recordings are mostly related to small magnitude earthquakes, for which the information associated to the earthquake source parameters (3D location and magnitude) is often affected by large uncertainties. Moreover, to obtain the largest usable frequency range over the largest number of records, ground motions recorded at both, accelerometers and broad-band seismometers are usually collected. However, information about seismic station installation conditions (housing, possible evolutions in station installation over time…) is most often lacking.

In this work we present the V&V strategy set up while implementing the EPOS-France ground motion dataset (Traversa et al., 2020 and Buscetti et al., 2024) for continental France. Using residual analyses with respect to an ad-hoc simple Ground Motion Model (GMM), inconsistencies and inaccuracies affecting recorded data and associated metadata could be identified and either, were corrected or led to data rejection. This analysis also allowed to assess the impact of the quality of the metadata (e.g. of the earthquake catalog) on the variability associated to a GMM developed based on the considered dataset.

This work highlights that significant epistemic uncertainties can still be hidden into what is interpreted as GMMs aleatory variability when datasets do not undergo V&V careful strategies.

POSTER 54

Usability of Records by China Earthquake Early Warning Network for Ground Motion Model Development

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Since 2020, the China Earthquake Early Warning Network (CEEWN) has acquired a substantial number of near-field ground motion records using high-density micro-electro-mechanical systems (MEMS) sensors and force-balanced accelerographs (FBAs). This has provided a valuable opportunity for the study of near-fault ground motion and the development of regional ground motion models (GMMs) in China. However, concerns about the usability of acceleration records from low-cost MEMS sensors have limited their application. The objective of this study was to evaluate the usability of CEEWN data by conducting a comprehensive analysis of noise levels, usable bandwidth, and the impact of various factors on data quality. Our analysis revealed that the usable bandwidth for both FBA and MEMS records increased with peak ground acceleration (PGA), with FBA records demonstrating significantly wider usable bandwidth.The FBA noise levels ranged from 10-4 cm/s² to 0.1 cm/s², reflecting ambient noise, while the MEMS records exhibited a concentrated distribution due to instrument-related noise. The MEMS sensors were categorised into high-noise and low-noise groups. The low-noise instruments exhibited noise levels ranging from 0.04 to 0.06 cm/s², while the high-noise instruments demonstrated noise levels that were comparable to those recorded by the Community Seismic Network in California. Wall-mounted installations resulted in an average noise increase of 1 to 1.5 times compared to ground installations, while vertical component noise exhibited a slight decrease. The MEMS records were classified into four categories: Very Broadband Record (VBBR), Broadband Record (BBR), Narrowband Record (NBR), and Rejected Record (REJ). PGA thresholds were established to distinguish between these categories. Limiting distances for events of magnitudes 5, 6, 7, and 8 were determined for low- and high-noise instruments.

Network Seismology: Recent Developments, Challenges and Lessons Learned

Oral Session • Tuesday 15 April • 8:00 AM Local

Conveners: Blaine M. Bockholt, Idaho National Laboratory (Blaine.bockholt@inl.gov); J. Renate Hartog, University of Washington (jrhartog@uw.edu); Kristine L. Pankow, University of Utah (pankowseis2@gmail.com); Dmitry Storchak, International Seismological Centre (dmitry@isc.ac.uk); William Yeck, U.S. Geological Survey (wyeck@usgs.gov)

Evolution and Optimization of the Raspberry Shake Data Center: Managing the World's Largest Real-time Seismic Network

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The Raspberry Shake Data Center (SDC) has undergone a comprehensive redesign in 2024 to meet the demands of both a large network and its ongoing rapid growth. Currently managing 2,500 online stations, ~7,000 channels, each streaming at 100 samples per second, the SDC supports all aspects of what it means to host and manage the world's largest real-time seismic network. The new infrastructure has been architected with an eye towards gracefully handling the network's future expansion, anticipated to exceed 10,000 stations.

We present the technical infrastructure and architectural solutions implemented to handle massive-scale data acquisition and distribution. Given the scaling requirements for a seismic data network intended to be up and available 24/7/365, open-source technologies in the seismological communities alone are not able to deliver a solution satisfying the network's myriad requirements. This led to the development of custom C/C++ solutions optimized for high-throughput data handling, automatic fail-over and recovery of critical systems, the ability to easily scale the server-side infrastructure both vertically and horizontally, and more. The integration of gempa GmbH's CAPS software has been crucial in enabling efficient data distribution at large scales.

This presentation details the implementation of multi-level redundancy systems and discusses how a citizen science initiative evolved to require enterprise-level data center capabilities. We focus on the technical challenges of scaling real-time seismic data acquisition and distribution beyond conventional boundaries, highlighting solutions for managing high-volume data streams, all the while maintaining system accessibility, reliability, and integrity.

Keywords: seismic networks, real-time data acquisition, data distribution, network scaling, data center infrastructure, raspberry shake

ISC: Supplementary Services for Seismology

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The primary mission of the International Seismological Centre (ISC) is to produce the most long-term and complete catalog of instrumentally recorded seismicity on a global scale by running a parametric event data exchange with ~150 seismic networks in ~100 countries. In addition, the ISC provides several supplementary datasets and services useful in many areas of geophysical research.

The *International Registry of Seismograph Stations* provides positions and reporting statistics of seismic stations that have shared parametric measurements with the ISC and its predecessors since 1904. The *Electronic Archive of Printed Station/Network Bulletins* holds the most comprehensive of all available global collections of observatory catalogues, including station parameters, produced up until the year 1998. The invited *Network Articles* in the Summary of the ISC Bulletin describe the history, current status, and procedures used by these networks to determine the location of seismic events, magnitudes, source parameters, event types, etc. So far, the articles from 18 networks regularly reporting to the ISC are linked to both the relevant agencies in the ISC Agency Registry and relevant hypocentre solutions in the ISC Bulletin. The *ISC Event Bibliography* provides references to scientific publications that describe seismic events (1904-2025) within the region of interest. The *ISC Seismological Dataset Repository* makes individual researcher's datasets openly available long term and thus also helps to provide access to data used in scientific publications. The *International Seismological Contacts* let seismologists find colleagues in other countries and thus facilitate joint research and capacity building worldwide.

Station Statistics Derived from the ISC Bulletin

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The International Seismological Centre (ISC) receives parametric data such as picked arrival times and amplitude measurement from seismic stations distributed across the globe, including some stations that are reported independently by multiple earthquake monitoring agencies. Approximately 20 million phases are reported to the ISC every year, providing an ideal dataset to evaluate the performance of seismic stations over time. One measure of station performance is the travel time residual of phases reported at the station for all reviewed events in the ISC Bulletin. Variations in the travel time residual at a station can be shown with respect to epicentral distance, and azimuth or over the operational time span of a station. A second metric of station performance is the variations in S-P relative arrival time, which can be used to identify anomalous events with tectonic features such as subduction zones also clearly apparent. third potential measure of station reliability is the reported amplitudes, which can be also used to identify variations or discrepancies associated with individual stations or reporters. This is done by comparing the individual station magnitude with the event magnitude in the Reviewed ISC Bulletin. The fourth and final station quality metric we consider is reported first motion polarities. Several agencies provide first motion polarity readings to the ISC, but this data can be challenging to use due to processing errors, reversed stations and other sources of noise. We compare these reported polarities against reliable reported moment tensors where available, in or order to assess the reliability of polarity measures at a given station, from a given reporter. In this presentation we provide examples of stations showing variations in travel time residual, S-P arrival times, reported amplitudes and first motion polarities, and discuss how this information can be used to identify systematic reporting problems for specific stations or reporters. The station metrics described here are available to view via the ISC website(https://www.isc.ac.uk/stations).

Geophysical and Sea-level Monitoring in Puerto Rico: Recent Developments, Challenges and Lessons Learned

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The Puerto Rico Seismic Network (PRSN) and the Puerto Rico Strong Motion Program (PRSMP) make up the PR network which is the regional authority for monitoring ground shaking in Puerto Rico and the Virgin Islands. The mission of the PR is to monitor and rapidly determine the parameters of all earthquakes, support the TSP (Tsunami Service Provider) and help the local and federal monitoring and emergency authorities to disseminate alerts in the Area of Responsibility to concerned agencies and stakeholders. The PR compiles the microseismic catalogue, continuous waveforms, and earthquake effects which serve as a foundation for basic and applied earth science & oceanography research in Puerto Rico and the Caribbean. The PR net also promote the education and preparedness of our population to mitigate the effects of a significant earthquake or tsunami, working together with local, commonwealth and federal partners.

The circum-Caribbean region has a documented history of large damaging earthquakes and tsunamis that have affected coastal areas, including the events of 1692 (Jamaica), 1867 (Virgin Islands), 1918 & 2020 (Puerto Rico), 1946 & 2010 (Hispanola). There is clear evidence that tsunamis have been triggered by large earthquakes that deformed the ocean floor around the Caribbean Plate (CP) boundary. Seismic events originating in the prominent NE Caribbean fault system are considered to be a near-field hazard for Hispaniola, Puerto Rico and the Virgin Islands because tsunamis generated by these events can reach coastal areas within a few minutes after the earthquake. Sources for regional and teleseismic tsunami-earthquakes have also been identified in the Caribbean and Atlantic Basins.

The goal of this presentation is to describe the PR system, including the real time earthquake and tsunami monitoring as well as the specific protocols used for location/analysis and to broadcast earthquake/tsunami messages locally.

In the Pursuit of 99% Data Return - Case Study of the Italian National Accelerometric Network

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99% of data return over an entire year - no timing issues - no micro gaps. These performance indicators tell the story of sound engineering, outstanding dataloggers, enterprise-class software, and rigorous maintenance. Data return is the primary benchmark of the success of any real-time monitoring network. Without data, operators, data users, and, ultimately, information consumers gain no value from the investment in the system. Moreover, monitoring systems related to the observational sciences, like seismology, rely even more so on high data returns because an earthquake cannot be repeated. If the system has data gaps, generates error-laced returns, or experiences downtime, critical information for real-time and future post-processing can be missed.

The mission-critical Italian National Accelerometric Network, RAN (*Rete Accelerometrica Nazionale*), informs the Italian Civil Protection Department, DPC (*Dipartimento della Protezione Civile*) about destructive and felt earthquakes. It consists of more than 700 stations, of which about 440 are closely monitored. Real-time data availability in 2024 was over 98.5%, with station availability beyond 99.5% since 2017. Typically, the network locates about 1800 events per year. Earthquakes with an M4 or larger magnitude trigger a temporary 10-station array deployment around the epicenter. These stations telemeter acceleration measurements in real-time to the data center, and the data streams are immediately included in the automatic processing flow, providing valuable information on the aftershock sequence. DPC shares the data with other government agencies and academic institutions in real-time and on request. The automatic processing results include, in between others, PGA, PGV, PGD, PSAs, Housner and Arias intensity, and response spectra.

Advancing Operational Earthquake Monitoring at Local and Regional Scales With Machine Learning-enhanced SeisComP Tools - as Demonstrated in Switzerland

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Machine learning (ML) has seen widespread use in seismology recently, with a significant focus on earthquake monitoring. ML models are now available for phase picking, first motion polarity determination, etc. Implementing them in standard monitoring software (e.g. SeisComP) could significantly improve the automatic earthquake monitoring and save time for human analysts, whilst leveraging all the existing benefits of existing mature monitoring frameworks. An important first step for moving the ML models from research into production has been the Python package SeisBench (Woollam et al., 2022; DOI: 10.1785/0220210324), which allows users to benchmark and access ML models and datasets. The scdlpicker SeisComP module (Tillman et al., 2023; DOI: 10.5194/egusphere-egu23-10046) created an interface between SeisComP and the trained ML pickers in SeisBench to allow event-based re-picking (i.e., not real-time phase onset detection) as demonstrated using teleseismic earthquakes and the GEOFON network. Here, we build on top of the existing scdlpicker module to provide both P and S picks at local distances, and add pick uncertainty and P-pick first motion polarity. We demonstrate the performance of this extended module in routine earthquake monitoring at the Swiss Seismological Service (SED) and show the improvements over classical pickers currently in use. We show that the ML pickers improve the automatic monitoring in both the number and the quality of the picks, leading to better automatic locations and magnitudes. We show that the ML picker's characteristic function provides a good proxy of the human analyst assigned pick uncertainty. Additionally, this extended SeisComP module provides the ML-determined first-motion polarity for each pick, fully characterizing the pick itself (pick time, pick uncertainty, first motion polarity) in the same way a manual analyst would do. This allows the adoption of streamlined workflows in which the automatic (i.e. ML) picks would only be reviewed (and in most cases accepted) rather than re-picked from scratch by the human analyst (as currently done at SED).

Using Machine Learning for Near Real-time Monitoring in Utah and Yellowstone

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Machine-learning (ML) has rapidly changed the field of seismology by creating statistical models that can mimic analyst-quality decisions in label-rich scenarios such as signal detection, arrival time picking, and first-motion picking. In particular, ML methods seem to provide substantial value when characterizing periods of enhanced seismicity. To exploit this potential advantage over traditional methods, University of Utah Seismograph Stations has been actively incorporating these ML capabilities into a near real-time monitoring seismic system; Utah Real-Time Seismology (URTS). Since November of 2024, URTS has been monitoring seismicity in both of the UUSS's authoritative Utah and Yellowstone National Park regions. In this presentation, we will provide a summary of the URTS implementation i.e., the detection, pick refinement, association, and location capabilities.Then, we will compare URTS to our production Advanced National Seismic System Quake Monitoring System (AQMS). Preliminary results from this activity indicate two main conclusions. (1) In Utah, there appears to be no clear benefit of URTS to our AQMS system. (2) In Yellowstone, URTS vastly outperforms our AQMS system in terms of detection and location of small, swarm-like earthquake activity.

An Explainable Phase-picking Model That Imitates Human Workflow

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Deep learning is becoming a standard approach for automating the task of picking seismic phase arrival times. Several studies have applied pre-trained models to build event catalogs, and a growing number of seismic network operators are adopting the technology in their monitoring workflows; however, the published deep learning models are often not explainable (and thus not always reliable), which can limit their applicability to mission critical applications where the tolerance to false positive and false negative detections may be low. One of the main factors that limits the explainability of these models is the design itself – the 'segmentation' approach that relies on an arbitrary kernel. We demonstrate how the segmentation approach limits model explainability and introduce a multi-step automated phase-picking process that better imitates a human analyst. Instead of relying on a single model for the task, we separate the problem into initial screening (a conventional trigger), arrival detection (analogous to an analyst checking the presence of an arrival from a zoomed-out seismogram), and arrival picking (analogous to an analyst making the pick from a zoomed-in seismogram). The arrival detection and picking rely on two separate neural networks. The detector network is calibrated to output a probability that scales with accuracy, and the picker network is designed to output a probability mass function. We test the effect of feeding seismograms filtered at different frequency bands that analysts commonly choose from. We show how this approach can make the results more explainable, the models more maintainable, and the process more intervenable by analysts.

Towards Consistent Event Classification at Mount Baker Volcano, Washington, USA

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Mount Baker has a very high volcanic threat potential, motivating continuous seismic monitoring since the 1970s by the Pacific Northwest Seismic Network (PNSN) in collaboration with the USGS Cascades Volcano Observatory. Mount Baker has produced few volcano-tectonic earthquakes during its instrumented history, but has produced a notable amount of deep, low-frequency seismic events (deep LFs). Deep LFs are attributed to trans-crustal fluid migration and may provide key insights on magmatic activity at Mount Baker. The glaciers cladding Mount Baker also produce low-frequency seismic events (shallow LFs). The similar characteristics of both LF source types, combined with sparse station coverage around Mount Baker, make consistent and accurate event detection, location, and classification difficult. Minor improvements to station coverage by the PNSN motivated new attention to characterizing LFs in this region in the past few years, providing an opportunity to reassess past event classifications with new insights. To do this, we cross-correlated 622 events within 30 km of Mount Baker cataloged between 2001 and 2024. Shallow LFs, tectonic earthquake clusters, and well-constrained deep LFs grouped at low correlation thresholds, even at modest station offsets. These groups contain a subset of likely misclassified events and provide a basis for matched filter processing that may improve event detection and classification consistency at Mount Baker. Weakly-constrained LFs predominantly correlated with the shallow LF group despite having depth estimates indicative of deep LFs, particularly in the past two years. This underscores the ongoing need for improved station coverage around Mount Baker to produce accurate event locations.

Implementation of AI/ML Detection of Seismicity as a Real-time SeisComP Module

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Rapid and precise detection of seismic phases is a priority for seismic monitoring networks. While various methodologies exist, recent advancements in machine learning (ML) techniques have demonstrated exceptional performance in automatically identifying seismic events. However, the real-time application of these methods remains challenging due to their high computational demands and limited integration with real-time processing workflows. Since 2023, the Texas Seismological Network (TexNet) has used the EarthQuake Compact Convolutional Transformer (EQCCT), a deep-learning ML model, to detect seismic phases automatically. This approach, matched with scanloc (gempa.de), has increased the detection of low-magnitude earthquakes by a factor of 50 compared to the traditional STA/LTA method. However, this implementation operates in a post-event mode, introducing delays of 10–45 minutes relative to the phase onset time.

To address this limitation, we developed a new SeisComP module, sceqcct, integrating EQCCT into TexNet's real-time data workflow. The development focused on three objectives: (1) optimizing the computational efficiency of EQCCT, (2) integrating EQCCT within SeisComP's framework, and (3) tuning critical parameters (e.g., bandpass filter) to enhance real-time performance. The sceqcct module processes real-time seismic data, achieving pick detections with delays less than one minute after phase onset time. It also supports playback mode for analyzing archived waveforms. We evaluated the sceqcct's performance by comparing its real-time results with TexNet's post-event EQCCT implementation. The new module achieved a high correspondence in pick and, eventually, event detection, with a near-perfect agreement for events of magnitude ≥1.2. After tuning parameters with region-specific settings, additional arrivals were detected, further enhancing performance.

Overall, these advancements represent a significant step forward in real-time seismic monitoring, enabling rapid and reliable automatic event detection with minimal delays (P and S arrival detection within 1–2 minutes) using an AI/ML-based methodology.

MAXI3D: A Novel Offshore Earthquake Location Workflow for the Endeavour Segment of the Juan De Fuca Ridge

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Ocean Networks Canada maintains the NEPTUNE offshore cabled network, which extends to the Endeavour segment of the Juan de Fuca ridge west of Vancouver Island. Endeavour is a highly active spreading centre, with hundreds of earthquakes occurring daily. This is the perfect laboratory to test earthquake detection, association, and location techniques. For seismic phase detection, recent deep neural-network methods, such as PhaseNet (Zhu and Beroza, 2019) and EQTransformer (Mousavi et al., 2020), show a vast improvement over traditionally proven methods, like STA/LTA detectors. Associating phases and locating events presents a more difficult problem due, in part, to the complexity of seismic velocities. Current deep-learning methods, such as GENIE (McBrearty and Beroza, 2022) and SUGAR (Tan et al., 2024), require regionally specific trained models and advanced computing resources. They also do not currently take advantage of robust 3-dimensional velocity models. We propose an alternative approach to these methods with an updated implementation of the maximum intersection method (MAXI; Font et al. 2004), dubbed MAXI3D. This implementation can both associate and locate seismic phases using 3-dimensional travel-time grids derived from local and regional seismic velocities and can provide robust hypocentre uncertainties without the need for machine learning techniques.

We present the early results at Endeavour for a unified approach combining the OBSTransformer detector (Niksejel and Zhang, 2024) with MAXI3D, and compare these results to the currently implemented automated location method (Krauss et al., 2023), as well as deep-learning associators and NonLinLoc (Lomax et al., 2000). Our workflow is designed to be easy to use and adaptive to regional seismic networks and heterogeneous velocity models.

A Virtual Experiment to Quantify Gains in Explosion Monitoring Techniques

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We describe a comprehensive, virtual experiment that was designed and executed by the United States National Laboratories to quantify the cumulative impact of scientific and engineering advances on core, explosion monitoring methods and algorithms. This experiment exploited waveform (seismic, infrasound, and electromagnetic) and synthetic radionuclide signatures sourced by real and simulated events within and near the Nevada National Security Site over multiple time periods, which were recorded by multi-modal sensors. This experiment processed these data with an event processing pipeline that is notionally representative of monitoring operations in two stages: an initial stage to establish a baseline monitoring performance, and a second stage to measure gains or losses in monitoring performance through execution of new methods and algorithms, relative to that baseline. Other phases of the experiment tested the ability of the monitoring community to containerize disparate algorithms that populate this pipeline and thereby establish the remaining challenges of orchestrating a virtual explosion monitoring architecture. This delivery describes key phases of this experiment during its execution phases from October 2022 through February of 2024.

Local Magnitude Practices in the United States of America

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Twelve U.S. Advanced National Seismic System (ANSS) participant organizations produce the authoritative parameters such as magnitude, latitude, longitude, and depth for earthquakes in the U.S.A. Due to regional and historical differences, these various contributors have practices that differ in how the parameters are determined. The ANSS has initiated an endeavor to document these practices in a central location, starting with the local magnitude. The local magnitude is based on the original Richter magnitude from Southern California, which used the peak amplitudes measured from Wood-Anderson seismic instruments, a distance correction, and where needed, a station correction. It defined that a magnitude 3 earthquake recorded at 100 km distance would have an amplitude of 1 mm on a Wood-Anderson instrument. Nowadays, data from digital instruments are instrument-corrected and convolved with a Wood-Anderson response to mimic the old practice. For much of the U.S., the local magnitude is the preferred magnitude for small to moderate-sized earthquakes (M<6). However, because the local magnitude saturates near magnitude 7, the National Earthquake Information Center's moment magnitude derived from the W-phase is preferred for earthquakes of magnitude 6 and greater.

We document and report how each ANSS catalog contributor performs the instrument response corrections, how they measure the peak amplitude, which distance correction they use, whether they use station corrections, and, finally, how they aggregate the station magnitude contributions to determine the final magnitude and uncertainty estimate. We discuss to what extent the different approaches may affect the consistency of local magnitudes across the nation.

Revamping the Oklahoma Geological Survey Statewide Seismic Network for the Next Generation of Earthquake Monitoring

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The Oklahoma Geological Survey (OGS) monitors seismicity in Oklahoma by utilizing permanent and temporary seismometers installed by OGS and other agencies to generate a real-time earthquake catalog. The OGS seismic network, functioning as a self-sustaining regional component of the Advanced National Seismic System (ANSS), provides earthquake information to the ANSS Comprehensive Earthquake Catalog, that is essential for the Oklahoma Corporation Commission to enforce their "traffic-light" mitigation strategy and other remedial measures. The occurrence of induced earthquakes in the state expedited the network's expansion from 10 permanent stations in 2010, to 34 permanent and 67 temporary stations as of January 2025. The spatiotemporal distribution of the seismic stations has largely been influenced by the advancement of seismic activity across the state. The network's development throughout time has resulted in the installation of a variety of instruments of varying quality, with most of the data transmitted via REFTEK Protocol.

We present a revamp of the OGS seismic network for the next generation of earthquake monitoring through a state legislative appropriation. We will be upgrading the seismic equipment at each of the OK and O2 network stations with new broadband sensors and convert the current temporary O2 network to the permanent OK network. We are expanding the network to 175 permanent stations with emphasis on reducing the close station epicentral distance, especially around faults that have proved to be prone to reactivation based on the last decade of earthquake history. Half of the permanent network will consist of additional accelerometers pertinent to seismic hazard studies across the state. In addition, we will purchase 50 short-period sensors for portable deployments. All the stations will stream real-time data via SeedLink protocol thereby improving data latency. We plan to incorporate infrasound sensors co-located with some of the equipment. We will discuss these plans and other upgrades required in back-end infrastructure and management that need to be made to handle the additional sensor data.

Network Design for Seismic Activity Monitoring in an Unconventional Oil Reservoir Exploitation Context

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Historically, the seismicity in Argentina is mainly concentrated in the central, western and north-western regions of the country. Important destructive earthquake with maximum intensity IX (Mercalli Modify scale) have seriously affected major cities, including San Juan, Mendoza and Salta. This concentration of seismic hazard in Argentina is also reflected in the distribution of seismic stations with more than 60% of stations located in the center, west and northwest of Argentina. Consequently, the entire south and east of the country have almost no-coverage for detecting and locating local seismicity, where the official catalogue is considered complete for magnitudes $M_L \geq 3.5$.

Since 2015, many infrequent earthquakes were reported in the Neuquén province in the south-west of Argentina. Local authorities of the province requested the National Institute of Seismic Prevention (INPRES, Argentina) to design a seismic network to better monitor felt events and to explore a possible relation with hydraulic fracturing. The latter is a method employed to produce oil and gas from unconventional shale reservoirs. To establish the seismic network, we used published criteria and applied a Network Quality Metric parameter (ΔU) defined by Bondár and McLaughlin for each point of the region of interest. We will report results from the seismic network design and the deployment of 26 permanent broad-band seismometers. The new network ensures precise seismic locations in a region of more than 15.000 km^2. The seismic network sensitivity allows to detect and locate earthquakes automatically with magnitude $M_L \geq 1.5$. Real lateral location errors are less than 5 km in the region of interest. Relocation and manual seismic data reprocessing allows to reduce these errors down to 1 to 3 km.

Network Seismology: Recent Developments, Challenges and Lessons Learned [Poster]

Poster Session • Tuesday 15 April

Conveners: Blaine M. Bockholt, Idaho National Laboratory (Blaine.bockholt@inl.gov); J. Renate Hartog, University of Washington (jrhartog@uw.edu); Kristine L. Pankow, University of Utah (pankowseis2@gmail.com); Dmitry Storchak, International Seismological Centre (dmitry@isc.ac.uk); William Yeck, U.S. Geological Survey (wyeck@usgs.gov)

POSTER 17

The Minimus Digitizer Platform: A User-friendly Ecosystem for Efficient Network Management and Seismic Station Configuration

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The Güralp Minimus broadband digitizer introduced innovative features to the market including easy network configuration; compact form factor; extensive State of Health (SOH) monitoring; and low latency digitization. Since it was launched in 2016, technological advances in semiconductors have significantly decreased their power requirements. The latest iteration of Minimus, Minimus Lite, utilizes modern microprocessors to reduce power consumption by over 50% whilst maintaining high levels of functionality. The resulting reduction in power consumption facilitates simplified field deployments for offline deployments.

The Minimus platform also provides a high level of functionality for online stations, including the industry-unique option of transmitting State of Health (SOH) data via the SEEDlink protocol. As well as simplifying SOH monitoring for larger networks, this facility also allows for time-series analysis of SOH data. This means that operators have the data they need to proactively manage their station network and diagnose issues before they result in data loss. The Minimus platform interfaces with Discovery software which seamlessly integrates new stations into existing networks. The use of Discovery also provides users with access to Guralp's data archival and station SOH monitoring services. These novel approaches to data management allow users to focus on data analysis by using a series of 1-click tools to automate data archival and station SOH monitoring procedures.

The Minimus platform was built from the ground up to provide one of the lowest latency digitizers available with digitization latencies down to 40ms, making it well suited to Earthquake Early Warning applications. This is achieved with the use of causal decimation filters, high sample rates, and Guralp's proprietary GDI protocol. The Minimus platform is built as a modular digitizer platform that is available within many different packages to suit a range of applications, including as a stand-alone digitizer or built within broadband seismic instruments and force balance accelerometer systems.

POSTER 18

Improvements in Seismic Station Noise Levels Through Budget Boreholes

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It has been known for decades that the noise performance of seismic stations at both high (1 Hz) and low (<0.05 Hz) frequencies can be improved through installing the seismometer within deep (>30 m) boreholes. However, the cost of these installations has historically been prohibitive for their widespread use in regional and national seismic networks. Consequently, most of the Advanced National Seismic System (ANSS) and aftershock stations operated by the Albuquerque Seismological Laboratory (ASL) utilize seismometers placed in shallow (<3 m) vaults. The development of direct bury, posthole seismometers has enabled a handful of these vault stations to be converted at low cost to posthole (<5 m) and shallow (< 10 m) boreholes in the past few years using a gas-powered, hydraulic auger. We examine the change in noise performance at these stations that were converted from vaults to posthole installations, including changes in sensitivity to atmospheric pressure variations. We suggest that the USArray Transportable Array vaults were often emplaced on top of sediment, which exacerbates low-frequency noise generated by pressure changes.

We additionally investigate how the emplacement material around the seismometer in a posthole or borehole installation impacts noise performance. Using best practices from the borehole strainmeter community, we successfully grouted in a seismometer at 10 m depth within fractured granite at ASL in the summer of 2023. By using a Nanometrics T120 Slim and forgoing borehole casing, we were able to contract a commercial water well driller to complete the station within a timeframe and budget comparable to a traditional vault installation. We present analysis from 1.5 years of this grouted-in data and discuss the potential benefits and drawbacks for incorporating this installation method into ANSS networks.

POSTER 20

Orfeus-coordinated Seismological Datasets in the Euro-mediterranean Region and Beyond

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ORFEUS (Observatories and Research Facilities for European Seismology, www.orfeus-eu.org) is a non-profit organization that harmonizes the collection, archival, and distribution of seismic waveform (meta)data, services and products based on international standards, and serves a broad community of seismological data users, on behalf of the Euro-Mediterranean seismic networks and monitoring agencies (orfeus.readthedocs.io/en/latest/governance.html). ORFEUS core domains comprise: (i) the European Integrated waveform Data Archive (EIDA; orfeus-eu.org/data/eida), providing access to raw seismic waveform data and basic station metadata; (ii) the European Strong-Motion databases (orfeus-eu.org/data/strong), offering automatically/manually processed waveforms, advanced station/site metadata, and associated products ; and iii) the European Mobile Instrument Pools (orfeus-eu.org/data/mobile), facilitating utilization of seismic instrumentation for temporary deployments. Currently, ORFEUS services distribute waveform data from more than 24,000 stations, including dense temporary experiments, emphasizing FAIR principles, open access, and high quality of datasets. ORFEUS services form a critical component of EPOS (www.epos-eu.org/tcs/seismology) and are seamlessly integrated into the EPOS Data Access Portal (www.ics-c.epos-eu.org). Access to data and products relies on state-of-the-art information and communication technologies, with a strong emphasis on web services for programmatic interaction. ORFEUS promotes the usage of transparent data policies and licenses and acknowledges the indispensable contribution of data providers. ORFEUS aims to enhance the existing services and facilitate access to massive & multidisciplinary datasets through collaborative efforts with global and regional initiatives, such as the FDSN and EarthScope, as well as support from EC-funded projects (e.g., www.geo-inquire.eu). ORFEUS also implements Community services that include software and travel grants, a vigorous training/outreach programme of webinars and workshops (www.orfeus-eu.org/other/workshops), and editorial initiatives.

POSTER 21

Upgrading the Liubeshka Station of the Ukrainian National Seismic Network: Modernization and Integration

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Understanding the geological and tectonic conditions of the territory of Ukraine in sufficient detail requires improvements of the regional earthquake monitoring capabilities through upgraded and new stations. Western, southwestern, and southern Ukraine lie within a seismically active belt formed by the Eurasian-African plate collision. This belt spans from the Azores through the Mediterranean, Black Sea, Caucasus, and Hindu Kush, including the Carpathian Arc with Vrancea subcrustal quakes and the Crimean-Black Sea region. In Ukraine's Carpathian region, the infrastructure for the Liubeshka (LUBU) station of the Ukrainian National Seismic Network (network code UT) has been upgraded and modernized as part of a network-wide improvement project.

The LUBU station, previously equipped with SM3 Soviet-era sensors, required significant enhancements. Key preparatory stages for installing new equipment at this site included: analysis of available satellite imagery to assess distances to potential noise sources, as well as a study of geological and tectonic conditions; site reconnaissance, including noise surveys and PPSD analysis; seismic profiling using a hammer source, which revealed details about the upper geological structure; drilling and construction of the necessary infrastructure. In December 2024, a new Trillium Slim posthole seismometer was installed. The configuration of data collection systems and transmission to the main server has been completed, along with integration into the EarthScope network for data exchange.

The modernization and expansion of Ukraine's national seismic network is currently underway, with a focus on deploying permanent posthole broadband seismic stations for uniform coverage. This progress is supported by the US Department of Energy's Seismic Cooperation Program and facilitated by the Science Technology Center of Ukraine. This partnership includes the Subbotin Institute of Geophysics of the National Academy of Sciences of Ukraine, Lawrence Livermore National Laboratory (USA), Michigan State University (USA), and EarthScope Consortium (USA).

POSTER 22

Implementing a Regional 1-D Velocity Model for Locating Earthquakes for Southern Texas

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Since 2018, the Texas Seismological Network (TexNet) has installed a densely distributed seismic network to monitor seismicity in southern Texas, covering the Eagle Shale play. Prior to the TexNet, a seismogenic zone has been identified using data from the Transportable Array (2009-2011). During that time, an Mw 4.8 event occurred on October 20th, 2011. In addition to the sufficient station coverage, an important factor to best constrain the earthquake hypocentral locations is to use a proper velocity model that can best reflect the regional tectonic setting and lithospheric structure. Currently the TexNet is using 1D global velocity model (i.e., IASP91) to locate earthquakes for southern Texas. While it can effectively constrain the epicentral locations, it however cannot well define the focal depth due to its overly simplified velocity content; which does not reflect the regional geology of the Eagle Ford Shale play.

To address this issue, the TexNet has decided to adapt a velocity profile obtained from a previous active-seismic experiment that used controlled sources. This experiment used two shot points as the seismic sources and sixty-one geophones to record the seismic signals. The recording array was in parallel with the trend of the Eagle Ford play roughly in NE-SW, and stretched nearly 260 km. The velocity profile sets the Moho discontinuity at 33 km depth, and mainly consists of 4 velocity layers within the crust. It places the depth of the basin-basement interface, a crucial depth constraint, at around 7 km depth. Because this active-seismic profile does not include S-wave velocity, we further used the Wadati diagram to determine the collective crustal Vp/Vs ratio for inferring Vs from Vp. We compiled a 1-D regional velocity model based on the obtained Vp and Vs. After revisiting the published catalogs, our preliminary test results have shown a much clustered seismicity running in an overall northeast-southwest direction; which comprises several secondary earthquake clusters. Going forward, we are going to do more tests to verify the robustness of this 1-D model.

POSTER 23

AdriaArray – a Passive Seismic Experiment to Study Structure, Geodynamics and Geohazards of the Adriatic Plate

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The densely populated area around the Adriatic Sea in Europe is prone to geohazards including earthquakes, tsunamis, landslides, flooding and volcanic activity as the Adriatic Plate is consumed in a tectonically active belt spanning from Sicily, over the Apennines to the Alps, Dinarides and Hellenides, generating earthquakes up to magnitude 7. To identify drivers of associated plate deformation, the plate boundaries, slabs, properties of active faults and of the stress field have to be determined. AdriaArray, a dense plate-scale regional seismic network, provides data for imaging of the crustal and upper mantle structure and for the analysis of seismic activity. The network consists of 1068 permanent and 440 temporary BB stations from 23 mobile pools. 97 % of the planned temporary stations have been installed. A homogeneous coverage by broadband stations in an area from the Massif Central in the west to the Carpathians in the east, from the Alps in the north to Sicily and the Kefalonia Fault Zone in the south, is achieved. The backbone network (2022 – 2025) is complemented by locally densified and largeN networks in the western Carpathians (Poland, Slovakia, Hungary), along the Dubrovnik fault (Croatia), in the Vrancea region (Romania), and in Albania. Data recorded by the temporary stations is transmitted in real-time and archived at 9 nodes of the European Integrated Data Archive (EIDA). Regular availability and quality checks ensure high data usability. AdriaArray, the largest passive seismic experiment in Europe so far, is based on cooperation between local network operators, mobile pool providers, field teams, ORFEUS (Observatories and Research Facilities for European Seismology) and EPOS (European Plate Observing System), encompassing 64 institutions from 30 countries. They form the AdriaArray Seismology Group, founded in 2022. Collaborative Research Groups are established to coordinate the data analysis. We present the maps of the AdriaArray Seismic Network, station properties, coverage, contributing institutions and collaborative research topics.

POSTER 24

Next Generation Multidisciplinary Geophysical Monitoring Station

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Increasingly, scientific advancement is enabled via the joint analysis and interpretation of multidisciplinary datasets which combine different data types from various co-located, independent geophysical sensing elements. Historically, sensors from different disciplines, and their supporting subsystems, have evolved independently. This often led to duplication of infrastructure and integration challenges associated with separate acquisition systems, with different characteristics and capabilities, attempting to share bandwidth-constrained communications links between remote stations and data centers. These factors can significantly increase monitoring station complexity and the associated cost to deploy, operate and maintain them. Recent initiatives, such as the European Plate Observing System (EPOS), the amalgamation of the SAGE and GAGE programs in the United States and the SZ4D implementation plan, aim to combine multidisciplinary geophysical applications into cohesive, streamlined deployments.

Modern seismic dataloggers, such as the Nanometrics Centaur, support integration of a wide range of sensing elements using various interfaces, while maintaining ultra-low power consumption, precise timing, local data storage and reliable real-time data transmission via a full-featured protocol, which can be optimized for different telemetry path constraints. Robust automatic outage recovery ensures maximum data availability at the data center, for all data types, as part of a single, unified acquisition system.

A case study is presented for a multidisciplinary monitoring station that leverages these capabilities to enable reliable and efficient data acquisition. The station design and end-to-end data pipeline, from remote sensing to science doorstep in the data center, are discussed.

POSTER 25

Station Operators Perspective as Input on the Development of the International Monitoring System Sustainment Strategy

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As part of its verification regime, the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) operates the International Monitoring System (IMS), a network of four technologies (seismic, radionuclide, hydroacoustic and infrasound). The completed network will consist of 337 facilities around the world. A questionnaire was distributed to all station operators. The questionnaire included 40 questions grouped in seven categories: 1) station information and characteristics; 2) lifecycle; 3) infrastructure; 4) environment; 5) climate change; 6) vandalism; and 7) station operator. Its aim was to obtain complementary information that could contribute towards the development of the IMS sustainment strategy. Responses were received from 197 out of the 301 currently installed stations, 91 of them from seismic stations. The results show that most of the systems have been in operation for more than 16 years; the main reasons for major changes in the systems are deterioration owing to changes in the station environment and end of life replacement. About 60% of stations might require some level of work on their infrastructure, mainly related to the power system or housing. The Station Operators identified that the main risk the stations face is related to the environment. Some have been impacted by an increased frequency of extreme weather events, pointing out to further upgrade the station infrastructure to mitigate against climate change. Further details, results and lessons learned will be part of this presentation.

POSTER 26

The Utility of Small Aperture Arrays for Assessing Subduction Zone Earthquakes: Insights From Temporary Nodal Deployments

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Out of network earthquakes–whether originating from an offshore tectonic source or across geopolitical boundaries–are more difficult to constrain than in-network, crustal earthquakes. This is due to a combination of factors but is largely due to a greater distance from the earthquake source to the nearest set of seismic stations. An ability to quickly constrain epicentral location and depth is especially important for Earthquake Early Warning (EEW) applications, as most current regional EEW algorithms rely on earthquake source characteristics for predicting ground motion and issuing accurate warnings. Small aperture seismic arrays offer a potential solution for quick and accurate determination of subduction-zone earthquakes through beamforming techniques and determination of a slowness vector. In addition, for remote areas that are difficult to access, utilizing multiple arrays for earthquake characterization may reduce maintenance costs without forfeiting data quality. Here, we investigate a trio of small aperture arrays deployed on Unalaska Island, Alaska, to assess the utility of arrays for fast and accurate earthquake determination. We use a dataset of earthquakes within 150 km of the arrays and occurred during the full-deployment of the three arrays. Comparing several commonly used array processing techniques (i.e. frequency-wavenumber, least-squares, and least-trimmed-squares), we find that there is no stand-alone technique that results in the most accurate earthquake location, yet different techniques offer improvements to precision. The most accurate array processing techniques and associated input parameters for a single array determined ~80% of the events within 10 degree error in backazimuth from the catalog earthquake location. The three arrays showed a consistent pattern in backazimuth error (array processing backazimuth minus catalog backazimuth) that could be easily corrected. Overall, small-aperture arrays show promising results for quickly and accurately constraining earthquake location in subduction zone settings and may prove to be a key aspect of developing an EEW system for Alaska.

POSTER 28

Evaluating the Performance of the Guralp Radian Posthole Seismometer Across Variable Tilt and Orientation Conditions

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The Guralp Radian Posthole seismometer is designed to operate at any angle, but how does tilt and orientation affect its performance? This study investigates its sensitivity to variations in tilt and azimuthal alignment through controlled laboratory experiments and field tests. Key questions include whether tilt or orientation impacts signal-to-noise ratios, horizontal component accuracy, or waveform fidelity, particularly for high-frequency signals. Preliminary findings suggest the Radian maintains functionality across all angles, but subtle effects may emerge in specific scenarios. These results aim to inform best practices for non-standard installations and enhance understanding of its performance in diverse environments.

POSTER 30

System Monitoring, Telemetry Quality Control and DAS Testing at SCSN

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The Caltech/USGS Southern California Seismic Network (SCSN) is a state-of-the-art digital ground motion seismic network. It develops and maintains data acquisition and delivery systems that support the rapid generation of earthquake information products, such as event origins, magnitudes, ShakeMap, and Earthquake Early Warning through ShakeAlert.

Tools have been developed to evaluate the system's state of health through regular measurements of data transport latency and telemetry link bandwidth between dataloggers and the data center. These tools enable performance analysis of connections to ensure they meet the requirements. Additionally, a quantitative framework has been introduced to evaluate station locations within the ShakeAlert mission. This approach calculates each station's expected contributions in terms of quake detection likelihood and the benefits to nearby populations, allowing for optimized station placement to enhance the mission's overall effectiveness.

To test the performance of seismic instruments and telemetry systems during simulated shaking, a bi-axial shake table is employed. By recreating past seismic events and analyzing system responses, we can design more robust sites and collaborate with field engineers on the installation improvements.

In addition, a lab-scale experiment was designed to investigate the DAS response and the influence of cable properties. This experiment utilizes a shake table to apply controlled deformations to a fiber cable, enabling accurate characterization of the instrument response. The setup also facilitates the examination of DAS phase unwrapping errors and the material behavior of cables under varying strain conditions.

SCSN has begun integrating DAS technology into its operations. A DAS instrument is currently deployed in the Ridgecrest, CA area, transforming a 100-km telecom cable into a 10,000-channel seismic array that is analyzed using PhaseNet-DAS. Selected waveforms and phase times from 18 DAS channels are incorporated into existing earthquake monitoring workflows, demonstrating the potential of DAS technology to enhance seismic monitoring capabilities.

POSTER 31

Challenges and Lessons Learned from Applying Machine Learning Models to Seismic Monitoring Across Diverse Tectonic Settings

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Machine learning (ML) is widely used for improving earthquake catalog production and, more recently, real-time seismic monitoring. However, implementing deep learning models in different tectonic settings poses unique challenges due to variations in seismicity rate and density, characteristics of seismic signals and noise, and network coverage. We highlight and address these challenges for two distinct regions: the Northeastern U.S. (NEUS), a stable continental region with sparse station coverage and low seismicity rate, and Axial Seamount, a submarine volcano with high event rates and complex ocean noise. In NEUS, the performance of pre-trained deep learning models such as PhaseNet is degraded due to regional-distance waveforms differing substantially from the local waveforms used in training. We therefore retrained PhaseNet using over two decades of regional analyst picks, and incorporated both time and frequency domain information to create PhaseNet-TF. Using the 2024 Mw4.8 Tewksbury, NJ earthquake sequence, we demonstrate significant improvements over the original PhaseNet model (F1-score increase from ~0.5 to ~0.9). At Axial Seamount, challenges arise from processing continuous OBS data with high event rates while efficiently distinguishing between earthquakes, various seismoacoustic signals (e.g., lava-water interaction, whales), and ocean noise. We designed and operate an ML-based real-time seismic monitoring workflow to detect, classify, and locate events with high precision (MLDD-RT). This framework tracks various source types, including eruption precursory events and impulsive events that track magma outflows. These studies show that, although deep learning models are intended to be generalizable, region-specific retraining is often necessary to adapt to specific tectonic environments with varying event and noise characteristics. We show the benefits of establishing best practices for model adaptation across diverse tectonic settings, as well as developing standardized datasets that better represent the full spectrum of seismic environments.

POSTER 32

The Southern California Seismic Network Earthquake Catalog: Completeness, Event Quality and Recent Improvements

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Since 1932, the Southern California Seismic Network (SCSN) has been maintaining a manually-reviewed earthquake catalog for Southern California as the regional earthquake authority. The catalog now contains over 900,000 events, with most recorded after the major expansion of the physical seismic network in the 1970s. Recorded events are primarily earthquakes but also include other events, such as quarry blasts and nuclear tests. In addition to an origin time, hypocenter, magnitude, and phase picks, quality parameters such as location errors are also tracked. In this study, we examine how the completeness and event quality of the SCSN catalog has changed over the network's history, focusing particularly on the past ~20 years. The largest change to nearly all parameters is during the 1970s network expansion, with more gradual improvements in the years since then. Network improvement and densification of key areas during the past 15-20 years have resulted in noticeable decreases in the mean depth error and azimuthal gap, a significant increase in the number of phase picks per event, and tighter distributions of the depth and horizontal errors and azimuthal gap. The current magnitude of completeness for the entire monitored region is around 1, although specific subregions or sequences may be higher or lower. Recent incorporation of machine learning algorithms into our event post-processing has also helped to produce more accurate automatic phase picks and origins before analyst review, and it may be applied to improve unreviewed events in the catalog backlog.

New Directions in Environmental, Seismic Hazard and Mineral Resource Exploration Studies

Oral Session • Thursday 17 April • 2:00 PM Local

Conveners: Claire Doody, Lawrence Livermore National Laboratory (doody1@llnl.gov); Md Mohimanul Islam, University of Missouri (mibhk@missouri.edu); Chiara Nardoni, University of Bologna (chiara.nardoni4@unibo.it); Shujuan Mao, University of Texas at Austin(smao@jsg.utexas.edu); Patricia Persaud, University of Arizona (ppersaud@arizona.edu); Valeria Villa, California Institute of Technology (vvilla@caltech.edu); Xin Wang, Chinese Academy of Sciences (wangxin@mail.iggcas.ac.cn)

Construction of 3D Finite Element Meshes from Drone Images: A Step Towards a Non-destructive Testing Framework for Engineering Structures and Their Response to Earthquakes

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We have developed a workflow to rapidly create 3D finite element meshes, which can then be used for viscoelastic wave propagation, starting with 2D photos acquired by an inexpensive consumer-level unmanned aerial system (i.e., a drone). Using open-source and low-cost industrial computer graphics and vision software, we then invert for a 3D surface composed of triangles. This 3D surface model is enclosed and then remeshed into hexahedra for use in spectral element wave solvers. Significant advances in hardware (digital cameras, GPS, drones, and GPUs) to more flexibly capture and process higher quality images coupled with improvements in key computer vision algorithms (namely, Structure-from-Motion and Multi-View Stereo) have made it practical to reconstruct 3D surface models from thousands of images – without the need to resort to expensive equipment, esoteric calibration methods, or priors (e.g., camera settings, motion, etc.). The time required to construct accurate 3D models is often significant and so the aim of this work is to minimize that overhead.

We have tested a first iteration of this workflow on the Via Contra (Verzasca) dam in Switzerland, whose results we will present. We will also discuss key stages, challenges, and learnings as we developed the processing pipeline. Next steps include further automating the workflow and integrating these meshes with sensor data to estimate the distribution of elastic parameters. Ideally, we would like to apply this methodology to historical structures in earthquake-prone regions to image and monitor their structural health.

Ambient Noise Tomography (ANT) as a Scalable Data Platform for Machine-learning Driven Mineral Discovery

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The transition from a carbon-driven economy to an economy driven by full electrification requires substantial additional inputs of critical minerals, in particular copper. However, currently forecast production is insufficient to meet projected demand. To meet this demand, we require a robust pipeline of future mining projects, beginning at the exploration phase. Future efforts in exploration furthermore require methodologies that can search for mineralization under substantial cover, as most accessible and economic near-surface deposits are thought to have been discovered. Ambient Noise Tomography (ANT) has, in the last few years, become increasingly utilized by the exploration geology community as a geophysical sensing methodology that is particularly useful for mineral exploration under cover due to its ability to illuminate the full mineral system at varying scales. This presentation outlines the integration of ANT into geophysical machine learning (ML) exploration tools, including local mineral prospectivity, hypothesis falsification of geological models and optimal experimental design.

Producing a State-wide Ground Deformation Map of Alaska With Satellite Remote Sensing

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Across Alaska, rapid environmental changes are occurring. Many of these are due to climate change, with Arctic temperatures rising four times faster than the global average. Varying distributions of permafrost, defined as ground that remains frozen for two years or more, cover large regions of the state and undergo seasonal freeze-thaw cycles, but increasing temperatures are causing the permafrost to degrade. Thawing permafrost leads to significant ground deformation and persistent subsidence, compromising ground stability and endangering critical infrastructure such as buildings, transportation networks, and pipelines. Beyond these local risks, permafrost degradation also presents a global challenge. As frozen soils melt, greenhouse gases such as carbon dioxide and methane can be emitted, intensifying global warming and perpetuating a concerning positive feedback loop.

While tracking this phenomenon and other causes of ground deformation is crucial, field measurements in Alaska, particularly in its Arctic areas, remain scarce. Using multitemporal interferometric synthetic aperture radar (InSAR) techniques, we process Sentinel-1 satellite data with wavelet-based InSAR (WabInSAR) software to generate a statewide ground deformation map. InSAR provides an efficient means of observing the entire state of Alaska regardless of cloud cover and solar illumination conditions. Our results reveal spatially varying trends of subsidence and uplift across the state. We also identify cyclical patterns in the deformation time series. The data we map offers a wide-scale overview of the state, providing possible insights into regions of rapid ground deformation across Alaska. Our study demonstrates the use of InSAR to map ground deformations from varying processes across a large and diverse region, with implications for infrastructure resilience, coastal hazards, permafrost thaw, and the complex interactions between climate change and geohazards.

Subsurface Geologic Controls on Seismic Site Response Across the Continental United States

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Earthquake ground motions are modified by local geologic site conditions, and the evaluation of site response is a crucial component of seismic hazard analyses. Horizontal-to-Vertical Spectral Ratio (HVSR) measurements provide inexpensive and noninvasive estimates of site resonant frequencies and amplifications. Here, we complete microtremor HVSR measurements at over 2,000 Transportable Array sites across the continental United States (US) and characterize the fundamental site resonance using an automated peak-identification procedure. In the central and eastern US (CEUS), we find smoothly varying fundamental site resonances that correspond to previously mapped subsurface geologic structures. Low-frequency fundamental site resonances (0.1–1 Hz) in this region are controlled by deep (>100 m) impedance contrasts, principally by the Great Unconformity separating overlying Phanerozoic sedimentary strata from Precambrian basement across the North American midcontinent as well as thick sedimentary deposits beneath the Atlantic and Gulf Coastal Plains. Higher-frequency site resonances (1–15 Hz) that vary smoothly across the CEUS are largely governed by shallower (<100 m) glacial sediments in the north-central and northeastern US. Given the presence of both shallow glacial sediments and the deeper Great Unconformity in this region, we investigate the prevailing controls on site resonance and amplification from layered subsurface structures. In the western US (WUS) and Alaska, where geologic features are shaped by complex tectonic histories, we find predominantly flat spectral responses and high variance in the fundamental site resonances among neighboring sites. Across the continental US, our results demonstrate the role of regional geology on seismic site response and hazard. We highlight the continued importance of detailed subsurface geologic models, dense seismic observations, and standardized site characterization techniques to improve existing seismic hazard estimates.

Probabilistic Seismic Hazard Assessment in Namibia

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Namibia is located in Southern Africa on a Stable Continental Region. Despite the fact that a number of earthquakes have been observed or recorded in Namibia since 1910, with July 31, 2009, and the April 4, 2021 earthquakes both of moment magnitude (Mw) of 5.6, no up-to-date country-wide seismic hazard study has been conducted. As a result, the purpose of this research is to conduct a comprehensive Probabilistic Seismic Hazard Assessment (PSHA) for the entire country to aid in planning and seismic risk mitigation. The earthquake catalogue developed for this study spans from 1910–2021 and includes both historical and instrumental events. Data from the International Seismological Centre, Advanced Network of Seismological System (ANSS), and Namibia's National Seismological Network (NSN) were used to create the catalogue. The catalogue was then declustered to remove fore- and aftershocks as well as similar events; the resulting catalogue was used in conjunction with available geological evidence to identify, delineate, and characterize 11 seismic source zones and one fault source, the Hebron/Dreylingen fault. Four Ground Motion Prediction Equations (GMPEs) were carefully selected and used in the seismic hazard computations. The GMPEs were implemented in the calculations using logic tree formalism with equal weights, which assisted in addressing the uncertainties associated with both the seismic sources and the ground motion models. Peak Ground Accelerations (PGA) obtained for a 10% chance of exceeding in 50 years ranged from 0.017 g to 0.149 g. The highest levels of hazard were observed in Namibia's north-western, north-central, central and southern regions. This study also produced seismic hazard maps that show the distribution of acceleration at different response periods (0s (PGA), 0.1s, 0.15s, 0.2. s, 0.3s, 0.5s and 1.0s) computed for a 10% probability of exceedance in 50 years. The findings from Namibia's first large-scale seismic hazard study are expected to make a significant contribution to future land use planning in facility and infrastructural development in the country.

Ten Days of Continuous Aftershock Hum Following the 2019 Ridgecrest, California, Mainshocks Observed With Borehole Seismometers

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Seismograms from two borehole seismometers near the 2019 Ridgecrest, California, aftershock sequence do not return to pre-mainshock noise levels until ten days after the M 7.1 Ridgecrest mainshock. The observed distribution of RMS amplitudes in these records can be explained with the Reasenberg and Jones (1989) aftershock occurrence model, which implies a continuous seismic "hum" of overlapping aftershocks of M > -2 occurring at an average rate of 10 events/second at the ten-day mark. This aftershock-generated hum prevents observing the background aseismic noise level at times between the body-wave arrivals from cataloged and other clearly observed events. Even after the borehole noise levels return at their quietest times to pre-mainshock conditions, the presence of overlapping low-magnitude earthquakes for at least 80 days is implied by waveform cross-correlation results provided using the Matrix Profile (MP) method. These results suggest a hidden frontier of tiny earthquakes that potentially can be measured and characterized even in the absence of detection and location of individual events.

Seismic Hazard from the Aftershocks of Subduction Interface Earthquakes

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Large Mw ≥ 8.0 subduction interplate earthquakes (also called megathrust earthquakes) typically trigger intense and prolonged aftershock sequences. While the main slip of the initial megathrust event typically occurs off-shore, the associated aftershocks are spatially more diverse and may occur closer to built environments. Given the potential proximity of aftershocks to communities, and the likelihood of them having magnitudes greater than Mw6.0, the aftershocks pose a significant societal threat. Recognizing the need to better understand the temporal and spatial distribution of damaging aftershocks following large subduction interface earthquakes, we compile and present an analysis of aftershock catalogues from 11 instrumentally recorded subduction interface earthquakes of Mw ≥ 8.0 from around the world. We compare aftershock activity rates to the baseline seismic activity rate before the mainshock for crustal, intraslab and interface aftershocks for each of these 11 subduction interface events. The annualized relative increase in seismic activity for all three types of earthquakes is at least two-fold. With respect to the largest aftershocks (Mw ≥ 6.5), we find that the vast majority of them occur within a zone proximal to the subduction trench and within the upper 50 km depth, regardless of whether they are crustal, intraslab or interplate aftershocks. With rare exceptions, the b-values for aftershock sequences are similar. This allows a comparison of the aftershock productivity of various subduction zones. We use this dataset to model activity rates and seismic hazard from subduction aftershock sequences spatially and temporally. Finally, based on these findings, we present (i) preliminary modelling of the activity rates of a future Cascadia subduction interface earthquake aftershock sequence, (ii) preliminary estimates of seismic hazard from a Cascadia aftershock sequence, and (iii) an initial analysis of spatial and temporal variation in aftershock hazard.

Does the Mississippi Embayment Edge Have Any Effect on Site Amplification?

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In this research, we focus on investigating the effects of the basin edge on site amplification in the Mississippi Embayment (ME) area considering the Horizontal-to-Vertical Spectral Ratio (HVSR) method. Recognizing the critical need to understand the subtle wave interactions and variations in ground motion amplification at the boundaries of sedimentary basins, this study focuses on the ME as a representative geological setting. By doing so, we aim to enhance our understanding of site-specific seismic hazards in this region. Our research initiative represents a pioneering effort in the exploration of basin-edge effects within the ME, contributing significantly to the expansion of knowledge in this field. Employing a comprehensive USGS dataset collected from a strategically positioned 280 km-long E-W array at 36°N spanning the ME, we conduct detailed analyses utilizing the HVSR method.

Findings reveal interesting insights into the distribution of site amplification within the ME. At lower frequencies around 0.3 Hz, amplification is higher in the central ME, indicating complex basin-induced effects. In contrast, at higher frequencies like 2.5 and 5 Hz, significant amplification is notably concentrated near the edges of the basin, where sediment thickness decreases. These contrasting patterns highlight the dynamic nature of site amplification phenomena in sedimentary basin boundries.

Analytical Approximations for Propagating Epistemic Uncertainty and Modeling Virtual Faults for Areal Sources in Seismic Hazard Analysis

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The computational requirements in Probabilistic Seismic Hazard Analysis (PSHA) have significantly increased with recent advances in ground-motion models (GMMs) and source characterization. The epistemic uncertainty is usually modeled using logic trees that discretize the distribution of the uncertain input parameter. The total number of end branches is the product of the number of branches on each node which grows rapidly as the complexity of the logic trees grows. Similarly, the aleatory variability for the source characterization for areal source zones can be modeled by filling the zone with virtual faults that sample a distribution of strikes, dips, and locations. The combination of the epistemic branches from the logic tree with a large number of virtual faults leads to long run times. To limit the run times, each node of the logic trees is often limited to just 3 branches, but this does not work well for non-ergodic GMMs. For virtual faults, the discrete samples of the strikes, dips, and locations is often crude to limit the number of cases in the hazard calculation. We propose an alternative approach to compute the hazard using analytical approximations for the distribution of the hazard or distribution of the input parameters for the GMMs (e.g., distance metrics) which can be combined with the full analytical distribution for a given node of the logic tree and the full distribution for the range of geometries for virtual faults. Rather than using exact hazard calcuations with crude sampling of the inputs, we use analytical approximations for the hazard calculation with the full distribution of the inputs. The calculation times can be reduced by one to two orders of magnitude with a small loss of accuracy. For the tails of the epistemic range of the hazard, the loss of accuracy from the analytical approximation is partly offset by using the full distributions rather than the crude discrete samples for each node of the logic trees and the aleatory range of the fault geometries for virtual faults. The analytical approaches make PSHA using non-ergodic GMMs practical on desktop computers.

Does Detailed Site Characterization and Ground Response Analysis Change Projected Building Damage Estimates?

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In regions such as the Central and Eastern United States (CEUS), the presence of soft soils and strong impedance contrasts can induce significant amplification of ground shaking, thereby exacerbating the effects of even low-magnitude earthquakes. Site conditions in the CEUS are not well captured by traditional VS30-based site categories. This study utilizes high-resolution subsurface data, including depth-to-bedrock maps and sediment velocity models that are available across the state of Massachusetts, in conjunction with a detailed building inventory, to assess the impact of soil conditions on the seismic vulnerability of buildings. By integrating these datasets with HAZUS-informed fragility functions, the study offers an in-depth evaluation of potential building damage across the state using design shaking levels provided by the U.S. Geological Survey National Seismic Hazard Model. Using a building inventory that includes a variety of building types and occupancy, this study identifies locations and building types within the state that are most at risk. The analysis is performed first using VS30-based soil amplification and then rerun using theoretical linear one-dimensional ground response analysis for each building location. These results are compared to highlight the limitations of VS30-based site characterization in a region like Massachusetts where amplification is driven by sediment thickness and strong impedance contrasts. These findings contribute to a deeper understanding of seismic vulnerability and resilience in regions of low- to moderate seismic hazard, emphasizing the necessity for region-specific approaches to enhancing building safety and community preparedness.

New Directions in Environmental, Seismic Hazard and Mineral Resource Exploration Studies [Poster]

Poster Session • Thursday 17 April

Conveners: Claire Doody, Lawrence Livermore National Laboratory (doody1@llnl.gov); Md Mohimanul Islam, University of Missouri (mibhk@missouri.edu); Chiara Nardoni, University of Bologna (chiara.nardoni4@unibo.it); Shujuan Mao, University of Texas at Austin(smao@jsg.utexas.edu); Patricia Persaud, University of Arizona (ppersaud@arizona.edu); Valeria Villa, California Institute of Technology (vvilla@caltech.edu); Xin Wang, Chinese Academy of Sciences (wangxin@mail.iggcas.ac.cn)

POSTER 107

Seismic Studies in Southern Nevada Using a Low-cost Raspberry Shake Network

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Low-cost Raspberry Shake (RS) seismometers have made seismic monitoring more accessible, engaging both citizens and researchers. In Southern Nevada, multiple RS devices are deployed, providing real-time open-access data to the Raspberry Shake StationView Data Center. This network offers an opportunity to evaluate the performance of RS devices in detecting and characterizing seismic events across various magnitudes and distance ranges.

In this study, we compare noise and signal characteristics of RS devices to nearby broadband sensors, assessing their suitability for seismic monitoring. Local seismicity—including earthquakes, quarry blasts, and casino implosions—is analyzed to determine the RS network's ability to map fault zones and refine upper crustal velocity models. Earthquake swarms are examined to estimate detection thresholds in tectonically active regions. Furthermore, we demonstrate the capability of RS devices to estimate moment tensors for events with short-to-intermediate period surface waves. Preliminary results highlight the potential of RS networks to complement traditional seismic stations in Southern Nevada. This study underscores the value of RS devices in advancing seismic hazard analysis, fostering community engagement, and promoting citizen science in academic and non-traditional contexts.

POSTER 108

Machine Learning-based Seismogenic Zones for Seismic Hazard Estimation in Mexico

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We explore a new approach for defining seismic zones intended to be the base of probabilistic seismic hazard calculations in Mexico. In order to reduce uncertainty in the PSH assessment, we evaluate the commonly used seismic zones in Mexico against the country's tectonic activity. We conclude that several discrepancies are observed, and a new approach is proposed to apply a machine learning algorithm designed to build seismic zones aligned with tectonic activity and geologic characteristics. To achieve the latter, we compiled focal mechanism data from an extended catalog by Franco et al. (2020), gravimetric data, and other geological features. The clustering algorithm HDBSCAN was selected for its suitability in handling the data distribution and density, providing optimal results for the task. Furthermore, we analyze b-values along a territorial grid to characterize seismicity and modify, evaluate, and validate the proposed zones. The results reveal a distribution of seismic zones that reflect the tectonic activity in Mexico, which brings more certainty to the seismic hazard estimations and opens a new direction in the definition of seismic zones.

POSTER 109

Nodal Seismometer Recordings of Aftershocks of the 5 December 2024 Mw 7.0 Offshore Cape Mendocino Earthquake

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On December 5, 2024, a Mw 7.0 earthquake occurred approximately 70 km southwest of Ferndale, California, just west of the Mendocino Triple Junction. Starting the same day, the U.S. Geological Survey began deploying nodal seismometers (nodes) in the Eel River Valley, Cape Mendocino, and the highway 101 corridor to compliment local permanent Northern California Seismic Network (NCSN) stations. Each of approximately 115 nodal stations contained a SmartSolo IGU-16HR 3-component node, recording continuously at a 2-ms sampling interval and time-corrected using GPS. The nodal stations, combined with the permanent network, provided more densely spaced recordings of events in the area, with the combined network recording 295 Mw 2.5+ aftershocks in the following weeks, 14 of which were greater than Mw 4.0, as determined by the permanent network. The combined dense nodal and permanent network stations expanded the recording azimuth (nodal stations capturing most aftershocks) and are expected to significantly increase the number of events in, and the accuracy of, the current earthquake catalog for the region during the deployment period, particularly when evaluated with machine-learning methods (Yoon et al., 2015; 2023).

POSTER 110

Predicting Site Amplification in New Zealand Using Measured and Inferred Proxies

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The performance of the built environment during earthquakes is strongly influenced by local and regional variations in ground conditions that influence the amplitude and frequency content of ground motions. Developing models to predict these local site amplification effects is a key ingredient for the modelling of seismic hazard and risk. This study investigates the capability of various measured site parameters (e.g., fundamental period - T0, HVSR) and/or inferred site proxies (e.g., slope, rock classification, curvature) to predict local site amplification in New Zealand (NZ). To achieve this, we compiled an extensive database of relevant site parameters at 582 seismic stations, derived from seismic data (ambient noise and earthquake recordings), geological and topographical maps, as well as site parameters included in the NZ-strong-motion database (Wotherspoon et al., 2024). Additionally, the NZ backbone model proposed by Atkinson (2024) was used to compute PSA site-to-site variability within the period range of 0.05 to 10 seconds, utilizing a comprehensive dataset of ground motion parameters from Manea et al. (2024). We then evaluated the robustness of correlations between site parameters and earthquake site-to-site variability to assess their performance both individually and in combination.

The results indicate that of any single metric, the strongest correlation with site-to-site variability is achieved by geological era, closely followed by site classes based on the 2004 NZ seismic design standard (SNZ 2004). Among measured parameters, VS30 shows the best performance at short periods, while T0 is more effective at longer periods. Inferred parameters such as slope, curvature, and relief perform similarly, although they may capture different aspects of site-to-site variability. In conclusion, while different geological and topographical proxies are effective for estimating site amplification at a regional scale, measured site parameters such as the the funamental period, VS30 and HVSR are also needed to capture the variability of site response at the local level.

POSTER 111

Dynamic Triggering of Earthquakes in Costa Rica

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We document for the first time in the modern seismological era, the dynamic triggering of microseismicity in Costa Rica due to the occurrence of large events at teleseismic distances. Dynamically-triggered failure is typically observed in volcanic or geothermal settings, characterized by the presence of fluid flow and/or high pore pressures weakening fault settings by reducing the normal effective stress, and has been found to be less common in continental or local faults. We use OVSICORI's broadband seismic stations in Costa Rica to look for teleseismic events with dynamic stresses higher than 1.1 kPa from 2010 until February 2023. We recovered a total of 25 events, including the 6 February 2023 M 7.8 Turkey earthquake. This addition was driven by our observation of increasing seismicity rates along the southern Pacific coast of Costa Rica following this large event. From our observations, two events were identified as prime examples of instantaneous triggering during the arrival of surface waves: the 7.55 Mw Swan Islands earthquake in 2018 and the 7.8 Mw Turkey earthquake in 2023. Both events have a distinctive strike-slip focal mechanism, this is an interesting point considering that the inverse mechanism is predominant and characterizes most of the earthquakes in our catalog. Our results reveal that the triggered seismicity primarily happened in the northern volcanic areas of Costa Rica. However, we also observed significant triggering along the subduction zone in the southern Pacific coast, specifically in Punta Uvita Puntarenas, and, in crustal shallow faults in central Costa Rica, a shear zone with a high population density. Our preliminary results provide evidence that dynamically-triggered earthquakes highlight the presence of weakened faults in central and southern Costa Rica, increasing the possibility of activating cascades of earthquakes that could potentially lead to a large-scale event, like the one devastating the city of Cartago in 1910 or the Osa Peninsula megathrust in 1983.

POSTER 112

Comparing Ambient Noise Methods for Estimating Dispersion Curves at the Local-to-regional Scale

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The Nevada National Security Site (NNSS) hosts a network of strike-slip faults known as the Rock Valley Fault Zone (RVFZ). A series of shallow (<3 km) earthquakes in 1993 challenge our understanding of how shallow earthquakes occur, where fault orientations, regional stress fields, and regional groundwater flow may be important factors but are not well characterized, especially in the shallow subsurface. The focus of this work is to improve a local-to-regional model of seismic velocities of the southern NNSS region using Rayleigh wave dispersion curves extracted from ambient noise data. We process continuous seismic data during a three-month period from February through April 2023, combining a large-N array seismic network over central Rock Valley with regional Northern Nevada and Southern Nevada network stations. The variable interstation distances ranging from 6 to 62 m and limitations in the bandwidth of noise signal pose a methodological challenge, potentially limiting feasibility of a one-size-fits-all solution. We therefore explore multiple methods of extracting dispersion curves from station pair cross correlations and compare results at different interstation distances, with the goal of improving dispersion estimates at close (<10 km) interstation distances. We compare the results of multiple methods, including frequency time analysis (FTAN), Aki's cross-spectral method, a continuous wavelet transform (CWT) method, and a recent machine learning method. We quantify the strengths and weaknesses of each, where each method agrees and disagrees, and expound on the potential of machine learning methods to overcome some of the challenges of conventional methods.

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POSTER 113

Inter-station Approaches to Identify Repeated Seismic Sources

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Many seismic sources on the Earth are small and complex, but repetitive. For instance, the small earthquakes in tremor repeatedly rupture fault patches. Trucks repeatedly drive on the same road. And water repeatedly flows over the same riverbed.

These repeated sources represent promising datasets to learn more about the shallow and deep subsurface, but they can be difficult to analyze. As a first step, we would like to obtain the Green's functions, or path effects, of sources recurring at particular locations. But we do not know the timing or source time functions of those sources, and we must somehow disentangle the source time functions from the data in order to retrieve the Green's functions.

Here I tackle this blind source separation problem by building on approaches in speech processing. I attempt to directly extract the Green's functions from long records of complex shaking, with an approach that effectively ignores the source time functions. Specifically, this approach searches for the set of Green's functions that promotes the maximum coherence between stations. Since the approach maximizes the coherence between stations, it has little sensitivity to the complex and unknown source time functions. And since the approach is a maximization, it can use many of our standard optimization tools.

This optimization problem is not without challenges. It is many dimensional, and in some ways underdetermined. I present initial results in addressing these challenges. I show that the analysis is effective in quickly identifying first-order features the Green's functions in synthetics and in tectonic tremor given some regularization. However, the method does not yet work to identify subtle features of the synthetics or without significant regularization.

POSTER 114

Shear Wave Velocity Profiling in Urban Areas Using Micro-array Microtremor HVSR Inversion and SPAC Method

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The magnitude of ground motions is significantly influenced by the shear wave velocity (V_S) profile of the site. Thus, estimating accurate V_S profile is required to better understand the seismic hazard and eventually to minimize potential earthquake damage. However, in urban areas, V_S data have not often been measured or have been lost. Due to environmental constraints such as limited space, traffic, and densely packed buildings, it is difficult to perform additional borehole-based geophysical surveys. Alternatively, noninvasive measurement techniques conducting in confined spaces can help to detect V_S profiles. This study aims to evaluate the applicability of a method that integrates the microtremor horizontal to vertical spectral ratio (mHVSR) and micro-array spatial autocorrelation (mSPAC) techniques for measuring V_S profiles in urban environments. Using micro arrays of geophones with a radius of less than 2 meters, microtremor data were collected. Then, shallow V_S profiles were obtained through phase velocity analysis with SPAC technique, and deep V_S profiles were derived using the HVSR technique. Two results were then combined to produce continuous V_S profiles. The derived V_S profiles were validated using in-situ borehole data. Additionally, azimuthal HVSR analysis was conducted to identify the optimal array geometry that minimizes distortions caused by artificial structures and topographical effects.

POSTER 115

Probing Seismicity Secrets With Five Nodal Arrays Around the San Jacinto Fault

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Clarifying the relationship between the frequent small earthquakes and the much rarer occurrence of large earthquakes is fundamental to better understanding fault mechanics and earthquake nucleation, but the connection is yet unclear. With more complete catalogs, we can address critical questions to clarify the connection, such as the prevalence and mechanics of foreshocks, the spatial-temporal evolution of swarms, and the fine-scale structure of faults. Although recent advances in template-matching and machine-learning approaches have improved our ability to detect events, the limits of detectability for tiny earthquakes have yet to be reached, and a hidden frontier of microearthquakes remains to be examined. Our recent analysis showed that beamforming applied to a large-N nodal array on the San Jacinto Fault detects about five times more earthquakes than those in the QTM catalog of Ross et al. (2019), which includes many times more events than the standard network catalog. However, locating the events with a single array can be difficult due to the deflection of the incoming waves by heterogeneous velocity structures.

Building on these advances, we deployed five 81-element nodal arrays of 100-m aperture around an active portion of the San Jacinto Fault for four months through February 2025. An array with a 9 by 9 grid of sensors spanning 100 m is practical for efficient installment and maintenance of the equipment and improves signal-to-noise levels to facilitate detection of tiny earthquakes. Template matching, waveform cross-correlation, and differential location techniques applied to multiple arrays enhance our ability to detect and precisely locate tiny earthquakes and provide unprecedented resolution of seismicity and fault structures. This multiple-array project will provide new insights into fault mechanics and seismicity by pushing the limits of microseism detectability. We discuss our preliminary results from this project and its implications for foreshock and swarm properties, such as their prevalence and temporal evolution near the San Jacinto Fault.

POSTER 116

Investigating the Subsurface Structure of the Chestnut Hill Embankment Dam Using the Ground Penetrating Radar (GPR) Method

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The Chestnut Hill Reservoir earth embankment dam is a component of water storage and flood prevention infrastructure for the city of Boston, MA. To study its internal structure, a Ground Penetrating Radar (GPR) survey was conducted to image and analyze the subsurface composition of the dam. Using the GSSI SIR 3000 GPR system, survey lines were taken along the embankment at 35-meter intervals, focusing on the two block houses located along the dam. The survey revealed strong horizontal reflections near a structure on the dam called the First Block House (FBH) at approximately 170 meters from the survey's starting point. These reflections indicate the presence of concrete slabs, and other underground structures that contained water pumping equipment. Multiple hyperbolas in the radargrams near the FBH suggest the presence of underground metallic pipes, which are essential for water passage and positioned very close to the surface. Similar features were observed near a Second Block House (SBH) at 625–680 meters from the survey start, with diffractions extending from 0.5 to 1.5 meters depth, confirming the presence of utilities. Additional findings include nearly horizontal layers of material overlaying the embankment, likely corresponding to gravel paths used as reinforcement. A drainage pipe was identified at approximately 285 meters from the survey's start, validated through ground truthing and imagery. Transitions between lithologies were observed at about 430 meters, marked by distinct changes in radar reflections, suggesting variations in the dam's construction materials. This study highlights the effectiveness of GPR in producing high-resolution images of the interior composition of earth embankment dams.

POSTER 117

Investigating Tremor-like Episodes at Salt Domes Used for Underground Energy Storage in the US Gulf Coast

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Underground storage caverns in salt domes have become increasingly critical in the energy transition, particularly for storing fuels such as hydrogen. The recent loss of structural and mechanical integrity at caverns in the Sulphur Mines salt dome and the potential threat to the Chicot Aquifer highlight an even greater need for monitoring hazards for environmental protection and the public safety of local communities. Monitoring and identifying structural instabilities and hazards at storage sites present significant challenges due to the small event magnitudes, waveform complexities, and the sparsity of observations. Microearthquakes offer important insights into the mechanical behavior of salt boundary shear zones. In addition, a previous study found that tremor-like episodes preceding the cavern collapse and sinkhole formation at the Napoleonville salt dome were associated with greater seismic energy release. These episodes were followed by quiet periods during which strain was built back up for new seismic events. The characteristics of such episodes could signal the weakening of the mechanism driving the seismicity. To better understand the characteristics of seismic signals at underground storage sites, we analyzed tremor-like signals recorded at two locations in Louisiana: the Sorrento salt dome near Sorrento and the Napoleonville salt dome near Bayou Corne. Previous research at Bayou Corne identified two large tremor-like episodes followed by 3+ hours of quiescence periods. Using data from 31 July to 6 August 2012 recorded at six broadband stations, we manually identified three additional episodes that occur for at least 2.5 minutes on 31 July 2012 and display at least eight microseismic events within a single episode. Tremor-like episodes are observed at all stations, however, they are difficult to identify as one might mistake them for noisy signals. We also present teleseismic data from the US Array station 545A showing that distant earthquakes from Mexico and Peru were recorded near Bayou Corne but are not tremor-triggering events.

POSTER 118

Shear Wave Imaging by Inverting Surface Wave Dispersion Curves Extracted From Train Induced Vibrations and Urban Traffic Noise

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Train induced vibrations are exceptionally good source of surface wave energy and provide a unique type of opportunistic source for subsurface shear wave velocity imaging using approaches based on seismic interferometry. Similarly, urban traffic noise is also abundant in surface wave energy in higher frequency range (1-15 Hz) and could be used to resolve the near surface structure. However, the presence of local sources outside the stationary phase zone causes bias in the estimation of surface wave dispersion via seismic interferometry. We develop a novel array processing technique, based on Matched Field Processing (MFP), for large-N style arrays to capture local source locations first and then extract more accurate surface wave phase velocity dispersion curves. The extracted multimodal dispersion curves are then inverted using a non-linear Markov chain Monte Carlo (McMC) method to retrieve the shear wave velocity structure. The addition of higher-mode dispersion curves reduces non-uniqueness and provide an improved high-resolution shear-wave velocity structure.

We analyze datasets from Tierra Grande nodal deployment which utilizes multiple sub-arrays of 10 to 20 elements placed at different locations from the railroad track over the Socorro Magma Body (SMB). We compare dispersion curves extracted from train induced vibrations using data from a spiral sub-array array deployed near railroad tracks with dispersion curves from a spiral sub-array far from railroad tracks. Our analysis clearly demonstrates the effectiveness of MFP approach for dispersion curve extraction using train induced vibrations as opportunistic sources in higher frequency band. We further demonstrate the potency of our approach with a DAS cable deployment at University of Louisiana at Lafayette, deployed for monitoring water table variation in south Louisiana that recorded urban traffic noise.

Numerical Modeling in Seismology: Theory, Algorithms and Applications

Oral Session • Thursday 17 April • 8:00 AM Local

Conveners: Alice-Agnes Gabriel, Scripps Institution of Oceanography, University of California, San Diego (algabriel@ucsd.edu); Martin Galis, Comenius University Bratislava (martin.galis@uniba.sk); Jozef Kristek, Comenius University Bratislava (kristek@fmph.uniba.sk); Peter Moczo, Comenius University Bratislava (moczo@fmph.uniba.sk); Arben Pitarka, Lawrence Livermore National Laboratory, Livermore (pitarka1@llnl.gov); Wei Zhang, Southern University of Science and Technology, Shenzhen (zhangwei@sustech.edu.cn)

Physics Informed Meshing for Accelerating the 3D Indirect Boundary Element Method Computation of Imaginary Part of Green's Function at the Source

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There are some unusual boundary value problems which appear when emergent theories generate new questions. Such is the case of Diffuse Field Theory in Dynamic Elasticity. Theory posits that within such a field, the average directional energy densities, really the power spectra, are proportional to the corresponding imaginary parts of Green's function at the source. For a given problem, the system's Green's function shares some properties with the classical elastic counterpart of the homogeneous full space; while the real part diverges at the source, the imaginary part is smooth. It is the basic building block to model energy ratios in layered medium. The H/V spectral ratio is a good example. The half-space with flat layers allows for a semi analytical solution. To deal with lateral inhomogeneities, the spectral element method has been used successfully. On the other hand, the Indirect Boundary Element Method (IBEM), formulated in the frequency domain, requires discretized boundaries with elements whose sizes decrease as frequency increases. This approach results in a significant growth in the number of equations, posing computational challenges.

To alleviate the burden, we developed an adaptive IBEM based on the physics of wave diffraction. It appears a viable alternative to use large discretization region and elements for low frequencies when diffraction is very strong, and small region and element sizes for large frequencies when geometrical effects prevail. Moreover, we account for distant elements that may contribute, if conveniently collimated, to the energy budget at the selected point. This fast, adaptive 3D IBEM is aimed to compute the imaginary part of Green's function for a layer over an elastic half-space with a smooth laterally varying interface. For this problem, we found the IBEM solution accurate once it is calibrated with the imaginary part of Green's tensor at the free surface. This solution, based on the principle of equipartition of energy, is well known. This work was partially supported by DGAPA-UNAM Project IN105523. J. G. González is supported by the UNAM Postdoctoral Program (POSDOC).

Dynamic Earthquake Rupture and Tsunami Modeling for the Gulf of Aqaba

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The Gulf of Aqaba (GoA) constitutes the southern segment of the Dead Sea Transform Fault, functioning as a left-lateral strike-slip plate boundary that separates the Arabian plate from the Sinai micro-plate. The GoA is also the seismically most active region of the Red Sea and has hosted well-documented historic large earthquakes and thus poses high seismic and tsunami risks for coastal communities. The rapid development of the NEOM project highlights the need for enhanced seismic and tsunami hazard assessments. However, the offshore nature of the fault system and limited data complicate the efforts.

In the study, we construct various 3D multi-segment fault geometry to represent alternative possibilities of the GoA fault system constrained by recent high-resolution multibeam imaging and local seismicity. Our models integrate regional seismotectonics, topo-bathymetry, off-fault plasticity, and different levels of fault roughness. We perform dynamic simulations with varying hypocenter locations to explore rupture dynamics, fault interactions, and mechanically plausible rupture scenarios in the GoA, analyzing their effects on seafloor deformation and the resulting tsunami excitation. In addition to successfully reproducing the 1995 Mw 7.2 Nuweiba earthquake, our results show that fault geometry, hypocenter location, rupture directivity, and prestress conditions affect how and if rupture propagates across the multi-segment GoA fault system. Our simulations lead to varying slip distributions across different fault segments and different magnitudes, and reveal that the GoA fault system can host up to Mw 7.6 earthquakes if the entire fault network ruptures. Tsunami simulations document pronounced directivity effects and highlight the critical importance of incorporating time-dependent seafloor displacement into tsunami modeling and hazard assessment for the GoA region. Additionally, the potential supershear rupture significantly amplifies seismic risk and seiche effects of the narrow Gulf geometry amplifies tsunami risk to coastal communities, underscoring the need for enhanced preparedness and mitigation strategies.

Implications of the Recent Findings for Practical Calculations and Designing the Time-domain Finite-difference Schemes

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Since the beginning of the time-domain finite-difference (FD) modeling of seismic wave propagation, the FD scheme developers have been analyzing consistency and order of approximation, stability, and temporal and spatial grid dispersions. In most cases the analysis was performed for the homogeneous medium assuming a harmonic wave. The stability analysis of the space-time FD scheme gives a relation leading to a condition for the temporal discretization (maximum possible time step). The stability condition is then used to obtain a grid-dispersion relation: a relation for the phase velocity as a function of the time step and spatial grid spacing. A choice of admissible difference between the true and grid velocities then determines a value of the grid spacing.

The outlined (in general simplified) traditional analysis does not account for the consequences of spatial discretization in the wavenumber domain. Moczo et al. (2022) and Valovcan et al. (2023, 2024) showed that such an analysis is necessary and leads to truly fundamental consequences for discrete representation of the heterogeneous medium and spatial sampling of the simulated wavefield. A heterogeneous medium must be wavenumber limited by the Nyquist wavenumber in order to avoid aliasing in the wavenumber domain. Then, however, the wavenumber-limited medium imposes a spatial sampling condition for the simulated wavefield. The wavefield should not be sampled by less than 4 spatial grid spacings per shortest wavelength to obtain sufficiently accurate results. This applies to any FD scheme. We present numerical results to demonstrate fundamental conditions for constructing time-domain FD schemes.

Bento: Benchmark for Assessing Topographic Site Effects Through 3D Numerical Simulations

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Understanding the impact of topographic site effects on seismic ground motion is a crucial topic in earthquake engineering and seismic hazard assessment. Numerous studies rely on numerical simulations to explore these effects. However, a key concern is whether numerical simulation methods provide consistent predictions of topographic amplification and de-amplification of ground motion in both homogeneous and heterogeneous media. To address this, the international Benchmark of 3D Numerical simulations on TOpographic sites (BENTO) was launched in September 2024, with a total of 20 teams participating from France, Italy, Japan, China, Slovakia, Switzerland, Germany, and the U.S. The benchmark, which is part of the ESG7 conference scheduled to take place in Grenoble, France, in the fall of 2026, will extend over the entire period leading up to the conference and will mainly consist of three phases: (1) a verification phase focused on very high-frequency 3D simulations of simple topographic shapes; (2) an initial validation phase involving more complex 3D simulations on real topographic terrain with existing earthquake recordings; and (3) a second validation phase involving 3D simulations on additional topographic sites identified during the benchmark, where seismic measurements will be collected based on conclusions drawn from the simulations. The goal of these three phases is to perform a cross-comparison of results from different numerical simulation codes, as well as to compare simulation results with real-world measurement data, available analytical solutions, and simpler proxies. This will help evaluate their alignment in assessing topographic site effects, provide insights into the meshing precision needed to capture small topographic features at high frequencies, define reference rock sites on topographic reliefs, explore the relative influence of topographic parameters on amplification patterns, and address other important aspects of the effect of topography on ground motion. This work is partially supported by the Cashima-3 and Sigma-3 research programs.

Modeling of HVSR for an Inhomogeneous Medium Over a Varying Lateral Interface Using 3D IBEM and the Diffuse Field Concept

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The single-station microtremor horizontal-to-vertical spectral ratio (HVSR) method is a powerful tool to retrieve the dominant frequency and shear velocity structure of soft soil locations. Its appeal lies on its simplicity: no artificial sources are required, and single-station, three-component observations are sufficient to estimate soil properties, making it a highly cost-effective technique. Numerous studies have explored the interpretation and modeling of HVSR. Assuming that seismic noise behaves as a diffuse field, which implies that microtremors are generated by random sources, accounting for multiple scattering effects and having sundry types of elastic waves. The diffuse field theory establishes a direct relationship between the average energy density and the imaginary part of the Green's function when the source and receiver coincide. Theory remains valid even for anisotropic and inhomogeneous media.

The Indirect Boundary Element Method (IBEM) is a numerical approach based on integral equations and fundamental solutions. It has been formulated in the frequency domain which makes it inherently well-suited for HVSR modeling. However, its application to heterogeneous media has posed a significant challenge due to the lack of suitable fundamental solutions for such materials. In this work, we present an analytical approximation for the fundamental solution for 3D elastic wave propagation in a vertically inhomogeneous medium with constant velocities gradients and demonstrate its application to HVSR modeling using the Diffuse Field Concept (DFC). This advancement not only extends the applicability of the DFC but also enhances our understanding of wave behavior in complex geological settings and demonstrate IBEM's ability to handle varying lateral interfaces effectively.

Implications of Recent Advances in Anelastic Seismic Ray-tracing Algorithms for Alluvium-basin Response and Seismic-tomography Models of the Crust and Mantle

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New developments in viscoelastic ray theory provide exact numerical models for seismic-engineering models of alluvial basins and anelastic seismic-tomography models of the Earth's crust and mantle, including new insights for anelastic earth-reference models such as PREM. These advances provide exact anelastic ray-tracing algorithms that reveal measurable changes in seismic ray paths, travel times, and amplitudes for Wide-Angle Refracted (WAR) waves. These changes are induced by contrasts in intrinsic anelastic material absorption at seismic boundaries in the Earth that are not predicted by conventional elastic or t* models. These new insights are confirmed by numerical model results that will be presented for anelastic layered models of alluvial basins, crust, and mantle.

Finite-domain Full-waveform Ambient Noise Inversion for Structure and Source Parameters

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Ambient seismic vibrations are a rich source of information about subsurface structures that can be probed by inversion approaches. Where noise fields are homogeneous, empirical Green's function retrieval methods can be used to extract this subsurface information. In heterogeneous noise fields, however, significant amplitude and phase errors can arise, presenting a serious obstacle for full-waveform applications.

Full-waveform ambient noise inversion bypasses emprical Green's function retrieval by treating noise correlations as observables in inversion. Unfortunately, existing formulations of full-waveform ambient noise inversion necessarily involve numerical simulation on the scale of noise source distribution rather than domain scale, an orders-of-magnitude discrepancy that makes small-scale applications impractical. This is a significant obstacle for reservoir monitoring applications, where ambient noise monitoring would otherwise be ideal.

We present an approach for achieving full-waveform ambient noise inversion on spatial scales that are small relative to the distribution of noise sources. This is achieved by reframing the problem in terms of boundary wavefield operations in place of out-of-domain wave simulations. When the out-of-domain medium is relatively simple, these boundary operations take the form of a relatively small number of simple correlations. We present numerical examples in which both material properties within a domain and direction of noise contributions outside a domain are simultaneously inverted for. We demonstrate that we are able to accurately recover both sets of properties without the need for out-of-domain wavefield simulations, even when all noise sources considered are external to the domain of interest.

Leveraging Boundary Integral Equations for Efficient, Fully-dynamic Simulation of Earthquakes and Aseismic Slip on Fault Networks

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Modelling sequences of earthquakes and aseismic slip on fault networks with inertia (dynamic) effects remains a significant challenge. In many contributions, these effects are either neglected or approximated via a quasi-static or quasi-dynamic approximation of balance of elastic momentum in fractured media.

Boundary Integral Equation Methods are particularly appealing as they are built on analytical (singular) solutions, which are used to enforce approximately specified boundary conditions directly on lower dimensional features like pre-existing faults and fractures. In elastodynamics, these methods are typically formulated in the space-time domain, involving double convolutions (in space and time) between boundary variables and integral kernels. The spectral formulation, obtained through a Fourier transform in space, offers additional advantages by effectively uncoupling the spatial convolution in the spectral domain. Despite this benefit, this formulation is traditionally limited to one single planar fault, although the restriction to planar fault can be partly relaxed [1].

In this work, we introduce a strategy that combines the advantages of different boundary integral formulations for an efficient modeling of earthquake sequences and aseismic slip on non-planar fault networks. Restricting here to out-of-plane (mode III) deformations, we present several examples that highlight the computational efficiency of our approach, and discuss the limitations inherent in the numerical method used, along with efficient computational strategies to address them.

Our approach enables fast, fully-dynamic earthquake cycle simulations on fault networks using personal computers or desktops, significantly reducing the need for supercomputers (at least in 2D settings).

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A Velocity Structure Model for Ground Motion Simulation in Japan

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Japan is in a complex tectonic setting with various subducting plates, and most urban areas are located on sedimentary basins. These lead to 3D complicated velocity structures, which have significant impacts on seismic ground motion in Japan. Therefore, for accurately simulating seismic ground motion, it is essential to accurately model the 3D velocity structure throughout Japan. Koketsu *et al.* (2009) proposed a standard procedure for modeling a regional 3D velocity structure in Japan, simultaneously and sequentially using various datasets such as those of refraction/reflection experiments, gravity surveys, surface geology, borehole logging, microtremor surveys, and earthquake observations. We applied this procedure to northeastern and central Japan in 2009, and to southwestern (SW) Japan in 2011. We then constructed version 1 (V1) of the Japan Integrated Velocity Structure Model by combining these regional models in 2012. A revised version of this (V1R) was published in 2023.

We have made the following modifications to V1R to create version 2 (V2): (1) the seismic basement in SW Japan was corrected to be less complex; (2) the structure of the accretionary prism along the Nankai Trough was revised to fit the relationships of Baba (2005a); (3) narrow accretionary prisms were added along the Japan Trench and Sagami Trough based on Baba (2005b). We have first performed a ground motion simulation for the 2004 earthquake off the Kii Peninsula using V2. Watanabe *et al.* (2014) also conducted a simulation for the earthquake using V1. In their results, the duration of ground motion in the Tokyo lowland was reproduced, but there is a problem with the amplitude. Our simulation with V2 improves the problem considerably, and slight overestimation is solved by introducing sea water into the simulation. We have secondly performed a ground motion simulation for the 2011 Tohoku earthquake using V2. The results of the simulation by Kawabe

et al. (2013) using V1 show slight underestimations in the Tohoku to Kanto region, and slight overestimations in the Kinki region. These problems are generally improved in our simulation.

Earthquake Rupture Propagation and Arrest in a Highly Variable Stochastic Stress Field

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Earthquakes occur in populations with few large events and many small ones, yet many earthquake rupture models employ a relatively smooth stress field and other conditions that prohibit the co-occurrence of both large M7 earthquakes and smaller M1 to M3 foreshocks and aftershocks. We present a model where the multi-scale geometrical complexity of rough faults and the heterogeneous stresses that develop within fault zones are represented with a stochastic stress field $Dt_{pot}(x)$. Sometimes referred to as effective stress, $Dt_{pot}(x)$ is related to the strain energy that can provide fuel for an earthquake and is defined as the initial shear stress level relative to the fault's residual sliding strength. We study populations of earthquakes that propagate and arrest in the stochastic stress field based on a highly simplified 1-D fracture mechanics framework (e.g. Ampuero, Ripperger, Mai, 2006). Specifically, we explore how properties of the earthquake populations—such as the magnitude dependence of stress drop and the Gutenberg-Richter frequency magnitude distribution—vary as a function of statistical properties of the stress field such as the coefficient of variation and the scaling exponent m (Beeler, 2023) which describes how $Dt_{pot}(x)$ changes as a function of wavelength. We find that realistic populations of earthquakes, with more small ones than large ones and magnitude independent stress drops, are produced for stochastic stress fields with $m < 0.5$ ($m = 1.5$ is self-similar, $m = 1.0$ is Brownian, $m = 0$ is white noise). This suggests that $Dt_{pot}(x)$ must be highly variable even at short wavelengths, a property that is absent from most state-of-the-art dynamic rupture models and unresolvable with kinematic finite fault inversions. The highly variable stress fields produce earthquake ruptures that nearly arrest and rapidly reaccelerate. These characteristics are consistent with observations of earthquake source time functions with multiple sub-events, and they provide a mechanism to generate high frequency ground motion that is lacking in many rupture models.

Numerical Modeling in Seismology: Theory, Algorithms and Applications [Poster]

Poster Session • Thursday 17 April

Conveners: Alice-Agnes Gabriel, Scripps Institution of Oceanography, University of California, San Diego (algabriel@ucsd.edu); Martin Galis, Comenius University Bratislava (martin.galis@uniba.sk); Jozef Kristek, Comenius University Bratislava (kristek@fmph.uniba.sk); Peter Moczo, Comenius University Bratislava (moczo@fmph.uniba.sk); Arben Pitarka, Lawrence Livermore National Laboratory, Livermore (pitarka1@llnl.gov); Wei Zhang, Southern University of Science and Technology, Shenzhen (zhangwei@sustech.edu.cn)

POSTER 119

AxiSEM3D - Fast, Efficient Seismic and Acoustic Synthetics for Complex 3D Models

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The AxiSEM3D method is a coupled pseudospectral-spectral element method which allows for efficient computation of synthetic seismograms in complex 3D models on global, regional, and local scales. It is a fully 3D version of the original, 2.5D AxiSEM method.

The code has recently been updated and now supports propagation of seismic and acoustic waves at global frequencies up to several Hz (on HPC architectures), for structural models including the Earth, Moon, Mars, and Sun. Additional functionality supported includes volumetric and topographic (surface and interior) models, fluid oceans, strong off-plane scattering, and atmospheres.

In this work we will illustrate some pertinent use cases across Earth and Solar System environments, and share recently-developed user guides and manuals designed to simplify the user experience whilst preserving computational efficiency.

POSTER 120

Computer Programs in Seismology – 50 Years of Progress

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The Computer Programs in Seismology package offers a comprehensive set of software tools designed to process and analyze seismic data, compute synthetic seismograms using a variety of computational approaches, investigate seismic source characteristics, and invert for Earth structure. This package is continuously developed and refined, often to respond to user needs. The latest distribution integrates cleanly with the most recent GCC/GFortran and Clang/Flang compilers on Linux and MacOS, and operates under Wayland with XWayland in addition to Xorg. Newly incorporated codes include srfpar96, which generates surface-wave dispersion inversion kernels; hwhole96strain, which calculates isotropic whole-space Green's functions and spatial partial derivatives for use with hpulse96strain to determine stress, strain, and displacement time series, as well as to validate the wavenumber integration tools employed for more complex models; rregn96 and rlegn96, which compute surface-wave eigenfunctions using generalized reflection matrices, which can be more stable for models with low-velocity layers. Tutorials added in 2024 address surface-wave inversion kernels, surface-wave eigenfunctions, quarter-wavelength site response, wave propagation for ocean-floor observations, and computations of strain and displacement in the context of DAS analysis, epicenter estimation, and testing of full moment tensor inversion codes.

The package is now available at GitHub as well as at the SLU site: https://rbherrmann.github.io/ComputerProgramsSeismology/https://www.eas.slu.edu/eqc/ComputerProgramsSeismology/

POSTER 121

Multidomain FDM/PSM Hybrid Method for Elastic Wave Simulation

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Efficient and accurate seismic wave simulations are important for waveform inversion and strong ground motion simulation in regions with complex surface topography. The finite-difference method (FDM) is widely used for these simulations due to its simplicity and high efficiency. High-order FDM mitigates dispersion and dissipation errors through higher-order schemes, allowing the use of larger grid spacings and increasing efficiency. However, achieving a high-order and stable implementation of the free surface boundary condition remains challenging. To address this, this paper introduces a novel multidomain finite-difference and Chebyshev pseudospectral hybrid method (multidomain FDM/PSM) for elastic wave modeling. This method divides the computational domain into multiple subdomains along the vertical direction, employing characteristic boundary conditions for patching subdomains and implementing the free surface boundary condition. Within each subdomain, a high-order finite-difference scheme is applied horizontally, complemented by a Chebyshev pseudospectral scheme based on Chebyshev-Gauss-Lobatto (CGL) points in the vertical direction. To prevent excessive point density at mesh edges and avoid overly small time steps, we only use grid configurations with 13 or less CGL points. Using a hybrid approach that integrates a 13-point central stencil finite-difference scheme with a 9-point Chebyshev pseudospectral scheme, we achieve waveform errors under 0.5% while requiring only four points per wavelength. Numerical examples demonstrate that the multidomain FDM/PSM effectively simulates the propagation of elastic waves in models with complex structures and topography.

POSTER 122

Estimation of Ground Motion Through Deconvolution-linear Scaling-convolution Method

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Ground motions can be estimated at sites using nearby reference station records. However, the estimated records have uncertainties due to differences of site and path conditions between source and target sites. To resolve this problem, this study evaluated the ground motions estimated using the deconvolution-linear scaling-convolution method (DLSC). The DLSC method consists of three steps: (1) determine the bedrock motion from the surface motion by performing deconvolution which removes the influence of local site effect; (2) adjust the difference of the amplitude of bedrock motion between source and target sites based on the rate using a ground motion model (GMM); (3) convolve for the surface motion. To validate this approach, we collected records from 14 local events with ML ≥ 3.5 and site information at stations. Then, we evaluated the root mean square error (RMSE) between the recorded and estimated PGA values, and compared the DLSC method result with those of two other methods (referred to as Model A and B). Model A calculates PGA using the region-specific ground motion model (GMM), whereas Model B uses the GMM and interpolation of measured ground motions to calculate PGA at a site. We found that the DLSC method is effective (less RMSE than Model A and B) for the distance range less than 78 km if source station is surface-type and 84 km if source station is borehole-type. While the effective distance would change region by region, we expect that the suggested DLSC method is effective to estimate a ground motion time history at a target site nearby the seismic station.

POSTER 123

Evaluation of Velocity Models of Sichuan-Yunnan Region on Strong Ground Motion Simulation

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The Sichuan-Yunnan region, located at the southeastern margin of the Tibetan Plateau, is characterized by complex geological structures and frequent seismic activity due to the collision between the Indian and Eurasian plates. Conducting physics-based quantitative simulations of strong ground motion can provide critical scientific support for earthquake disaster prevention and mitigation in this region. In recent years, researchers have developed several three-dimensional (3D) velocity structure models for the Sichuan-Yunnan region based on various datasets and methodologies. However, there remains a lack of systematic comparisons and evaluations of how different velocity models impact simulation results in strong ground motion modeling.

This study focuses on the September 5, 2022, Mw6.6 Luding earthquake as a case study. Using finite fault rupture processes derived from real data inversion and different velocity models, we conducted strong ground motion simulations. By comparing station-specific and spatially distributed PGV (peak ground velocity) and SA (spectral acceleration) values, we quantified the influence of different velocity models on simulation results. The findings aim to provide references for selecting velocity models in strong ground motion simulations for the region and offer insights into optimizing velocity models.

The tested velocity models include various regional and continental velocity models of China. Results indicate that in the high-shaking regions near the fault, source effects dominate, and the PGV distributions across models are largely consistent. Spatial distributions of the response spectrum reveal that shallow low-velocity structures and topographic effects significantly influence spectral characteristics. The average results from ensemble predictions using multiple velocity models align more closely with observed values, suggesting that combining multiple velocity models can enhance the accuracy of ground motion simulations in complex geological regions.

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Unraveling Supershear Dynamics of the 1995 Mw 7.2 Multi-segment Nuweiba Earthquake in the Gulf of Aqaba

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The Dead Sea Transform Fault in the Gulf of Aqaba (GoA) functions as an ~180 km long left-lateral strike-slip plate boundary that separates the Arabian plate from the Sinai micro-plate. The GoA is the seismically most active region of the Red Sea and has hosted several large historic earthquakes and thus poses a high seismic hazard to coastal communities. The rapid development of the NEOM project near the GoA highlights the need for enhanced seismic hazard assessment (SHA), however, the offshore nature of the fault system and limited data complicate SHA efforts. Studying past earthquakes provides valuable insights into stress loading, failure mechanisms, and the likelihood for cascading rupture on complex multi-segment fault systems. Such information is critical for accurate seismic hazard assessment in the region.

In this study, we use back-projection and dynamic simulations to analyze the 1995 Mw 7.2 Nuweiba earthquake, the largest instrumentally recorded event in the GoA and along the entire Dead Sea Fault. Our findings reveal a multi-segment cascading rupture on strike-slip and step-over normal fault segments. Our simulations indicate supershear rupture on the optimally pre-stressed Aragonese fault, in agreement with the back-projection observations and surface-wave analysis of Rayleigh waves. Supershear rupture significantly amplifies expected shaking, and hence consequences for coastal communities of this narrow gulf region, with energy radiation more concentrated within the Mach cone causing intensified and prolonged ground motions. The 1995 event only partially ruptured the GoA fault system, notably increasing Coulomb failure stress on the unbroken southern Arnona Fault, which has likely remained silent since 1588. This stress loading could accelerate a future rupture on this vulnerable segment, requiring close monitoring and heightened preparedness for a potential large earthquake in the region.

POSTER 125

CRAM3D-SPECFEM3D Hybrid Simulations of Seismic Waves from Nuclear Explosion Based on Interface Discontinuity

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Nuclear explosion monitoring is crucial for maintaining global security, verifying compliance with the Comprehensive Nuclear Test Ban Treaty (CNPT), and prevent-ing the development and proliferation of nuclear weapons (Dunn, 2009). A signifi-cant challenge in this field is the discrimination of nuclear explosions from earthquakes and other seismic sources based on seismic waveforms, which requires accurate seismic wave modeling at regional distances for nuclear explosions. However, simulating high-frequency seismic waves in heterogeneous media over distances of hundreds of kilometers remains computationally expensive, especially when the complex emplacement conditions of nuclear explosions are incorporated. To address this challenge, a hybrid method first simulates the detailed explosion physics in a small region and then uses the wavefields at the region's boundary as input for seis-mic wave simulations in a larger domain. Specifically, we employ a Lagrangian finite element method using the CRAM3D code (Stevens & O'Brien 2018) within the explosion region to capture complex explosion emplacement conditions and nonlinear seismic effects. For elastic wave propagation in the surrounding heterogeneous re-gion, the SPECFEM3D package based on the spectral element method is applied. To couple these two computational frameworks, we developed a systematic approach based on the theory of waveform interface discontinuity (Liu et al., 2024, submitted). Benchmark tests demonstrate that our coupling method accurately models seismic wave interactions across the interface, providing a robust tool for nuclear explosion monitoring.

Reference

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POSTER 126

Waveform Modeling of Hydroacoustic Records From Autonomous Mermaid Floats

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We present a computational technique to model hydroacoustic waveforms from teleseismic earthquakes recorded by mid-column MERMAID floats taking into consideration bathymetric effects that modify seismo-acoustic conversions at the ocean bottom and acoustic wave propagation in the ocean layer, including reverberations. Our approach couples spectral-element simulations performed for moment-tensor earthquakes in a one-or three- dimensional solid Earth to a three-dimensional Cartesian fluid-solid coupled spectral-element simulation that captures the conversion from displacement to acoustic pressure at an ocean-bottom interface with accurate bathymetry. We use a wavefield injection methods that couples displacement and traction across the boundary between our modeling domains, which are the entire globe on the one hand, and a smaller portion of the Earth that includes the ocean-bottom interface. One the receiver side the three-dimensional Cartesian fluid-solid coupled spectral-element method honors the three-dimensional bathymetry and captures the conversion of displacement to acoustic pressure. We apply our methodology to over 30,000 seismograms from 3,000 earthquakes recorded by over 60 MERMAID floats over the last 6 years. We compute travel-time residuals by cross-correlating our synthetic seismograms with the observed seismograms to make database suitable for regional seismic tomography with teleseismic earthquakes. We compare our travel-time measurements with measurements made on the same data set by ray-tracing. Our procedure encompasses a complete workflow to close the seismic coverage gap for global tomography by the addition of a fleet of mobile marine sensors, in a manner that can integrate ocean-bottom instrumentation, and traditional land sensors on continents and oceanic islands.

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Yield and Depth of an Explosion From Regional Seismograms With Source Complexity - Illustration of the Effectiveness Using Synthetic Seismograms

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A method for inverting waveforms to estimate yield and depth of an explosion when accompanied a double couple (DC) and a strong compensated linear vector dipole (CLVD) source contribution will be presented. This paper points out an amplitude correction for the generalized CLVD source green's functions (GFs) represented as a combination of contributions from three orthogonal force dipoles without torque. For a vertically symmetric CLVD GFs, they are a factor of 2 smaller than the 45º dipping dip-slip fault observed at 45º azimuth (often referred to as ZDD or RDD GFs for the DC mechanism) which are routinely used in waveform inversions. This amplitude discrepancy is also evident in the radiation coefficients of force dipole (FDP) vs DC sources (Saikia *et al.*, 2008) which is also noted in waveforms simulated using three-dimensional SW4 and F-K codes using 1D velocity models. Using this correction, a set of regional waveforms were constructed including a source complexity and effects of regional wave propagation. The explosion sources were represented by the yield and depth dependent time-domain source function (TDSF) and non-isotropic sources just by the impulse source functions. These waveforms were used to set up an inversion scheme which requires partials of the simulated explosion waveforms with respect to yield and depth including the partials of green functions at each depth. We modified the TDSFs (Saikia, 2017, *https://doi.org/10.1093/gji/ggx072*) and the F-K code (FKPROG, Saikia and Burdick, 1991,*https://doi.org/10.1029/91JB00921*) to formulate analytic expressions for the partials of the GFs with respect to the yield and depth using only the source layered matrix. The newly derived partials of explosion sources are independent of the elastic radius of the explosion source which we validated using against the numerical partials. Using numerically simulated waveforms, results from this new set of codes will be presented to illustrate the method effectiveness

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Fully-dynamic Seismic Cycle Simulations in Co-evolving Fault Damage Zones Controlled by Damage Rheology

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Both short-term coseismic off-fault damage and long-term fault growth during interseismic periods have been suggested to contribute to the formation and evolution of fault damage zones. Most previous numerical models focus on simulating either off-fault damage in a single earthquake or off-fault plasticity in seismic cycles ignoring changes of elastic moduli. Here we developed a new method to simulate the damage evolution of fault zones and dynamic earthquake cycles together in a 2D anti-plane model. We assume fault slip is governed by the laboratory-derived rate-and-state friction law while the constitutive response of adjacent off-fault material is controlled by a simplified version of the Lyakhovsky-Ben-Zion continuum brittle damage model. This newly developed framework opens a window to simulate the co-evolution of earthquakes and fault damage zones, shedding light on the physics of earthquakes on natural faults.

We find that the model can reproduce key features of fault damage zones including the spontaneous generation of flower structures, coseismic seismic velocity drop, interseismic healing, and long-term fault zone growth. Both the coseismic shallow slip deficit and long-term fault slip deficit accommodated by inelastic deformation are successfully captured. Moreover, we find that fault zone strength modulates seismicity through changing the spatial distribution of off-fault damage. A weak fault zone results in deep intense damage and cascading events including foreshocks and aftershocks with a migration speed of several kilometers per day. We also find an inherent difference between the energy budget of large and small earthquakes: a larger portion of strain energy is consumed by off-fault damage for smaller events. The fracture energy density of simulated earthquakes inherently scales with earthquake slip, which agrees with seismologically inferred values.

Performance and Progress of Earthquake Early Warning Systems Around the World

Oral Session • Wednesday 16 April • 8:00 AM Local

Conveners: Glenn Biasi, U.S. Geological Survey (gbiasi@usgs.gov); Angela Lux, University of California Berkeley (angie.lux@berkeley.edu); Jessica Murray, U.S. Geological Survey (jrmurray@usgs.gov); Jessie K. Saunders, California Institute of Technology (jsaunder@caltech.edu); Alan Yong, U.S. Geological Survey (yong@usgs.gov)

Shakealert Version 3, Current Status and Future Possibilities

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The primary goal of the ShakeAlert Earthquake Early Warning System is to provide useable warning times before potentially damaging shaking. Version 3 of the underlying algorithm base, live since March 2024, includes numerous improvements aimed at ensuring success in large earthquakes including: multiple ways to initiate events, independent data streams for seismic and geodetic data, and multiple algorithms that characterize large ruptures. It prioritizes speed over accuracy to some extent within 100 km of the epicenter by limiting alerts to that distance for the first five seconds after a detection. Significantly more data become available in that interval to improve ground motion estimates at greater distances. I will give an overview of expected performance in large earthquakes from offline testing and highlight a few recent examples from the production system including successes in the 2021 Petrolia and 2022 Ferndale earthquakes [Lux et al., 2024]. In the 2024 M7 Off-Mendocino earthquake, the MMI 3 and 4 contour products produced maximum warning times of about 10-40 s, 10-20s, and 0-15s at locations with peak shaking of MMI 6, 7 and 8, respectively.

ShakeAlert has clear remaining challenges and several promising areas for system refinement. ShakeAlert allows our partner organizations a range of choices in how they alert their users which requires accurate estimates across a range of magnitude and ground motion levels. While our primary goal is clear, a key need is to clarify what types of alerts we seek to avoid. The answer varies widely among delivery mechanisms and can be tied to legal constraints. Research to-date into the negative outcomes of alerting is limited and represents a key area for improved clarity. Also, ShakeAlert has a well-documented weakness for earthquakes that initiate outside the sensor networks, particularly offshore, and several possibilities exist to improve this. Lastly, new data types may improve our ability to track rupture growth. Improvements in these areas could lead to additional alert products that would better achieve our goals.

Shakealert Earthquake Early Warning: Testing New Vs30 With Population Weighted Values, New Epic With Bayesian Priors, and Finder Triggering With CE Stations

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The ShakeAlert West Coast Earthquake Early warning system has been sending public alerts since October 17, 2019. To assess continuing algorithm development and proposed improvements, ShakeAlert has a System Testing and Performance (STP) platform. The overarching principle is that proposed changes should improve either the warning time and/or accuracy location and magnitude estimates while minimizing additional complexity to the system and alerting. Performance analysis must balance these competing goals. To properly assess the value of proposed software changes, STP replays a suite of waveforms (recordings of moderate to large earthquakes plus a few synthetic earthquakes) through 4-8 instances of the algorithm stack and assesses with metrics from Cochran et al. (2017). In addition, proposed software is run on a set of test systems which are configured like the production system to process real-time data for a minimum period of 2 weeks.

In two major ShakeAlert algorithm stack submissions a number of new features are tested. In the v.3.0.2 submission, the EqInfo2GM algorithm uses Vs30 values with population-weighting within 1km of a ShakeAlert grid cell. This module generates ground motion estimates from source parameters. The change is being tested vs baseline with an MMI tolerance criteria that displays the degree of over- and under-alerting in ground motion space. In the v.3.1.0 submission, the major changes are to EPIC and FinDer, the core algorithms for determining source parameters from seismic data. This version of EPIC uses a Bayesian prior to determine source locations of events, which should significantly improve out-of-network earthquake detections where the data could be limited. The new version of FinDer now incorporates CE network stations for creating a new trigger. (CE stations are strong ground motion stations operated by the California Geological Survey.) This should speed up FinDer's first alert in some cases and potentially allow FinDer to trigger for more earthquakes in sparse networks.

EEW Station Connectivity (Latency) Is Shockingly Low. Here's How We Know

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Telemetry plays a crucial role in the operations of Earthquake Early Warning Systems, such as ShakeAlert, along the West Coast of North America. Previous studies, such as Stubailo et al. (2021), have shown that telemetry systems can become overloaded during large seismic events. Commonly this is due to increased data volume caused by reduced compression efficiency. To explore this issue, we evaluated data volume variability at seismic monitoring stations in Northern California during the December 5 M7.0 Offshore Cape Mendocino Earthquake. We also assessed typical telemetry quality by analyzing latency (archived in real-time as the channel L1Z) across multiple pathways to evaluate the robustness of the connectivity infrastructure. Factors such as data logger type, telemetry type, distance from the data center, and pathways to other partner data centers were investigated to determine which characteristics most significantly affect telemetry health and data delivery efficiency.

Preliminary analysis of latency values for a subset of BK stations received at the University of Washington, Caltech, and UC Berkeley revealed no noticeable delays attributed to the data pathway. Latency data for the same set of BK stations was consistent across these partner agencies when evaluated during the same time period.

When examining latency by telemetry type for all BK stations, no significant variations were observed. However, an analysis of latency by data logger type revealed distinct differences. Comparisons with similar analyses performed at Caltech for CI stations showed comparable patterns in the relative quality and speed of latency based on logger type, indicating a correlation between logger characteristics and telemetry performance.

Development and Testing of an Alaska Earthquake Testsuite Within Epic

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The ShakeAlert earthquake early warning system, and specifically the EPIC detection algorithm, has successfully detected and facilitated public alerts for numerous events along the west coast of the contiguous United States over the past six years. Through ongoing analysis of algorithm performance, we can identify areas that need improvement and propose changes to the system. Historic earthquakes provide an important supplement to real-time testing to account for less common earthquake rupture parameters. One scenario that can likely benefit from more testing and development is large, offshore, and deep earthquakes. Understanding EPIC's performance in these environments is important when preparing for potential future earthquakes, including offshore ruptures along the Cascadia subduction zone.

To this end, we create a new testsuite of recent moderate to large earthquakes focused on a range of environments in the South Central and Aleutian Islands regions of Alaska as recorded at locally managed broadband and strong motion sensors. We then use this developed testsuite to test the current production version of EPIC as well as currently proposed versions (bEPIC) for its alert quality and timeliness. Through this test we will do two things: first we will assess EPIC's usefulness in any expansion of earthquake early warning to Alaska, and second, we will gain a diverse set of solution results that we can use to improve EPIC's performance over its current alerting zone within California, Oregon, and Washington.

From Shakealert to Post-earthquake Assessment – Applied Technologies to Improve Situation Awareness in Buildings

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Early warning systems must be optimized through a combination of science and technology that provide a foundation to deliver alerts in the form of actionable information in a manner relevant to the recipient of the alert. The potential disconnect between the systems' technical innovations and the layperson's human behavioral needs can call into question the value of the application. Maximizing the effect of Earthquake Early Warning Systems (EEWS) requires integrating them into the everyday systems and processes of those who rely on them. Because an EEWS serves multiple participants and must address the needs of each in a manner consistent with their expectations – detailed technical information for scientists and engineers, actionable information for emergency responders, and safety instructions for building occupants – the programs, processes, and tools must be carefully designed for and seamlessly integrated into the application for improving situational awareness in buildings.

The EEW alert process flow, from USGS-published ShakeAlert messages to alerting the information user, includes critical design aspects to organize and implement programs to acquire, process, format, and distribute alerts. A dedicated message-handling process for each building minimizes latency and increases overall system reliability and serviceability. Moreover, the parallel processing threads enhance the platform's scalability. Benchmark testing and real-world data have shown that alerts arrive on average in less than 0.5s at the building's management console and less than 1.5s at the mobile app. Following the shaking, however, emergency management personnel and responders require another level of information to help guide their actions and decisions. For this reason, our platform delivers earthquake early warning messages as a component of a larger workflow incorporating programs to produce information on the impact of ground motion on the structure, nonstructural elements within the structure, and the occupants. The mobile app enables emergency response personnel to submit safety check reports.

How Did People React to the Early Warning During the M7.8 Kahramanmaras-Pazarcik (Türkiye) Earthquake?

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The Earthquake Network (EQN), the first operational smartphone-based public earthquake early warning system (PEEWS) and the sole system in operation during the M7.8 Kahramanmaras-Pazarcik (Turkey) earthquake, issued a cross-border alert within 12 seconds of the initiation of the rupture. The EQN provided a lead time of several tens of seconds for users exposed to intensities greater than VIII (and located at a distance greater than 40 km from the epicentre).

Nevertheless, the efficacy of a PEEW in mitigating individual risk is contingent upon the individual's decision to take protective actions. In order to understand users' reactions, a questionnaire was made and disseminated via the EQN application in April 2023. A total of 11,988 responses were received, including 808 from individuals who had installed the app before the earthquake. Of these 808 individuals, 26% indicated that they had received the warning before experiencing the tremor. The majority of these individuals estimated the lead time to be less than 15 seconds. Nevertheless, 47% of these 808 respondents indicated that they had taken protective actions. Although the estimate is based on limited statistical data, it is significantly higher than the two other studies on the subject that the authors are aware of, which show a rate of 25% in Japan and South America. This may be indicative of a cultural divergence or a disparate perception of seismic risk. This type of study is vital for gaining insight into how the public perceives a PEEWS and how it is actually utilised. While the reduction in casualties remains difficult to estimate, the studies converge on the conclusion that there is a strong public demand for and appreciation of PEEWS, even if people do not make themselves safe and consequently even if the reduction in individual risk is limited. One of the benefits identified by users is the psychological advantage of the warning (rather than being taken by surprise). Further studies of this nature are recommended to gain a deeper understanding of the public's expectations and reactions, with the aim of optimising the use and benefits of PEEWS.

Earthquake Impacts on Traffic Safety Using Crowdsourced and Police Reported Accident Data

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Earthquakes pose significant threats to people and physical infrastructure. However, recent developments of regional earthquake warning systems (e.g., ShakeAlert) have revealed a gap in research on impacts of earthquakes on moving vehicles and drivers. This research integrates earthquake shaking data, crowdsourced Waze navigation application data, and police crash reports to quantify the changes in the likelihood of crashes during seismic events.

The study focuses on earthquakes with at least magnitude 4.0 within the contiguous United States between 2017 and 2023 to align with Waze data availability. An average of the Modified Mercalli Intensity measure of shaking from the U.S. Geological Survey's (USGS) ShakeMap raster data product is applied over constant road network geographies across the affected areas. These links are then geographically matched with accident and other road hazard reports generated by users of the Waze navigation application. Police crash reports from state agencies are also matched to earthquake-affected road segments. This geographic matching analysis produces a database of over 50 million road network segments that were impacted by the 412 earthquakes. Statistical analysis is used to compare the crash and hazard frequencies after earthquakes to similar time periods throughout the previous year, considering factors such as shaking intensity, roadway types, and crash severity. Specific earthquake events are studied as well, including recent events such the Magnitude 7.0 earthquake off the coast of northern California that resulted in ShakeAlert warnings as well as tsunami warnings being issued in the region.

The findings from this research can inform earthquake early warning alerting strategies, specifically the geographic extent of earthquake warnings. The results may also be used to inform public investment in earthquake emergency response planning, or to predict travel delay times from accidents related to seismic activity.

Real Time Characterization of Earthquakes in the Mexican Subduction Zone Based on a Seismogeodetic Network

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A twenty-station seismogeodetic network operates in the Mexican subduction zone spanning the states of Guerrero and Oaxaca. The stations are composed of a GNSS receiver, and the geodetic data are applied an RTX correction in real time and a Kalman filter based on the input of a forced balance accelerometer. Tests show that the resulting real time displacement using these two corrections is as accurate as the post-processed data. Based on these data, the static displacement of large and great earthquakes is estimated. An algorithm was developed to continuously monitor coastal deformation along the subduction zone for potential coseismic displacement. The algorithm triggers when three adjacent seismogeodetic stations report deformation of the coast. The observed horizontal components of the geodetic data are rotated to coincide with the strike and dip of the subduction zone. The source area and length are inverted using Okada´s formulation based on the deformation data recorded by the seismogeodetic instruments. The inversion is done using simulated annealing. The result of the inversion allows the real time estimation of source size and magnitude of large and great earthquakes, for which the national seismic network normally saturates. No large or great earthquakes (*Mw* >7.5*)* have taken place in the Mexican subduction zone since the installation of the seismogeodetic network. The algorithm was tested using three recent great earthquakes for which there are coseismic deformation data: the Maule and Illapel earthquakes in Chile in 2010 and 2015 and the Tohoku, Japan event of 2011. The magnitude and source dimensions obtained by the inversion simulating real time acquisition of the geodetic data of the Chilean earthquakes agree with those presented by other authors. In the case of the Tohoku earthquake, the magnitude and source dimension were underestimated probably because the geodetic stations on land are far from the rupture area. Our results show that the seismogeodetic network in the subduction zone is capable of characterizing in real time the source and magnitude of large and great earthquakes.

Enhancing Earthquake Early Warning With Real-time Ground Motion Assimilation for Rupture Directivity Effects via Kalman Filter

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Earthquake early warning (EEW) is the primary approach for mitigating earthquake hazards, offering the public a lead time of a few to tens of seconds before destructive ground shaking arrives. The widely used point-source algorithm has achieved great success in estimating timely and reasonable ground motion values for given sites, provided rapidly-determined source magnitude and location. However, its accuracy is limited by several factors. First, rupture directivity, a critical source property that amplifies shaking amplitude in specific directions, is not accounted for in most EEW frameworks. Second, Ground Motion models (GMM) used in EEW do not capture event-to-event variability, leading to missed or false alerts. Furthermore, in real-world scenarios, underestimates of earthquake magnitude derived from early P-wave data often occur due to instrumental saturation issue and long rupture process of large events also increase these uncertainties and lead to inaccurate warnings. To address these challenges, we apply the Kalman Filter method to calibrate and update GMM coefficients using real-time peak amplitude data from stations, accounting for variability across different events. By including a new rupture directivity term, our anisotropic GMM also captures directional ground shaking amplification in real time. Applications to several M6+ earthquakes in Taiwan demonstrate the efficacy and relevance of our approach for EEW systems. More importantly, our method can handle the issue of magnitude underestimation during the EEW. For the April 3, 2024 Mw 7.4 Hualien earthquake that caused missed warnings in seven prefectures (including the Taipei metropolis) due to lower estimate of the initial magnitudes, the method can rapidly calibrate predicted ground motions and identify primary rupture direction within 20-25 seconds after origin time, successfully addressing the missed alerts during this event. The data-assimilated anisotropic GMM via the Kalman Filter could provide a practical solution for accurate ground motion predictions and timely source property information, supporting post-event emergency response efforts.

Improving Detections by Reducing Problematic Triggers in the Epic Earthquake Early Warning Algorithm

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EPIC is one of three earthquake detection algorithms currently operating within the US West Coast ShakeAlert system. EPIC is the only point-source algorithm in that system, is typically the fastest ShakeAlert algorithm to detect an earthquake, and has been responsible for all but one of the 140+ public alerts created by the system.

EPIC's rapid detection capability is primarily attributed to its simple yet highly sensitive triggering mechanism. The algorithm employs a Short-Term Average/Long-Term Average (STA/LTA) method to detect seismic waves as soon as they are recorded by a station. Detected triggers undergo a series of checks to filter out spurious triggers. Triggers that pass these checks are then associated and used to estimate the earthquake's location and magnitude once data from at least 4 stations are available.

However, the algorithm's high sensitivity comes with a trade-off as it is prone to triggering on noisy signals, which can lead to false or erroneous alerts. While the system includes measures to reduce spurious triggers - such as evaluating peak acceleration, velocity, and displacement, as well as the horizontal-to-vertical amplitude ratio - the high volume and variability of triggers make it challenging to reliably exclude all non-P-wave signals.

In this study, we present our recent efforts to improve EPIC detections through refined filtering of problematic triggers.

Performance and Progress of Earthquake Early Warning Systems Around the World [Poster]

Poster Session • Wednesday 16 April

Conveners: Glenn Biasi, U.S. Geological Survey (gbiasi@usgs.gov); Angela Lux, University of California Berkeley (angie.lux@berkeley.edu); Jessica Murray, U.S. Geological Survey (jrmurray@usgs.gov); Jessie K. Saunders, California Institute of Technology (jsaunder@caltech.edu); Alan Yong, U.S. Geological Survey (yong@usgs.gov)

POSTER 114

Installation and Optimization Advances in Earthquake Early Warning System (Rast-Vs) for Business Continuity and Public Safety in Mexico

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Earthquake Early Warning (EEW) systems are critical tools for mitigating the impacts of seismic events, offering crucial seconds for protective actions. This work presents the installation and optimization advances of an innovative EEW system in Mexico, developed together by SeismicAI and VASE Sísmica, tailored to the country's unique seismogenic conditions. The system integrates both regional and local networks equipped with cutting-edge seismic monitoring technology capable of rapidly detecting seismic activity, estimating ground motion, and issuing real-time alerts. The system operate with artificial intelligence algorithms that enhance epicenter localization precision, ground motion prediction, and minimize false alerts. By leveraging cloud-based data processing, the system ensures real-time alerts with reduced latencies and improved accuracy, achieving a 62% improvement in lead times in simulations of significant events, such as the Sept 19th 2022 Michoacán earthquake (Mw 7.7).

The EEW network supports both public safety and business continuity by delivering timely alerts and contributing valuable seismic data for research. The regional network prioritizes high-risk areas such as Oaxaca, Guerrero, and Michoacán, while the local network focuses on densely populated zones like Mexico City and the State of Mexico.

Furthermore, the system's planned expansion to Baja California includes hybrid stations enabling geotechnical and seismic studies, such as base noise analysis and seismic profiling. These advancements highlight the importance of interdisciplinary collaboration to improve EEW coverage, accuracy, and adoption. This approach integrates technological solutions, seismic research, and risk management, establishing a scalable model for global applications.

POSTER 115

Enhancing Earthquake Early Warning with FinDer: Advances in Rapid Finite-source Modeling, Performance Evaluation, and New Features

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The Finite-Fault Rupture Detector (FinDer) algorithm offers a fast and straightforward method for computing finite-source models for earthquakes from seismic data using template matching. These models are essential for providing rapid forecasts of spatial shaking patterns and potential damage in moderate and large earthquakes, which are critical for earthquake early warning (EEW) and response efforts. In this presentation, we will review FinDer's performance within the US West Coast ShakeAlert system, as well as in other installations, during recent large earthquakes, including the M7.0 Cape Mendocino earthquake in Northern California. We will also showcase new developments in FinDer, including accelerated magnitude estimtation using displacement amplitudes, the use of fault-specific templates for large earthquakes, integration with ShakeMaps, and a new EEW Performance Viewer to improve analysis of performance during earthquake sequences.

POSTER 116

Testing DAS-integrated Earthquake Early Warning in Northern California: Design and Implementation

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Distributed Acoustic Sensing (DAS) arrays can expand the coverage of seismic networks and therefore improve real-time earthquake detection and Earthquake Early Warning (EEW). In the current U.S. west coast EEW system ShakeAlert, edge-of-network regions and known active faulting systems of special interest could benefit from additional observation from DAS. For example, when applying DAS to submarine fiber optics cables, it could provide earlier and more accurate detections to improve the EEW system for offshore regions, such as the San Gregorio Fault zone and the Mendocino triple junction in Northern California.

We have developed a DAS-based EEW algorithm designed to fully digest and utilize the dense array nature of DAS. The algorithm includes a machine learning-based seismic phase picking module, a grid-search location module and an empirical magnitude estimation module. By leveraging Graphics Processing Units (GPUs) and parallelization, we optimized the algorithm to meet real-time streaming requirements, achieving comparable data processing speeds to the existing EEW systems. We integrated the algorithms with the point-source EEW algorithm (EPIC), introducing new modules to associate detected events from the DAS arrays with detections from traditional seismic stations, and communicating real-time phase picking information to solve for the earthquake location jointly. We are expecting to run the integrated algorithms in real-time as a parallel version of EPIC in the Monterey Bay region with data from the permanent DAS deployment project SeaFOAM (Seafloor Fiber-Optic Array in Monterey Bay), testing newly added modules and logic for alert issuance. This work serves as a foundation for incorporating potential future DAS arrays into ShakeAlert, to enhance EEW for specific regions.

POSTER 117

Real-time Correction of Ground Motion Amplification for a Rapid Seismic Intensity Reporting System

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The Korea Meteorological Administration (KMA) currently provides near real-time earthquake information based on estimated magnitude. However, magnitude-based warning has led to confusion among the public, as they often misunderstand that a high magnitude earthquake does not necessarily indicate strong shaking. The earthquake early warning and rapid reporting system operated by KMA employ an automatic algorithm to determine the magnitude and hypocenter. The expected intensity is then estimated using empirical ground motion models. However, this two-step process introduces unnecessary delay and uncertainty in the estimated intensity. To address these issues, it is necessary to provide earthquake information and issue localized warnings based on the seismic intensity, which directly measures the strength of ground shaking. Timely provision of earthquake information and warning based on accurate estimation of local seismic intensity requires a real-time streaming based automatic intensity estimation system, accounting for the site amplification in real-time. However, the majority of accelerometers in the KMA network is installed inside a borehole without a collocated surface accelerometer. To estimate the surface ground motion based on the real-time streaming of borehole motion, we developed a a time domain filter approach to correct the real-time streaming of ground motion for the site amplification. In this approach, a site-specific time domain filter response can be easily obtained by inverse-transforming a borehole-surface transfer function after correction to ensure causality. Real-time application of conventional frequency domain transfer function method is not straightforward, but the proposed time domain filtering is straightforward for real time applications, where signals are continuously received, as it does not have constraints of the discrete Fourier transformation. We are planning to validate the proposed method using past earthquake records, and we plan to test the real-time performance by operating a trial real-time seismic intensity reporting system.

POSTER 118

An End-to-end Approach for Earthquake Early Warning Using IoT and Deep Learning

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The primary priority of an earthquake early warning (EEW) system is to detect an earthquake, determine its properties, such as intensity and time of origin, and then send an alert to important locations where vital safety measures need to be taken before the devastating seismic wave arrives. Large-scale EEW systems are currently operational in several countries around the world. Many countries that intend to build systems attribute the decline in fatalities to the large-scale, technologically advanced EEW system. However, deploying such a system on a larger scale has limitations, including communication challenges, response actions, and system deployment and monitoring costs. Due to the high costs of a seismometer, a dense conventional earthquake network is not possible, resulting in a blind zone, an area surrounding the epicenter of an earthquake that cannot be warned before the violent shaking begins. Here, we present low-cost MEMS IoT sensors that have the potential to detect low, moderate, and high earthquake waveforms. Moreover, we take advantage of the advantages of IoT and artificial intelligence and established a dense seismic network that covers the entire Korean peninsula. Furthermore, in real-time, we evaluate our dense seismic network for several low-magnitude earthquakes.

POSTER 120

Mitigating Noise in Real-time GPS Positions to Improve Reliability of Geodetic Magnitude Estimates in the ShakeAlert Earthquake Early Warning System

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The ShakeAlert® earthquake early warning system uses two algorithms based on seismic data to infer source parameters such as magnitude and location from which it calculates expected ground motion at user locations. A third algorithm, GFAST-PGD, is triggered when the seismic algorithms detect an earthquake and estimates magnitude (M_{PGD}) using peak ground displacement (PGD) measured with real-time, high-rate (1 Hz) Global Positioning System (GPS) data. GFAST-PGD calculates M_{PGD} as it receives new positions, but for any given estimate, ≥3 of the contributing GPS stations must have observed PGD meeting an empirical threshold that grows with time due to nonstationary noise (evident as drift or steps in PGD time series). Ideally, PGD thresholds are only met during displacement due to a large earthquake. However using real-time data recorded in the absence of earthquakes large enough to generate GPS-detectable motion, we found that PGD calculated relative to hypothetical earthquake origin times often still exceeds thresholds. When PGD threshold exceedances due to noise coincide with ShakeAlert's detection of a small earthquake, GFAST-PGD could produce spuriously large M_{PGD}. Processing raw GPS data to find an individual station's position requires externally provided real-time satellite orbit and clock correction products. We assess the effect of new products that are lower latency and more frequently updated. By quantifying how often stations in the ShakeAlert network exceed PGD thresholds in the absence of earthquakes before and after switching products, we find fewer exceedances with the new products, reflecting a noise reduction. This improvement may allow lowering PGD thresholds so that GFAST-PGD can contribute to more events, like the December 2024 M7.0 Cape Mendocino earthquake. Although GFAST-PGD did not contribute to ShakeAlert's magnitude estimate for this event because <3 stations met existing PGD thresholds, retrospective analysis shows GFAST-PGD would have yielded a M_{PGD} estimate of ~M6.5 in real-time.

POSTER 121

Real-time GNSS Data in ShakeAlert: Potential Improvements for Subduction Megathrust Earthquakes Through Network Design and Distributed Slip Models

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The ShakeAlert® earthquake early warning system characterizes an earthquake's location, magnitude, and rupture extent with three algorithms and calculates anticipated ground shaking from these source parameters. The EPIC algorithm uses the first few seconds of the P-wave to estimate magnitude but can exhibit magnitude saturation for M7+ events. The FinDer algorithm applies template matching to observed ground acceleration to infer the location, orientation, and length of a line source. The GFAST-PGD algorithm, in use since March 2024, uses peak ground displacement (PGD) measured by real-time Global Navigation Satellite System (GNSS) data to estimate magnitude, assuming the point source location estimated by ShakeAlert's seismic algorithms. GFAST-PGD's inclusion was motivated by its ability to estimate non-saturating magnitudes for very large (e.g., M8+) earthquakes.

I explore the impact of GNSS station distribution on the warning times GFAST-PGD might provide and the potential of distributed slip models derived from real-time GNSS data (rtGNSS DSMs) to improve warning times, both in the context of subduction megathrust earthquakes. For the former I develop a method to rank existing or potential GNSS station locations based on their ability to improve warning times at population centers where earthquakes of a given magnitude on the slab interface are expected to produce shaking of a chosen intensity. The method accounts for the minimum number of stations required by GFAST-PGD and additional criteria for observed PGD that ShakeAlert uses to mitigate the effect of noisy data. Separately, I explore the impact of rtGNSS DSMs obtained with the BEFORES algorithm in a simulated ShakeAlert implementation. Ground motion calculated from the time-evolving slip models can enable longer warning times for locations experiencing MMI 6+ shaking. However, depending on the MMI threshold used to determine which locations are alerted, large geographic regions with only weak shaking would likely receive alerts as well. Performance might be improved by reducing BEFORES' assumed subfault size and the depth to which rupture may extend.

POSTER 122

Evaluating the Impact of Earthquake Early Warning Systems on Casualty Reduction: A Global Framework With a Focus on Central America

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Earthquake Early Warning (EEW) systems can provide alerts before strong ground shaking, these systems offer the potential to save lives by allowing individuals to take protective actions or by triggering automated responses. The effectiveness of EEW depends on the timely and accurate issuance of warnings. Despite improvements in EEW algorithms and the installation of denser seismic networks, the full extent of the benefits in terms of risk reduction remains unquantified. We apply a probabilistic framework to quantify the potential benefits of EEW systems in reducing casualties. By evaluating expected warning times, actions taken by individuals upon receiving alerts, and system performance, the framework allows for the estimation of human losses under various EEW scenarios.

The primary focus is on Central America, where EEW has recently been implemented, a region where frequent seismic activity and vulnerable building stocks present significant risks. Preliminary findings indicate that mature EEW systems could lead to a ~10% reduction in average annual fatalities. We also explore strategies to enhance EEW effectiveness in the region, such as densifying the seismic network to increase warning times and evaluating different protective actions (e.g., Drop, Cover, and Hold On vs. evacuation). A cost-benefit analysis demonstrates that the economic advantages of public EEW systems significantly outweigh the associated costs, confirming EEW as a cost-effective mitigation strategy. Further, an approach of evacuation on ground floor leads to significant increase in fatality reduction as compared to DCHO.

While the study focuses on Central America, the framework is adaptable to other seismic regions. We will present key scenarios from around the world, illustrating how EEW systems can optimize casualty reduction in diverse seismic contexts. To ensure global relevance, exposure and vulnerability data from the Global Earthquake Model (GEM) are used, offering a consistent foundation for hazard, exposure, and vulnerability modeling.

POSTER 123

The Value of Distributed Acoustic Sensing for Earthquake Early Warning in Southern California

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Distributed Acoustic Sensing (DAS) instruments, deployed on existing telecommunications fiber optic cables, have emerged as a powerful tool for seismological studies. Their ability to transform long stretches of fiber into dense seismic arrays offers significant observational advantages over traditional seismic stations. Despite substantial advancements in utilizing DAS data for earthquake research, challenges remain in continuous earthquake monitoring and integrating real-time DAS data streams into earthquake early warning (EEW) algorithms.

The extensive fiber-optic infrastructure in Southern California presents a promising opportunity to enhance current EEW capabilities. Offshore cables landing in Los Angeles, in particular, provide an ideal testbed to explore the transformative potential of DAS for EEW. Using simulated waveforms from a hypothetical M7.05 event along a known offshore fault, we evaluate EEW performance through two tests: one using data exclusively from ShakeAlert stations and another combining station data with simulated DAS data from an existing offshore cable connecting Los Angeles to San Diego.

Our results indicate that incorporating offshore DAS observations into the finite-fault EEW FinDer algorithm could increase warning time and improve magnitude estimation accuracy compared to station-only data. We also highlight critical steps for integrating DAS into operational EEW networks, such as assessing the impact of phase clipping on DAS signals and developing real-time methods to convert strain-rate measurements into along-cable ground accelerations.

These findings underscore the significant potential of DAS to improve EEW systems, particularly in offshore regions where traditional seismic networks are sparse or absent. They also demonstrate how current DAS-specific challenges can be addressed to unlock its full utility in real-time seismic monitoring and early warning applications.

POSTER 124

Evaluating the Effectiveness of Past and Present Seismic Arrays in Detecting Off-shore Earthquakes in Cascadia

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The Cascadia Subduction Zone is known to produce devastating large-magnitude earthquakes. Rapidly detecting and locating offshore megathrust earthquakes can be difficult using current seismic station network geometries. Dense arrays and advanced array processing techniques offer the potential for more accurate locations and earlier detections for both small and large earthquakes. This study evaluates the effectiveness of incorporating small-aperture seismic arrays (<2 km) to improve the accuracy of locating offshore and out-of-network events. It focuses on data from earlier array experiments and a new array near Forks, installed specifically for this purpose. Using modern FK-based array processing techniques, we evaluate the potential improvements arrays can bring to the Pacific Northwest Seismic Network's routine operations and the USGS ShakeAlert earthquake early warning system. Preliminary results indicate that using the arrays helps constrain early initial earthquake locations within 1000 km. Enhancing offshore earthquake detection and location is crucial for effective earthquake early warning in Washington and Oregon, and seismic array methods show significant potential to improve the Pacific Northwest Seismic Network's capabilities.

POSTER 125

Testing Cascadia and San Andreas Fault-specific Finder Templates with the 5 December 2024 M7 Offshore Cape Mendocino Earthquake and Scenario Earthquakes

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FinDer is a finite-source characterization algorithm that estimates the rupture-area, magnitude, and centroid location of an ongoing earthquake by matching interpolated images of observed peak ground acceleration (PGA) to precalculated PGA distribution templates. We test FinDer's performance with Cascadia Subduction Zone (CSZ) and San Andreas Fault (SAF) fault-specific templates and apply code changes that optimize the fault-specific template matching process. The CSZ template set contains more than 18,000 templates. To streamline the template matching process, FinDer limits its search to templates within a specified magnitude range and distance range from the epicenter. Our code has been modified to check templates within a specified distance of the centroid, which can change significantly during a large rupture, instead of the epicenter. The logic for selecting the starting PGA threshold for template matching has also been modified to default to the overall best-fitting PGA threshold from the previous iteration of template matching instead of a per-set threshold. Our suite of test events includes real waveforms from the December 5, 2024 M7 Cape Mendocino earthquake, synthetic seismograms from six simulated M9 earthquake scenarios on the Cascadia fault with varying hypocenters, down-dip rupture extents, slip distributions, and locations of high-stress drop subevents, and three M7.8 SAF earthquake scenarios with different hypocenters. The Cape Mendocino event, located west of the Mendocino Triple Junction, is ideally located for testing performance for a large, but not great, offshore earthquake with onshore ground motions that FinDer could falsely match with one of the CSZ or SAF fault-specific templates. Preliminary results show that constraining the matching process to templates corresponding to ruptures with centroids within a specified distance of the centroid estimate rather than the estimated epicenter and the modifications to the PGA threshold selection logic improve the agreement between matched templates and observed ground motions in the M9 earthquake scenarios.

Predictability of Seismic and Aseismic Slip: From Basic Science to Operational Forecasts

Oral Session • Wednesday 16 April • 4:30 PM Local

Conveners: Jessica Hawthorne, University of Oxford (jessica.hawthorne@earth.ox.ac.uk); Maximilian J. Werner, University of Bristol (max.werner@bristol.ac.uk)

The Time-saturation of Tectonic Tremor With Low-frequency Earthquakes

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The low-frequency earthquakes (LFEs) that make up much or all of tectonic tremor are often interpreted as resulting from the acceleration and then deceleration of slip on isolated portions of the plate interface. This allows one to estimate the moment and duration of individual LFEs, leading to inferences of their magnitude-frequency and moment-duration relations. However, in existing stochastic models of tremor generation, what we call "an LFE" instead represents the superposition of numerous concurrent accelerations and decelerations of slip in distinct locations, as modified by different source-station travel times. Attributes of tremor seismograms from southern Vancouver Island suggest the latter view.

Here we examine inter-event times in an LFE catalog derived in Song & Rubin (2025) by deconvolving continuous tremor records with empirical Green's functions, the latter made from stacks of cataloged LFEs belonging to a single LFE family. Over time windows as large as a few seconds, the catalog contains detections for each consecutive peak in the seismograms, which occur at a rate of approximately 4 per second. This renders it doubtful that each detection represents just a single LFE. Across a 6-fold range of amplitude, tremor often appears to be saturated with LFE arrivals in this way, meaning that on average their temporal separation is no larger than the characteristic LFE duration. Quiet tremor differs from loud tremor most obviously in that the time delay between clustered detections continually increases as tremor amplitude decreases. If saturation is a general characteristic of tremor, it may render LFE magnitude-frequency and moment-duration relations essentially unknowable with existing data. If, in addition, LFEs are drawn from a time-invariant magnitude-frequency distribution, much of the seismic moment is "missing" from the standard tremor passband. While saturation-corrected LFE moment need not violate the geodetic limit, it leaves little room for aseismic slip, which may be incompatible with the mechanical heterogeneity type of LFE models where a large fraction of the fault slips aseismically.

A Unified Fracture Mechanics Model for Fault Slip Throughout the Seismic Cycle: Interseismic Decoupling, Precursory Transients and Earthquake Nucleation

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Laboratory experiments suggest that fault slip evolves in predictable ways prior to frictional instabilities. However, precursory processes on tectonic faults remain enigmatic: how does slip evolve throughout the seismic cycle, and under what conditions are earthquakes preceded by slow transients? Here I introduce a minimal fracture mechanics model to describe fault slip throughout the seismic cycle on heterogeneous faults. Slipping patches are represented as 2-D cracks with propagation controlled by energy balance at the crack tip. In contrast to previous models, this approach explicitly accounts for interseismic loading, and it seamlessly describes the transition from quasi-static interseismic slip to nucleation, thus providing new insights into precursory slip.

I consider two types of heterogeneity: 1. frictional heterogeneity in lithology or normal stress, 2. stress heterogeneity due to non-uniform loading. The early interseismic cycle is characterized by steady migration of creep fronts into regions of decreasing stress or increasing strength. For uniform loading and a low degree of heterogeneity, this is followed by an abrupt transition to earthquake nucleation, without precursors. In contrast, a higher degree of heterogeneity gives rise to an intermediate stage characterized by slow transients, akin to "failed nucleations". I discuss several applications, including fault slip induced by fluid injection; slow slip at the boundary between locked and creeping faults; slow slip driven by the presence of subducted seamounts. In each case, the fracture mechanics criterion defines stress conditions favorable to slow transients, which are confirmed by numerical simulations of rate-state faults. These results indicate that fault heterogeneity can produce diagnostic and predictable changes in interseismic slip behavior throughout the seismic cycle, including precursory slow transients. The emergence of these slip patterns in a minimal fracture mechanics model suggest that they may be rather universal, driven by the stabilizing effect of crack propagation into regions of decreasing stress or increasing strength.

The Search for Time-dependent Coupling Changes in Southern Cascadia

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Estimates of earthquake hazards in subduction zones are heavily dependent on models of interseismic coupling on the megathrust. Recent studies have challenged the long-held assumption that fault coupling on the megathrust remains constant during the interseismic period. In particular, Materna et al. (2019) proposed that dynamically triggered increases and decreases in plate coupling could occur due to regional earthquakes. This study aims to investigate and detect these time-dependent changes in plate interface coupling in southern Cascadia by employing a semi-automated method to reproduce previous findings and explore additional earthquake events. Our analysis focuses on the dynamic stressing from medium to large regional earthquakes in Cascadia and their potential to induce coupling changes on the subduction plate interface, especially updip from the Episodic Tremor and Slip (ETS) zone. We observe localized coupling changes coinciding with the -30km depth contour around 40.3°N and prominently offshore along the -10km contour along the Cascadia margin. These observations suggest potential connections between earthquake-induced stress changes and the geometry of the plate interface. The roles of plate interface geometry and fluid transport from the ETS zones in triggering substantial temporal variations in interseismic coupling are also examined.

A better understanding of when and where dynamically triggered coupling changes occur could improve the accuracy of time-dependent earthquake hazard forecasts in the future. Additionally, we are extending our investigation to Chile to identify if similar phenomena occur in that region as indicated in the past literature. This work will provide valuable insights for future research on the temporal variability of fault coupling and its implications for seismic hazard assessment in subduction zone settings.

Earthquake Predictability, Insight From Dynamical Models of Earthquake Sequences

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The study of induced seismicity shows that spatial and temporal variations of seismicity rate can be predicted well based on the calculation of Coulomb stress changes, informed by reservoir operations and surface deformation measurements, and a nucleation process represented by rate and state friction. Forecasting the timing, location and magnitude of individual events is the next challenge. To investigate possible avenues in that direction, we analyzed the predictability of individual events in dynamical models of earthquake sequences based on rate and state friction. We start with a model designed to reproduce slow earthquakes, which have been shown to result from a chaotic system with deterministic predictability, albeit over a short duration. In such a system, predictability arises from self-organization resulting in spatial correlation of rate and state parameters, hence of stress. This understanding provides in principle an avenue for time-dependent probabilistic forecasting of individual events, although applicability to nature is far from warranted.

Automatic Speech Recognition Predicts Contemporaneous Earthquake Fault Displacement

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Significant progress has been made in probing the state of an earthquake fault by applying machine learning to continuous seismic waveforms. The breakthroughs were originally obtained from laboratory shear experiments and numerical simulations of fault shear, then successfully extended to slow-slipping faults. The elusive step is translating the laboratory analogy to seismogenic stick-slip fault motion associated with earthquakes on active fault systems that produce strong, damaging ground motions. Here we apply the Wav2Vec-2.0 self-supervised framework for automatic speech recognition to continuous seismic signals emanating from a sequence of moderate magnitude earthquakes during the 2018 caldera collapse at the Kīlauea volcano on the island of Hawai'i. This sequence of repeating moderate magnitude earthquakes offers an excellent case study to determine if the advancements developed in the lab are applicable to this tectonic environment. We pre-train the automatic speech recognition Wav2Vec-2.0 model using caldera seismic waveforms and augment the model architecture to predict contemporaneous surface displacement during the caldera collapse sequence, a proxy for fault displacement. We find the model displacement predictions to be excellent. The model is adapted for near-future prediction information and found hints of prediction capability, but the results are not robust. The results demonstrate that earthquake faults emit seismic signatures in a similar manner to laboratory and numerical simulation faults, and artificial intelligence models developed for encoding audio of speech may have important applications in studying active fault zones.

Predictability of Seismic and Aseismic Slip: From Basic Science to Operational Forecasts [Poster]

Poster Session • Wednesday 16 April

Conveners: Edward Field, U.S. Geological Survey (field@usgs.gov); Matt Gerstenberger, GNS Science (m.gerstenberger@gns.cri.nz); Kenny Graham, GNS Science (k.graham@gns.cri.nz); Maximilian Werner, University of Bristol (max.werner@bristol.ac.uk)

POSTER 40

Use of Repeating Earthquakes to Discriminate Slow Earthquakes in the Central Pacific Subduction Zone of Costa Rica

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The complexity and dynamics of subduction zones exhibit a mix of fast (seismic) and slow (aseismic) slip, whose physical interaction strongly influences fault system behavior and can promote the nucleation of potentially catastrophic events. Therefore, understanding how seismic and aseismic processes interact is crucial to improve earthquake hazard assessment. Repeating earthquakes (RE), events with highly similar waveforms and magnitudes that rupture the same fault patch at different times, provide a unique opportunity to advance our understanding of this complex relationship. Using the local seismic network and modern template-matching techniques, we studied 20 RE families, with a total of 430 events ranging from 2010 to 2023, located in the Central Costa Rica Subduction Zone, one of the most seismically active and heterogeneous regions in the country due to the subduction of seamounts and the presence of slow slip events (SSEs) every 22 months or less. We show how the spatiotemporal distribution of RE correlates with the occurrence of large earthquakes ($M > 6.0$) and well-characterized SSE episodes. Additionally, the emergence of localized, uncatalogued SSEs with magnitudes below the detection threshold of GNSS—but observed at the two closest stations—is accompanied by tremors and the continued rupture of an abundant RE family including hundreds of events. The slip rate, calculated from RE assuming constant stress drop, agrees with the previously measured plate convergence rate. Our results suggest that, along with tectonic tremor, RE represents the seismic manifestation of SSEs and could be used as markers to indicate their occurrence, duration, and spatial distribution, especially in areas where GNSS networks are non-existent, lack resolution, or when their magnitude falls below the minimum required for standard identification and localization techniques.

POSTER 41

Synchronization Among Characteristic Earthquakes

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We note that characteristic earthquakes at all scales can exhibit synchronization such that nearby faults repeatedly fail together, but not simultaneously. Synchronization sometimes persisting over many cycles suggests a degree of predictability. Such regularity is remarkable considering that earthquakes are extraordinarily sensitive to the details of the nucleation. What distinguishes earthquakes prone to synchronization from the far more common irregular earthquake occurrence? Characteristic earthquake repeaters in the creeping section of the San Andreas Fault provide a data-rich testing ground to understand the phenomenon. Theory poses the basic, and testable, ingredients for synchronization: proximity, regularity, similarity in size, and the limited external perturbation. Provided that the clock advance is phase dependent, synchronization can be robust to irregularities in earthquake nucleation. Interaction between earthquakes can regularize the earthquake cycle. Measurable characteristics delineate a phase space of synchronization which can be populated using both observations of characteristic repeating earthquakes and numerical simulation.

POSTER 42

Rupture Propagation Dynamics in Branch Fault Systems: A Case Study of the San Andreas–Garlock Fault Junction Applying a Machine Learning Approach

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Determining whether rupture propagates in a branch fault system and in what direction remains a complex geophysical challenge. This process depends on understanding the evolution of critical parameters, such as stress, strength, and friction, across different fault segments and evaluating their influence on rupture behavior. In this study, we apply a machine learning framework to analyze rupture propagation dynamics in a branch fault system, using synthetic earthquake catalog generated by the Rate-State Earthquake Simulator (RSQSim). Focusing on the San Andreas–Garlock fault junction in southern California, we incorporate realistic fault geometries and input parameters derived from the Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3), to build a comprehensive earthquake catalog.

Our dataset includes approximately 9,800 simulated rupture events, which are used to train machine learning models employing gradient boosting and random forest algorithms. These models identify critical parameters influencing rupture propagation and accurately predict the direction of rupture with high precision and recall. Our findings reveal that the nucleation conditions at the fault branch are the most significant factors governing rupture direction. This study highlights the potential of integrating physics-based simulations with machine learning to advance our understanding of complex fault systems and their rupture dynamics, providing a novel methodology for exploring earthquake processes.

POSTER 43

Bayesian Inference of Stress Evolution in Rate-and-state Governed Faults Constrained by Seismicity Rate Observations

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Distinguishing between competing mechanical theories of earthquake nucleation requires advancing our ability to resolve fine-scale temporal variations in stressing rates driving fault slip. An improved characterization of fault stressing rates can be achieved by analyzing the mechanical response to variations in seismicity rates of a representative crustal volume. Two main end-member hypotheses prevail in current earthquake science literature: the pre-slip model which emphasizes slow slip in promoting large ruptures, and the cascade model which relies on stress transfer between earthquakes and does not require a slow slip phase. If pre-slip occurs before earthquakes, it is expected to generate a seismicity rate above background levels before the mainshock, providing a potential indicator for identifying pre-slip processes.

Here we introduce a novel methodology to infer the timing and evolution of slow slip from seismicity rates based on rate-and-state friction law (Heimisson & Segall, 2018). The temporal evolution of stressing rates is modelled as an asymmetric ramp function, selected to capture various fault behaviors: acceleration, steady-state, and deceleration. From the rate-and-state model, we derive an integral form for R/r, the ratio of observed to background rate, and obtain its closed-form expression. Using a Bayesian framework, we estimate probability distributions for model parameters, such as the time and amplitude of shear stressing, frictional-stress parameter, and characteristic time. We can reliably reconstruct stress history from synthetic simulations. Using this framework, we reanalyze the 2008 Mogul seismic swarm near Reno, Nevada, where previous geodetic studies identified significant aseismic slip (Bell et al., 2012). Our model reveals two phases of elevated stress rates above background levels, interpreted as separate slow slip phases: the first from Jan 20 to Apr 18, and the second from Apr 19 to Apr 25. These results suggest that stress evolution before an energetic event can be inferred from seismicity rate observations, providing new insights into earthquake nucleation physics.

POSTER 44

Synergizing Seismo-geodetic Coupling and Slip Models with Optimal Transport and Machine Learning to Determine if Megathrust Earthquake Ruptures are Slip-deficit Controlled

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Geodetic coupling models are a widely recognized tool for evaluating earthquake hazards. Conventionally, megathrusts marked as highly coupled in these distributions are expected to slip in subsequent large earthquakes, while creeping areas are believed to act as barriers to rupture propagation. However, recent studies indicate that creeping faults may host earthquakes, while locked areas could impede ruptures, thereby challenging our current assessments of earthquake hazards. Unfortunately, our seismo-geodetic observational record of subduction interfaces -typically spanning less than twenty years at a single megathrust, a mere fraction of the timescales over which seismic cycles operate - does not allow us to determine whether seismic slip and coupling are linked.

Here we develop an innovative framework that merges optimal transport principles with machine learning, employing the Wasserstein Generative Adversarial Networks algorithm (WGAN). We use this framework to train neural networks on decades-long geodetic coupling distributions, and compute geodetically and physically consistent geometric mappings between megathrusts into a single unifying coupling model. These coupling mappings are then utilized to project coseismic slip across megathrusts, integrating finite slip models from dozens of earthquakes from Chile, Japan, the Himalayas, and other subduction zones into a cohesive space. This approach extends our seismo-geodetic observational record several-fold, enabling us to assess statistical correlations between the unified coupling model and projected seismic slip, and to investigate whether earthquake slip is driven by interseismic slip deficits. This is particularly crucial for regions such as the Cascadia subduction zone, where historical earthquakes are rare, and seismic hazard is assessed based on coupling models.

POSTER 45

Role of Foreshock Sequences in Triggering the 2016 Mw 6.9 Fukushima Mainshock

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Large earthquakes are sometimes preceded by foreshocks, which are regarded as precursory activity of the fault that can potentially inform us of the forthcoming mainshock. However, the physical mechanism behind the seismic triggering process remians elusive. Two end-member triggering mechanisms have been hypothesized, namely the cascade triggering and the aseismic slip triggering model. Here, we perform a comprehensive analysis to investigate the nucleation process of the foreshock sequence before the 2016 Mw 6.9 Fukushima earthquake (22/11/2016 05:59:46 JST) with the goal of determining the possible underlying triggering mechanisms of the mainshock. We first used the Hypoinverse algorithm to relocate earthquakes using the JMA arrival-time catalog and visually picked arrival times of S-net ocean bottom seismometers. Then we applied the Match & Locate method on continuous waveform for small events detection using 7 template events, all occurring within 6 hours before the mainshock. With an improved earthquake catalog, we characterized the spatiotemporal evolution of seismicity patterns. Preliminary results show that the foreshock sequence began with 90 minutes of seismic activity including the largest foreshock of Mw 4.6 (03:25:49 JST), followed by a quiescence period of 40 minutes, and a second burst of seismicity before the mainshock. It does not exhibit an expansion pattern and is concentrated within 10 km SW of the mainshock location, but we observed a weak migration pattern towards the mainshock epicenter just before the mainshock occurred. Based on waveform correlations and rupture diameter, we did not observe repeating earthquakes. The lack of repeating earthquakes and spatial expansion, and the overall spatiotemporal migration patterns towards the mainshock suggest that cascade triggering is responsible for the triggering of the foreshock-mainshock sequence. Our ongoing work focuses on analyzing static Coulomb failure stress changes (ΔCFS) induced by the foreshock sequence to assess the potential of cascade triggering, as ΔCFS larger than 0.01 MPa has been identified as a threshold for this mechanism.

POSTER 46

Sliding and Healing of Frictional Interfaces That Appear Stationary

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Frictional interfaces are found in systems ranging from biological joints to earthquake faults. When and how these interfaces slide is a fundamental problem in geosciences and engineering. It is commonly assumed that there exists a threshold shear force, called static friction, below which the interface is stationary, despite many studies suggesting that this concept is outdated. In contrast, rate-and-state friction (RSF) formulations predict that interfaces are always sliding, but this feature is often considered an artifact that calls for modifications. Here, we show that nominally stationary interfaces subjected to constant shear and normal loads, with a driving force that is significantly below the classically defined static friction where creep is known to occur, are indeed sliding, albeit with diminishingly small rates down to 10^{-12}m/s. Our precise measurements directly at the interface are enabled by Digital Image Correlation. Such behavior contradicts classical models of friction but confirms the prediction of RSF. The diminishing slip rates of nominally stationary interfaces reflect interface healing, which would manifest itself in higher peak friction in subsequent slip events, such as earthquakes and landslides, significantly modifying their nucleation and propagation and hence their hazard.

POSTER 47

Towards an InSAR Catalog of Creep Events on the Imperial Fault

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The Imperial Fault (IF), located in Southern California's Imperial Valley, is one of the fastest partially-creeping faults in California (Field et al., 2015). Deformation models suggest right-lateral slip rates of 20-35 mm/yr, showing the IF poses a significant source of hazard. The IF hosted Mw7.0 and Mw6.5 earthquakes in 1940 and 1979 (Rockwell & Klinger, 2013; King & Thatcher, 1998). Aseismic slip is a frequent mode of seismic moment release on the IF, and can be classified into distinct creep modes: afterslip, triggered slip (in response to teleseismic earthquakes), spontaneous slip, and continuous creep. All four of these modes are present on the IF. Studies show centimeter-scale episodic creep events occur several times a decade (Donnellan et al., 2014; Materna et al., 2024), and the depth of creep is suggested to be about 3-4 km (Lindsey & Fialko, 2016).

To study the time-dependence and kinematics of aseismic slip on the IF, we utilize ten years of Sentinel-1 InSAR data, combined with GNSS and creepmeters, to test kinematic and dynamic models of creep events. Using ISCE, we construct nearest neighbor interferograms and visually inspect each for evidence of fault creep. Using deformation profiles of creep events identified in InSAR, we perform MCMC simulations of dislocation models to constrain depth of creep events and the slip of each dislocation. The scaling between slip and depth can be used to constrain stress drop. By comparing the stress drop to the stressing rate calculated from backslip arguments, a prediction of recurrence time can be developed (Loveless & Meade, 2011). This study will also address the geographical segmentation of creep, temporal correlation, depth of creep events, and scaling relationships between creep event length, depth, duration, and slip. Understanding the kinematics and dynamics of creep events on the IF will help quantify the seismic hazard associated with one of California's most active faults. Such findings have implications for stress transfer on faults in the area (i.e., Brawley Fault) and a more unified understanding of the drivers of slip in Southern California.

POSTER 48

Ultrasonic Probing of Slow Slip Fronts in a M-scale Laboratory Fault

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Strain energy accumulation within Earth's crust provides the fuel for earthquakes. Active acoustic sensing techniques offer the opportunity to continually monitor strain fluctuations, including precursory phenomena and post seismic relaxation surrounding large earthquakes. Currently, it is poorly understood what causes P and S wave travel time and amplitude changes along a fault. We present laboratory experiments where we observe both fast and slow slip, including slow slip fronts that migrate from one end of the sample to the other. The sample consists of a 5 mm thick quartz gouge layer sheared between 760 mm long PMMA forcing blocks. Changes in the gouge layer were monitored with active source acoustics. 4 piezoelectric pulser and receiver pairs were placed incrementally along opposing sides of the fault trace. The fault geometry elevates the normal stress at the fault ends, creating localized unstable mechanical behavior with cumulative shear strain. These unstable regions initiate seismic slip at one end, and then a slow slip front propagates to the other fault end at a speed ranging from 0.1 to 10 m/s. Using the piezoelectric pulser-receiver pairs, we investigate the P and S wave arrival amplitudes as a function of on-fault slip, slip rate and shear stress drop, which all vary along the fault length. Initial results show slow slip fronts create a decrease in the P wave amplitude. Connecting ultrasonic variations with slip behavior along a m-scale laboratory fault is a step toward better discerning fault processes from active seismic methods in the earth.

POSTER 49

How Did the 2016 Mw 7.8 Kaikōura Earthquake Affect the Megathrust Earthquake Potential in the Hikurangi Subduction Zone?

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The 2016 M_w 7.8 Kaikōura Earthquake occurred near the Hikurangi subduction zone (HSZ) and triggered slow slip events (SSEs), but not a megathrust earthquake. Considering the widespread SSEs along the HSZ, it is of interest to understand whether background and triggered aseismic processes may affect the megathrust earthquake potential. In this study, we use numerical simulations to investigate how the Kaikōura earthquake affected ongoing sequences of seismic and aseismic slip events in the HSZ. We use the open-source software *Tandem* to model quasi-dynamic seismic cycles with realistic slab geometry, convergence rate, and velocity structure along several representative profiles across the HSZ with varying degrees of interseismic locking, paleoseismicity, and spatiotemporal distribution of ongoing SSEs. For example, shallow and frequent East Coast SSEs and deep and less frequent Kaimanawa SSEs in northern HSZ are reproduced using depth-dependent normal stress with small asperities of increased pore fluid pressure embedded in a predominantly creeping fault. These seismic cycle models also produce occasional megathrust earthquakes that rupture areas of preceding SSEs. We validate the cycle models by comparing modeled surface displacements with GNSS data and comparing synthetic and data-driven locking models. These data-guided cycle models match the observed characteristics of the SSEs in different margins of HSZ, allowing the exploration of realistic triggering scenarios. We perturb the seismic cycle models using dynamic and static stress changes on the HSZ due to the Kaikōura earthquake calculated from existing dynamic (Ulrich et al., 2019) and kinematic (Inchin et al., 2021) models. The stress perturbation is applied at different stages in the megathrust earthquake cycle, with and without active SSEs. We examine the conditions in which megathrust earthquakes and SSEs are triggered in each profile. This study highlights the role of aseismic activities on the triggering potential of a megathrust earthquake as a response to a nearby crustal earthquake. Tandem Apps are accessible through QuakeWorx Science Gateway.

Recent Advances in Modeling Near-source Ground Motions for Seismic Hazard Applications

Oral Session • Wednesday 16 April • 8:00 AM Local

Conveners: Jeff Bayless, AECOM (jeff.bayless@aecom.com); Nick Gregor, Consultant (nick@ngregor.com); Evan Hirakawa, U.S. Geological Survey (ehirakawa@usgs.gov); Grace Parker, U.S. Geological Survey (gparker@usgs.gov); Badie Rowshandel, California Earthquake Authority (browshandel@calquake.com); Kyle B. Withers, U.S. Geological Survey (kwithers@usgs.gov)

Orientation Dependence of Probabilistic Seismic Hazard Results From Physics-Based Simulations

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Probabilistic seismic hazard analyses (PSHA) currently consider ground motion intensity measures that reduce the variability of horizontal motion into a single value. For example, the U.S. Geological Survey National Seismic Hazard Model uses the median pseudo-spectral acceleration (PSA) of all horizontal orientations, commonly referred to as RotD50. However, ground motion intensities from earthquake records often exhibit significant variation with horizontal orientation, primarily due to physical mechanisms that polarize seismic waves. If these effects are consistent across the earthquakes considered in the analysis, they can introduce a dependence of seismic hazard results on horizontal orientation. This study investigates the dependence of PSHA results on horizontal orientation using outputs from CyberShake Study 22.12, a physics-based PSHA model of Southern California with simulated ground motions from over 600 thousand earthquake scenarios. PSAs were computed at periods from 1 to 10 s and at all possible horizontal orientations directly from the simulated ground motions, bypassing the use of ground motion models typically employed in conventional PSHA. The results reveal that PSAs with a 2% probability of exceedance in 50 years, a standard hazard level used for designing earthquake-resistant structures, can vary significantly with horizontal orientation at several sites, particularly those near active strike-slip faults. For instance, at a period of 5 s, the variation of PSA with horizontal orientation averages around 35% (maximum relative to minimum PSA), with some sites experiencing variations exceeding 100%. Since most structures have mechanical properties that also depend on horizontal orientation, at these sites, the same structure would be subjected to different seismic hazard levels depending on its orientation. These findings suggest that orientation-dependent PSHA could provide more accurate seismic hazard estimates for designing structures with known orientations, especially at sites where the seismic hazard varies considerably with horizontal orientation.

Modeling of Ground-motion Amplitude Saturation at Large Magnitudes and Short Distances

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As part of the NGA-West3 project, ground-motion models (GMM) are being developed for the Fourier amplitude spectra (FAS). Current observational datasets of ground motions are sparsely populated at large magnitudes and short distances, a range that usually governs the seismic hazard for sites close to active faults. To better constrain near-fault shaking effects for the FAS GMMs, we consider multiple approaches to evaluate the near-fault scaling. First, we adopted empirical modeling based on the available sparse data, which is better constrained at distances beyond 50 km from the rupture, a domain in which the dataset is more populated. Second, we performed a series of simulations using the Graves and Pitarka (GP) method for kinematic rupture modeling as implemented in the Broadband Platform (BBP) of SCEC. An initial exploration led us to remove the stochastic scheme of the GP method and extend the deterministic simulations up to frequencies of 10 Hz. We are using the GP method in an experimental range, in which not only are the small-scale heterogeneities in the source more important, but also the wave propagation becomes more complex. Thus, we included a third element to constrain our modeling based on macrointensity data set which includes more observations at short distances from large magnitudes than the ground-motion data sets. We developed an empirical model to convert intensity measures into Fourier amplitudes. The GP simulations show that there is a partial saturation of the ground-motion amplitude at short distances and large magnitudes: for magnitudes above 6.7 and at short distances, the ground-motion amplitude continues increasing, suggesting a scaling of a factor around 1.5 to 2 at high frequencies between earthquakes of M6.7 compared to M7.5. The intensity measure analysis also supports these findings. As the next step, we will develop constraints on the near-fault scaling based on the three approaches for use in the NGA-West3 project.

Ground Motion Variability and Near-fault Amplification: Insights From Modeling of the Central Italy Earthquake Sequences

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This study explores ground motion variability to better understand the complexities introduced by earthquake rupture kinematics. Broadband simulations were conducted using hybrid deterministic and stochastic kinematic rupture models to analyze significant seismic events (M > 6.0) in central Italy, including the 2016 Amatrice Mw 6.2 and 2009 L'Aquila Mw 6.3 earthquakes. These events caused extensive damage and severe ground shaking, with recorded peak ground accelerations (PGAs) reaching 850 cm/s²—significantly exceeding predictions from the Italian Ground-Motion Model (GMM). Observed ground-motion variability has been linked to rupture characteristics such as directivity effects, as revealed by recorded data. Our simulations aimed to evaluate the impact of source rupture models on near-source ground motions and the role of topography in amplifying seismic waves in the most affected regions.

We utilized SW4, a 3D finite-difference code with a conforming curvilinear mesh, to model surface topography with high numerical accuracy. End-to-end simulations were validated against extensive recorded data and regional GMM predictions. Results demonstrated that near-fault amplification patterns strongly correlate with slip distribution, where large slip patches amplify ground motions and increase inter-event variability in Peak Ground Velocity (PGV), surpassing the constant variability assumed in GMMs. Our models successfully reproduced the amplitude and duration of observed near-fault motions, offering valuable insights into the factors influencing ground-motion variability during the earthquake sequences in central Italy. These findings advance the understanding of ground-motion complexities and their implications for seismic hazard assessment.

Developing a Near-fault Non-ergodic Ground Motion Model for the Ridgecrest, CA, Area

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One major obstacle in earthquake research is the lack of near-fault recordings (<10 km). Abundant near-fault recordings could provide important new information about the physics of earthquakes and generation of ground motion at very short distances. In the current ground motion models (GMM), the near-fault motions (and hazards) are extrapolated from the data recorded at moderate and large distances assuming a linear behavior, which is not necessarily correct. However, near-fault seismic motions are crucial for resilience of near-fault structures, as they impose the most severe hazards due to the strongest shaking and possible significant displacement.

Starting at ~8 days following the M7.1 Ridgecrest, CA, earthquake, 15 1D or 2D dense arrays (461 sites) were deployed in the area of the rupture zone, which include four 1D arrays deployed across the surface rupture of the mainshock. The dense arrays recorded continuously for ~30 days and captured numerous aftershocks between magnitude 0 and 5.2. The majority of recordings have epicentral distances smaller than 20 km, with the smallest distance being ~0.1 km, which make it an unprecedented dataset for studying near-fault ground motions. In this work, we first compute FAS and PSA from aftershocks listed in a relocated earthquake catalog, after removing signals from overlapping aftershocks and anthropogenic noise. Next, we combine the dense array ground motion dataset with a regional Ridgecrest ground motion dataset and develop a non-ergodic GMM. Then, we investigate several aspects of the near-fault ground motions that are caused by source, site or path effects. Our current main findings include: 1) much weaker energy radiation at short periods from the shallowest part of the fault zone; 2) significant variations in site responses within the fault zone in both fault-normal and fault-parallel directions; 3) strong amplifications of ground motions within the fault zone by trapped waves and other damage zone waves; 4) evident changes of radiation patterns at short and long periods.

A Slip-based Directivity Model

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It has been demonstrated in various studies (e.g., NGA-W2 Directivity Working Group) that the largest ground motion directivity effect at a site is achieved when the direction of rupture and the direction of slip are both toward the site. Directivity models, such as the ones developed in NGA-W2 project, rely mainly on hypocenter location and direction of rupture to capture the effect. The role of slip, i.e., rake angle and slip size, is commonly disregarded or only minimally or implicitly considered. Acknowledging that the direction and magnitude of slip on a rupturing fault affects directivity at a site, then information such as co-seismic slip distributions on faults can be used to develop models which need not rely on knowledge of hypocenter location and can also be used to enhance and improve "rupture-based" models.

The directivity model developed by the author in the NGA-W2 project, which explicitly includes the direction of slip, i.e., "rake-effect", and which can also incorporate slip size and other slip heterogeneities, such as asperities and creeping zones, has been used for this purpose. In this work, the "slip-based" directivity parameter at a site (X_s) is defined in terms of the magnitude and the direction of slip on neighboring faults with known geometry and slip distribution on sub-faults and the direction and distance of the site relative to the slipping sub-faults. Correlation of X_s with intra-event ground motion residuals of NGA-W2 GMMs for the earthquakes in the NGA-W2 database for which co-seismic slip distributions are available, are investigated and directivity coefficients C are obtained. This combination of directivity parameter and directivity coefficients, i.e., "slip-based directivity model" (after necessary adjustments and tapers), can be used to capture directivity effects when information on hypocenter is minimal; and when applied to intra-event ground motion residuals, to correct for directivity effects, could result in significant reduction of their dispersions, especially for long-period ground motions.

Beyond -1 Geometric Spreading in the Near-field: Insights From Theory and Simulation

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In many subfields of seismology, it is very common for researchers to assume that the rate of geometric spreading for peak shaking follows the canonical -1 slope in log space that follows from the spreading of a body wave in a half-space. However, there is a large body of evidence from ground-motion modeling studies showing that in the real Earth, the true geometric spreading is much larger in the near-field (distances 10 < R < 50 km). This has implications for the modeling of small earthquakes that are well modeled as point sources, such as induced earthquakes. In this work, we seek to develop a theoretical framework to explain these observations. We simulate broadband waveforms from two end-member simple, plane-layered 1D velocity models and show that the rate of geometric spreading for peak shaking metrics, such as peak displacement and peak velocity, is stronger than -1, and varies with earthquake depth. We understand this phenomena in terms of the partitioning of seismic wave energy across layer boundaries that may represent the transition from deeper unweathered crust to shallow weathered rock or sedimentary layering. We also show significant variability in the rate of geometric spreading in our near-field range. Finally, our simulation results indicate that models with a more complicated near-surface structure tend to have steeper geometric spreading; we attribute this to a loss of energy arriving at the surface due to underside reflections from a greater number of layers. Our results strongly underscore the need for the rate of geometric spreading used for downstream applications such as stochastic-deterministic ground motion simulation, stress drop estimation, or the study of site effects, to be established from the data gathered for the region of interest, rather than to be assumed to be -1 a priori.

Physically-based Non-ergodic Event Terms in the 2023 U.S. National Seismic Hazard Research and Development Model

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We create new physics-based spatially varying (non-ergodic) event terms for the research and development model of the U.S. Geological Survey's 2023 National Seismic Hazard Model (NSHM) for the conterminous U.S. The 2023 NSHM is developed by synthesizing the latest science on potential earthquake ruptures and ground motions and using these to make models that are incorporated in public policy documents such as building design codes, risk assessments, insurance rates, and other official applications. For the next several years we will be proposing updated research and development model components. In this application of the research and development model, we explore alternative physical parameters that can reduce event variability and uncertainties across hundreds of thousands of sites in the hazard maps. We compile spatial data on potential physical parameters: crustal temperature, Bouguer gravity, shear wave velocity, stress drops, relative stress, strain rate, fault density, fault misalignment, smoothed seismicity rates, geologic-physiographic provinces, topography, slope, and quality factor to investigate optimal parameters for reducing the event-term variability. Current ground motion models (GMMs) depend on magnitude and the depth to the top of rupture parameter (Z_{TOR}) to estimate event terms. We do not have better size estimates, but we can compare the new potential physical parameters (described above) with Z_{TOR} to assess the potential improvements in the model. Our assessments show that several of these new physical-based spatially varying parameters are better than applying the Z_{TOR} parameter alone in reducing variability. These other spatially varying parameters may be applied in conjunction with Z_{TOR} to reduce regional variability and improve ground motion event terms. However, additions of several new parameters may lead to model overfitting making the model too complex. Therefore, it is important to assess the correlations in these new inputs to provide the most efficient and effective GMMs that allow for incorporation of significant new spatially varying physical data and models to be considered.

Modeling the Rupture Dynamics of Strong Ground Motion (>1 g) in Fault Stepovers

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Following the July 2019 Ridgecrest, California earthquakes, multiple field investigators noted that pebble- to boulder-sized rocks had been displaced from their position in the desert pavement within a stepover along the right-lateral strike-slip M7.1 rupture trace, without evidence of dragging or shearing. This implies localized ground motions in excess of 1 g, in contrast to the instrumentally recorded peak of 0.57 g. Similar rock displacement occurred in a stepover in the predominantly strike-slip 2010 M7.2 El Mayor-Cucapah earthquake. Together, these examples suggest that some aspect of how earthquake rupture negotiates a strike-slip fault stepover produces extremely localized strong ground acceleration. Here, we use the 3D finite element method to investigate how rupture through a variety of strike-slip stepover geometries influences strong ground acceleration. For subshear ruptures, we find that the presence of a stepover in general matters more than its dimensions; the strongest ground acceleration always occurs at the end of the first fault. For supershear ruptures, the stepover is effectively irrelevant, since the strongest particle acceleration occurs at the point of the supershear transition on the first fault. Our model subshear and supershear ruptures alike do produce horizontal particle acceleration above 1 g, but over a region so close to the fault (< 1 km) that a seismic network may not catch it. We suggest that the physics of rupture through a fault stepover could have been responsible for the displaced rocks in the Ridgecrest and El Mayor-Cucapah earthquakes, and that stepover regions may have particularly high ground motion hazard. Our study suggests that ground motion predictions and local hazard assessments should account for much stronger accelerations in the immediate near field of active faults, especially around stepovers and other geometrical discontinuities.

Ground-motion Processing of Near-fault Ground Motions Preserving Forward Directivity and Fling Effects: An Application to the 2022 Chishang, Taiwan, and 2023 Pazarcik, Türkiye Earthquake Sequences

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Near-fault effects, such as forward directivity and residual displacement, significantly influence the seismic demand on structures near active faults. However, the limited empirical dataset poses challenges in deriving models to describe such effects, making it essential to develop ground motion processing tools that are able to preserve these characteristics and can help expand the available dataset. Traditional baseline correction methods, which rely on pre-event noise, often fail to eliminate drifts in the later parts of near-fault ground motions. Similarly, high-pass filtering, commonly used to address drifts, tends to remove low-frequency near-fault characteristics. Since these drifts often result from seismometer tilting, we propose a ground motion processing approach designed to preserve these near-fault effects. Our method extends the bilinear and quadratic correction techniques introduced by Boore (1999, 2000). The key improvement lies in selecting the correction time for linear and quadratic fit based on all components simultaneously, improving the stability of the corrections. We demonstrate the effectiveness of this approach by applying it to ground motions from the 2022 Chishang, Taiwan earthquake sequence and the 2023 Pazarcik, Türkiye event. A comparison with GPS network data demonstrates that the proposed method is able to successfully recover permanent slip in the processed ground motions.

Application and Adaptation of Global Ground Motion Models to the Eastern Caribbean Lesser Antilles

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The Eastern Caribbean Lesser Antilles regions experiences seismicity from shallow crustal earthquakes in active tectonic regions, subduction earthquakes (both interface and intraslab), and volcanic zone earthquakes. A regional study by Bozzoni et al. (2011) has formed the basis for probabilistic seismic hazard analyses (PSHA) in recent years. The ground motion models (GMMs) used in those PSHA studies were published between 1997 and 2008, were originally intended for global or regional (Japan) applications, and were not checked or calibrated using data from the Eastern Caribbean region. As a consequence, there is large and unquantified uncertainty associated with the application of those models to the region.

Our work aims to utilize regional data to test more recent global GMMs, from the NGA-West2 and NGA-Subduction projects, against regional data. We specifically aim to evaluate the effectiveness of the GMMs' source, path, and site relationships for this region. We gathered earthquake catalog data and associated recordings (including recording station properties), processed the ground motions, computed intensity measures (IMs), and developed necessary source, path, and site metadata. We performed mixed effects residuals analyses for shallow crustal events using the Abrahamson et al. (2014), Boore et al. (2014), Campbell and Bozorgnia (2014), and Chiou and Youngs (2014) GMMs and for subduction events using the Kuehn et al. (2020) and Parker et al. (2022) GMMs. The residuals are partitioned into overall bias, event terms, and within-event residuals and examined for trends with source, path, and site terms. Finally, adjustments to the GMM model coefficients and weighting for use in logic trees are recommended for the region.

Recent Advances in Modeling Near-source Ground Motions for Seismic Hazard Applications [Poster]

Poster Session • Wednesday 16 April

Conveners: Jeff Bayless, AECOM (jeff.bayless@aecom.com); Nick Gregor, Consultant (nick@ngregor.com); Evan Hirakawa, U.S. Geological Survey (ehirakawa@usgs.gov); Grace Parker, U.S. Geological Survey (gparker@usgs.

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POSTER 50

Rupture Process and Ground Motion Complexity of the February 6, 2023, Mw 7.8 Kahramanmaraş Earthquake in Türkiye: Insights from Analysis of Deterministic Broad-band Simulations using a Regional 1D Velocity Model

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On February 6, 2023, two of Türkiye's most destructive earthquakes struck the Kahramanmaraş region, causing severe casualties and widespread destruction across south-central Türkiye and northwestern Syria. The first event, an Mw 7.8 earthquake, occurred circa 20 km east of the main strand of the East Anatolian Fault Zone (EAFZ), followed nine hours later by an Mw 7.6 earthquake near the Sürgü-Cardak Fault Zone. These two earthquakes, separated by 90 km and exhibiting comparable magnitudes, generated exceptionally high ground motions, with peak ground accelerations exceeding 1000 cm/s^2 and peak ground velocities surpassing 100 cm/s. The extreme motions, particularly pronounced in Hatay Province near the Amik Basin, caused catastrophic structural failures, including the collapse of modern reinforced concrete buildings. These collapses demonstrated uprooting mechanisms, underscoring the inadequacy of current seismic design codes to address large impulsive near-fault ground motions. The complex rupture processes, characterized by varying velocities, geometries, and time delays across branched fault segments, offer unique insights into rupture dynamics and seismic hazard in the region.

This study examines the rupture process of the Mw 7.8 mainshock using kinematic rupture modeling with the Graves and Pitarka (2016) hybrid-source method and the frequency-wavenumber approach. Simulations, validated against strong-motion data from over 50 stations within 50 km of the fault, capture near-fault ground motions in the 0–3 Hz frequency range and incorporate multi-scale heterogeneity with high-slip patches and stochastic variations. Sensitivity analyses evaluate the effects of key kinematic parameters, such as rupture velocity, rise time, and slip distribution, on ground motion amplification. These findings enhance understanding of rupture dynamics and provide valuable insights for seismic hazard mitigation in tectonically active regions. This framework applies to similar earthquake scenarios worldwide, such as those along the Hayward and Calaveras faults in California.

POSTER 51

Kinematic Source Variability in Ground-motion Simulations and Implications for Seismic Hazard Analysis

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Traditional Probabilistic seismic hazard assesment (PSHA) uses empirical ground-motion models (GMMs) under the ergodic assumption, often overestimating hazard for low-probability events. Simulated ground-motions eliminates the ergodic assumption as they are explicitly site-based and the variability is from variations in source parameters and wave-propagation effects. While physics-based earthquake rupture source characterizations enable efficient rupture scenario generation, understanding the contribution of source parameters to total variability is crucial for their application. In this study, we use a new rupture generator based on a machine-learning method applied to previous rough-fault dynamic rupture simulations to generate a suite of rupture scenarios for a Mw 6.5 strike-slip event. In total, we generate 1080 rupture scenarios with variations in fault length (5 variations), slip realizations (8), hypocenter locations (9) and average rupture velocity (3). We compute broadband seismograms within a 100 x 100 km computational domain in a 1D crustal velocity model at 441 stations (Rjb < 65km) upto a maximum frequency of 7 Hz.

Our results show that while the between-event variability (τ) of the simulations aligns with GMMs, the within-event variability (ϕ) exceeds GMM estimations. Using mixed-effects models, we partition variability across input parameters and azimuths. We observe that in regions of directivity (±45° from fault strike), variations in hypocenter position along strike account for ~90% of τ, independent of spectral period. Conversely, in fault-perpendicular regions, slip and fault length explain ~80% of τ. Hazard computations in terms of probabilities of exceedance reveal under- or overestimations relative to GMMs when using a single fault geometry. Finally, by incorporating fault-length and hypocenter location into a logic tree framework with weighting scheme from the respective empirical models, we compute mean exceedance curves. This study underscores the importance of source parameter variability in reducing bias and improving the reliability of PSHA using physics-based simulations.

POSTER 52

Nonergodic Seismic Hazard Assessment Based on Multi-cycle Earthquake Simulations

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Seismic hazard assessment (SHA) is crucial for mitigating earthquake-related risks, yet, the short duration of recorded seismicity, the sparse distribution of seismic stations, and the paucity of ground motion data for short epicentral distances challenge accurate SHA-estimation. Physics-based simulations offer a pathway of enhancing SHA reliability and to improve estimating epistemic uncertainties. Focusing on the seismically active region of the Gulf of Aqaba, the southern extension of the Dead Sea fault zone, we conduct earthquake-cycle simulations using the MCQsim engine. We run 132 different realisations to address the epistemic uncertainties governing the (a) friction coefficients (μ_s, μ_d, and D_c), (b) spatial connectivity of fault segments, (c) total number of segments, and (d) seismogenic depth. The resulting synthetic seismic catalogues, spanning over 10,000 years and magnitudes $3 \leq M < 7.5$ provide insights into recurrence rates, multi-segment ruptures, and complex source rupture characteristics.

In addition, we introduce a SHA methodology that integrates our simulated rupture scenarios with wave propagation modelling, using a discrete wavenumber method in horizontally layered medium. This approach efficiently models ground motions while incorporating nonergodic effects due to the simulated source characteristics of the synthetic catalogues. We compare our seismic-wave based intensity measures with non-parametric probabilistic estimates from the OpenQuake engine and from stochastic simulations using aspects of our simulated seismic catalogues (a and b-values of magnitude-frequency distribution, aspect ratios and faulting style of ruptures, seismogenic depths). Our results reveal a significant effect of fault-segment connectivity and seismogenic depth on peak ground velocities. We observe that tighter fault-segment continuity enhances the likelihood of multi-segment ruptures, leading to broader areas of higher peak ground velocities. Furthermore, our ability to constrain near-source ground motions using our synthetic ruptures provides critical insights for reliable seismic hazard applications.

POSTER 53

Linear and Nonlinear Site Effects at Several Sites in the Noto-hanto Area in Japan and Its Possible Cause as 2D/3D Deep Basin Resonance

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On January 1, 2024, the Noto-Hanto earthquake of Mw7.6 occurred in the northern part of the Noto Peninsula in Japan. The shaking caused devastating damage to wooden houses in rural cities and towns as well as local roads and expressways in the peninsula. The rupture of the seismogenic fault was extended bilaterally to SSW and NNE directions for about 70 to 80 km from the epicenter. About 20 strong motion stations are operated by NIED and JMA within 60 km of the fault. Before the earthquake, we performed the generalized inversion analysis (GIT) to separate source, path, and linear site terms for both the S-wave portion with the maximum duration of 15 s and the whole duration of motion. The resultant horizontal site amplification factor for the former is named sHSAF, while the latter is wHSAF. Among 20 sites inside the Noto Peninsula, we found three sites with extraordinarily large (80~100 times) sHSAFs and wHSAFs in the frequency range equal to or less than 1 Hz, which we cannot explain by simple 1D structures; we desperately need to model 2D/3D resonance of the deep basins below these sites.

As for the mainshock records, we performed GIT in two steps. The first step is a linear GIT for only far-field records with peak ground acceleration (PGA) less than 200 cm/s^2. From this first step, we determined source and path terms for the mainshock. In the second step, we determined the bed-rock spectra for S-wave portions at the sites with PGA larger than 200 cm/s^2 and calculated nonlinear horizontal site amplification factors, sHSAF_NL and wHSAF_NL as the ratios of observed spectra with respect to the bed-rock spectra at a specific site. We found that the peak frequencies at these sites with extraordinarily large HSAFs were clearly shifted toward the lower frequency side during the mainshock (about 1/2 of the linear one). Still, the peak amplitudes were not so much reduced or even became higher than the linear HSAFs. To account for these peculiar empirical observations, we need to model the deep basin structures and their nonlinear behavior in a quantitative manner as much as we can.

POSTER 54

Modeling Path Effects From 3D Velocity Structure in the San Francisco Bay Area

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We investigate relationships between earthquake ground-motion path effects and 3D velocity variations in the San Francisco Bay Area (SFBA) using residual analysis of ground-motion models (GMMs). GMMs are a key component in probabilistic seismic hazard analysis but can be limited in predictive power due to uncertainties in modeling earthquake source, path, and site effects. Much work has been done to constrain the source and site using known physical properties, while our understanding of effects of 3D crustal properties along unique source-to-site wave propagation paths is limited. Current GMMs use simple physical terms to describe the path (e.g., a distance metric and uniform Q-attenuation) or entirely statistical ones, which can lead to greater uncertainty and inaccurate partitioning of ground-motion effects. We seek to reduce uncertainty in GMM estimates by quantifying more complex 3D effects of crustal properties on ground motions, specifically focusing on S-velocity variations along 3D raypaths.

We test the impact of two 3D velocity models developed using different methods: a smooth model derived using tomographic inversion and a model with sharp velocity contrasts derived using geologic features. We raytrace through both models and compute velocity metrics for each path, including the integral of velocity gradients (dVI) and the derivative of dVI (ddVI). We explore relationships between the velocity metrics and non-ergodic path terms computed using mixed-effects maximum likelihood regression of GMM residuals. The non-ergodic path terms exhibit linear correlations with both dVI and ddVI. We estimate path terms using these simple relationships, and we additionally apply random forest regression to estimate path terms from multi-parameter combinations. Applying the estimated path terms reduces errors in GMM estimates, especially for the multi-parameter model. These findings have the potential to improve modeling complex path effects via a simple model parameter and reduce uncertainty in seismic hazard assessments.

POSTER 55

A Near-source Saturation Model for EAS Based on the NGA-west3 Database

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We develop a model for the near-source saturation of ground motions for shallow crustal earthquakes using the NGA-West3 database of effective amplitude spectra (EAS, the smoothed quadratic mean of two horizontal-component Fourier amplitude spectra). Observations of ground motions show amplitude saturation at the closest source-to-site distances. This is a geometrical effect: at near-fault stations, the relative distance between the closest and farthest portions of the rupture is larger. Large-magnitude earthquakes have larger fault ruptures, and a larger proportion of those ruptures are also farther away from any given near-fault location, causing stronger saturation. Ground-motion models account for this by using a magnitude-dependent modification to the distance metric (here termed h), sometimes referred to as a pseudo-depth term. Most work on this topic has been performed using the distance to the closest point on the rupture surface, R_{Rup}. Here we use the closest distance to the surface projection of the fault, the Joyner Boore distance, R_{JB}. However, no magnitude-dependent models for h compatible with R_{JB} exist. We develop an empirical h model that depends on moment magnitude, M, depth to top of rupture, z_{TOR}, and frequency, f, assuming a geometrical spreading of 1/R and adjusting near-fault data for site response and Q using fits to far-fault data. We parameterize a function of h with M that has a f-dependent breakpoint, with a constant h value for large M above the breakpoint, where z_{TOR} is 0. Below the breakpoint for small magnitudes there is a f- and z_{TOR}-dependent slope. Using a grid-search approach we find parameters that minimize the L1 norm for records with $R_{JB} \leq 10$ km. Our model predicts h values for large M, where $R_{JB} = R_{Rup}$, that are consistent with previous models for response spectra (~15-30 km). However, we find that saturation distances for smaller M depend on f and z_{TOR}, where shallow earthquakes and high frequencies have shorter saturation distances, a previously unmodeled behavior. Overall, our new model fits the data better compared to existing models without these added input parameters.

POSTER 56

Regional Variations in the Site-amplification Variability

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The site-amplification variability in ground motion models (GMMs) has traditionally been estimated as 0.3 ln units. The recent advances in non-ergodic GMMs and the impact of the site-amplification variability on seismic hazard demand a more precise quantification of the site-amplification variability. Recent studies based on borehole array data show that the site-amplification variability is not significantly different from 0.3, with values ranging from 0.3 to 0.35 ln units at different oscillation periods. However, more significant differences are observed when the available global data is split into regional datasets. In this study, we investigate regional variations in the site-amplification variability. We use weak ground motions recorded at 15 borehole array sites in California, 518 sites in Japan, and 30 sites in Taiwan. The site-amplification variability is quantified as the standard deviation of the empirical ratios of the surface-to-borehole ground motion pseudo-spectral acceleration response spectra. Our results indicate that the site-amplification variability in Japan and Taiwan is similar between oscillator periods ranging from 0.5 to 0.9 seconds. However, an increasing discrepancy is observed for longer periods. Meanwhile, the site-amplification variability in California is lower than it is in Japan and Taiwan. This presentation will discuss the differences in the site-response variability, the factors behind the long-period discrepancy, and the impact on forward seismic hazard estimates.

POSTER 57

Quantifying Uncertainties in Earthquake Source Models: Implications of Slip Distribution Variations and Fault Parameters on Ground Motion Studies

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Accurate prediction of ground motion is important for seismic hazard assessments. One important aspect of ground motion prediction is understanding the uncertainties in earthquake source models, particularly those related to the choice of slip distributions and fault parameters. Here, we quantify such uncertainties. Some models assume that the k-square slip distribution will produce the omega-square spectral shape of radiation. This assumption is based on a point-source geometry and an instantaneous fault motion. To test this assumption, we solve the representation integral of elasticity, which allows us to isolate important physical parameters of faulting and their effects on the entire relevant frequency range. By applying a kinematic approach, we can prescribe a finite-fault geometry considering a non-instantaneous fault motion. This approach reveals variations in the slopes of the spectra generated by the k-square slip distributions varying between -6 and -3.5. This contrasts with the expected slope of -2 resulting from the omega- square spectral shape. We produce the same spectral shape independent on the modeled slip distribution (k-square or random). Density plots were used to visualize the slip distributions across the fault plane, revealing heterogeneity and showing fault complexity. The k-square slip distribution proves effective in identifying consistent patterns of amplitude distributions across different frequencies making it valuable for theoretical investigations. In contrast, randomized slip distributions provide a comprehensive range of variations, enhancing our understanding of complex fault behaviors. Furthermore, we explore the effect of hypocenter position on the spectral shape, revealing that variations in hypocenter location significantly influence the frequency content of the seismic waves. Our findings show that the choice of slip distribution model does not constrain the spectral shape outcomes, as both k-square and randomized models yield similar spectral characteristics when accounting for finite-fault geometry and other fault parameters.

POSTER 58

Methods for Evaluating and Improving Rupture Directivity Modeling in Seismic Hazard Assessment

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Recent advancements in modeling near-source effects using more realistic features in simulations of earthquake rupture have led to an improved characterization of ground motions. Specifically, these contributions have led to a better understanding of how hypocenter changes for a specific fault geometry affect the rupture and resulting ground motions. Incorporating these source characteristics and near-fault ground motion behavior may contribute to improved modeling of azimuthally varying effects that include the effects of rupture directivity. One example is the application of machine learning methods to support integration of new predictor variables in rupture directivity model development and to introduce more evaluation approaches to assess residuals. Here, we utilize several techniques leveraging an extensive synthetic database. We showcase two examples of how rupture directivity models can be developed, expanded upon, or constrained using artificial neural network models (ANNs).

One approach uses a set of hypothetical earthquakes with corresponding synthetic ground motions from the Southern California Earthquake Center (SCEC) CyberShake study to develop a ground-motion model adapted to incorporate rupture directivity information using an ANN. This extensive database enables us to train the model to capture magnitude, period, and distance variations of the rupture directivity effects and how these parameters relate to hypocenter locations within the finite faults. In some cases, misfit is reduced by better-representing source features not included in ground motion models that neglect hypocenter location (e.g., azimuthal variation, source-to-site terms). Another ANN model uses a shallow-layered neural network model to fit a hypocenter-independent model better. This method adjusts the median and aleatory variability to account for the averaged impact of various hypocenter distributions to fit the underlying directivity adjustment model. This method is a template for applying to other directivity models, improving computational efficiency and enabling more readily integrated integration in hazard codes.

POSTER 59

Assessment of Site-specific Features in and Around Varanasi City, Uttar Pradesh, India, Using Microtremor Measurements

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We present the spatial distribution map of the seismic vulnerability index (Kg) for Varanasi City and its surroundings in Uttar Pradesh, India. This holy city, located along the Ganga River, has been analysed using the predominant frequency estimated from microtremor data. The seismic vulnerability index is a critical parameter for assessing site response and mitigating the risk of earthquake disasters. It is defined using the Horizontal and Vertical Spectrum Ratio (HVSR) method, also known as Nakamura's technique. Microtremor measurements were conducted at 77 locations within and around Varanasi city. The predominant frequencies obtained range from 0.34 Hz to 0.94 Hz, site amplification varies between 1.96 and 3.88, and the vulnerability index (Kg) spans 4.82 to 39.61. Furthermore, the synthesis of a 1-D velocity model indicates a low shear wave velocity of approximately 291 m/s down to a depth of 30 meters. The primary goal of this study is to determine the dynamic properties of soil response during a potential earthquake in Varanasi. The results will aid seismic microzonation, identify areas prone to liquefaction, and help mitigate risks associated with near-surface site failures during seismic events in and around Varanasi city.

Scientific Machine Learning for Forward and Inverse Wave Equation Problems

Oral Session • Tuesday 15 April • 4:30 PM Local

Conveners: Tariq Alkhalifah, King Abdullah University of Science and Technology (tariq.alkhalifah@kaust.edu.sa); Arash Fathi, ExxonMobil Technology and Engineering (arash.fathi@exxonmobil.com); Lu Lu, Yale University (lu.lu@yale.edu); Kami Mohammadi, University of Utah (kami.mohammadi@utah.edu); Harpreet Sethi, NVIDIA (hasethi@nvidia.com)

Helmholtz Neural Operator for Full Waveform Inversion Tomography of California

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Neural Operators (NOs) are a class of machine learning algorithms to learn the solutions of differential equations. NO models are trained with a large set of forward simulations run on high-performance computing (HPC). A recent study by Zou et al. (2024) described how Helmholtz NOs (HNOs) can simulate seismic waveforms in three-dimensions by considering solutions for a subset of the frequency bandwidth. Importantly, HNOs can be evaluated for new solutions with arbitrary 3D structure and source properties much faster than forward simulations. HNOs can be used to compute sensitivity kernels for full waveform inversion (FWI) by automatic differentiation and provide an alternative to adjoint-state simulations in waveform tomography to infer Earth's seismic wavespeed structure. This study describes work-in-progress exploring the efficacy of HNOs for regional-scale FWI tomography of parts of California. We assembled a data set of broadband waveforms from moderate (MW 4.0-6.0) earthquakes with reported source properties spanning the broad plate boundary (Pacific Ocean to western Nevada; Gulf of California to the Mendocino Triple Junction). Conventional multiscale FWI based on the adjoint-state was performed with Salvus with a simple starting model building on our past experience with tomography of the region. The conventional FWI tomography provides a benchmark for which to compare tomography based on HNOs. Results will be presented with attention on comparison of the efficacy and accuracy of solutions using these different approaches.

Simulating Seismic Wavefields Using Generative Artificial Intelligence

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Simulating realistic seismic wavefields is crucial for a range of seismic tasks, including acquisition designing, imaging, and inversion. Conventional numerical seismic wave simulators are computationally expensive for large 3D models;, and discrepancies between simulated and observed waveforms arise from wave equation selection and input physical parameters such as the subsurface elastic models and the source parameters. To address these challenges, we adopt a data-driven artificial intelligence (AI) approach, and propose a Conditional Generative Modeling (CGM) framework for seismic wave simulation. The novel CGM framework learns complex 3D wave physics and subsurface heterogeneities from the observed data without relying on explicit physics constraints. As a result, trained CGM-based models act as stochastic wave-propagation operators encoded with a local subsurface model defined by training datasets. Given these models, we can simulate multicomponent seismic data for arbitrary acquisition settings within the area of the observation, using source and receiver geometries and source parameters as input conditional variables. In this study, we develop four models within the CGM framework (CGM-GM-1D/3D, CGM-Wave and CGM-FAS), and demonstrate their performance using two seismic data sets: one small low-density data of natural earthquake waveforms from the San Francisco Bay Area, a region with high seismic risks; and one large high-density data from induced seismicity records of the Geysers geothermal field. The CGM framework reproduces the waveforms, the spectra, and the kinematic features of the real observations, demonstrating the ability to generate waveforms for arbitrary source locations, receiver locations, and source parameters. We address key challenges, including data density, acquisition geometry, scaling and generation variability, and outline future directions for advancing the CGM framework in seismic applications and beyond.

Efficient Solutions to the Acoustic Wave Equation Using Extreme Learning Machines With Domain Decomposition

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In this study, we propose a novel approach for solving the acoustic wave equation to model seismic wavefield by leveraging Extreme Learning Machines (ELM) in combination with domain decomposition techniques. Traditional numerical methods, such as finite difference and finite element methods, face computational limitations when handling large-scale data and complex boundary conditions. Physics-Informed Neural Networks (PINNs) have shown promise in addressing these limitations, yet they often struggle with computational cost and scalability. This research seeks to address these challenges by integrating ELM, a neural network model with fixed hidden layer weights and optimized output weights, with local neural networks across subdomains (locELM). This combination allows for efficient and parallelizable solutions, significantly enhancing computational speed and accuracy in seismic wave modeling.

Initial results indicate that our method not only rivals PINNs in accuracy but also reduces computational overhead, making it suitable for large-scale seismic problems. Additionally, the locELM framework incorporates physical continuity constraints across subdomain boundaries, achieving high accuracy in both forward and inverse seismic problems. This approach advances computational geophysics by enabling scalable and rapid seismic simulations, fostering better subsurface imaging and resource exploration. This work contributes to the scientific machine learning community by extending ELM applications to the seismic acoustic equation, an area largely unexplored, thereby highlighting the potential of ELMs in PDE modeling across geophysical and engineering fields.

Keywords: Extreme Learning Machine, Acoustic Wave Equation, Domain Decomposition, Seismic Modeling, Physics-Informed Neural Networks, Computational Geophysics

An End-to-end Physics-based Deep Learning Approach for Robust Seismic Inversion

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Seismic Inversion (SI) enables the estimation of several geophysical properties, such as velocity, a key marker for hydrocarbon exploration, earthquake analysis, and other geophysical tasks. Full Waveform Inversion (FWI) for velocity estimation in SI is computationally demanding, often requiring minutes to process as low as 32 shot gatherers on a 256 × 256 grid. Furthermore, its performance is dependent on a well-fine-tuned initial model, failing which the algorithm may face a cycle-skipping problem. Although techniques such as source encoding improve latency, FWI remains impractical for large datasets. Recently, Deep Learning (DL) has inspired physics-based SI models using unsupervised seismic data or supervised ground-truth data. However, existing DL methods often adapt designs from computer vision for their inverse networks, which are ill-suited for sensor-based inputs of SI. These methods also fail to address cycle skipping because the inverse network remains largely disconnected from the forward PDE process, leading to convergence issues during training.

We propose “SI-KCPNET,” a novel unsupervised method for efficient SI and Ultrasound Computed Tomography (UCT). SI-KCPNET embeds the physics of the second-order acoustic wave PDE into its design via three core modules: a velocity Crude Estimation Module (CEM) for roughly inverting the PDE and refinement using a Squeeze Excitation network, a Pressure Generation Module (PGM) for obtaining dense seismic data by integrating the pressure derivative using a Recurrent NN (RNN), and a Velocity Update Module (VUM) that iteratively refines the CEM estimates using an advanced RNN. The velocity map was processed using a k-t operator-based FD model with perfectly matched boundary layers. Differentiable physics enables end-to-end training, whereas a unique cycle consistency loss term mitigates cycle skipping and improves the convergence. Our unsupervised method outperforms conventional and supervised approaches on simulated UCT data, using only 25% of the training data required by supervised DL methods, and achieves greater computational efficiency than the FWI variants.

Seismic Geotechnical Imaging Using Full-waveform Inversion and Physics-informed Neural Networks

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Large uncertainties in natural geomaterials constrain the practical application of theoretical predictive models in geotechnical engineering. Although geophysical techniques have been employed to reduce the epistemic part of these uncertainties, current methods often rely on sparse surface or borehole measurements and selectively utilize limited data such as first-arrival times. Full-waveform inversion (FWI) techniques provide a comprehensive approach by leveraging entire seismic records; however, their high computational cost and complex formulation have limited their widespread adoption. This study presents a novel approach using Physics-Informed Neural Networks (PINNs) to develop a seismic inversion framework for geotechnical applications that is both robust and computationally efficient. By integrating the underlying physics into the loss function of the optimization process, PINNs enable more accurate subsurface characterization with fewer data points and improve the prediction of responses beyond the range of the training dataset. PINNs can also be used to solve seismic inversion problems by defining unknown *P*- and *S*-wave velocities as trainable parameters. To demonstrate the efficacy of our approach, we focus on the 1-D problem involving site response analysis and geotechnical subsurface characterization. Geometric and material parameters are consolidated into normalized parameters, such as dimensionless frequency and normalized thickness, to enhance the generality of the results. We generate synthetic training datasets using a Finite Volume forward solver for the Navier-Cauchy equation and apply our FWI-PINNs approach to retrieve unknown material properties and wavefield components. Given the rapid advancements in GPU-based machine learning algorithms, coupled with their increasing accessibility and ease of use, we believe our proposed method can evolve into a fast, robust, and practical site characterization tool for the geotechnical engineering community.

Scientific Machine Learning for Forward and Inverse Wave Equation Problems [Poster]

Poster Session • Tuesday 15 April

Conveners: Tariq Alkhalifah, King Abdullah University of Science and Technology (tariq.alkhalifah@kaust.edu.sa); Arash Fathi, ExxonMobil Technology and Engineering (arash.fathi@exxonmobil.com); Lu Lu, Yale University (lu.lu@yale.edu); Kami Mohammadi, University of Utah (kami.mohammadi@utah.edu); Harpreet Sethi, NVIDIA (hasethi@nvidia.com)

POSTER 137

Auto-linear: A Self-supervised Framework for Robust Subsurface Imaging Through Latent Space Correlations

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Subsurface imaging, central to geophysics, involves solving Full-Waveform Inversion (FWI) to predict geophysical properties from measurements. Conventional methods rely on encoder-decoder networks trained with paired data from two domains: geophysical properties and measurements. Building on recent work (InvLINT), we demonstrate that only the linear mapping between latent spaces requires paired data, while the encoder and decoder can be trained independently through self-supervised learning.

This discovery, termed Auto-Linear, reveals that self-learned features from two domains are inherently linearly correlated. The Auto-Linear framework offers key advantages: (a) simultaneous forward and inverse modeling, (b) applicability across diverse subsurface imaging tasks with superior per-

formance, (c) robustness with limited paired data and noisy inputs, and (d) strong generalization across datasets. These findings advance data-driven subsurface imaging and open new avenues for geophysical modeling.

POSTER 138

Extensions for the Reversibility of First-arrival Travel-times using PINNs

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The numerical solution of the Eikonal equation can be used to determine first-arrival travel-times in laterally varying media. However, after caustic formation, the information in first arrivals become increasingly incomplete as the wavefronts fold back on themselves, resulting in a loss of reversibility using just first-arrivals. This can be improved by smoothing the medium which moves caustic formation out to greater distances. It can also be addressed by using full ray-tracing in phase-space which is reversible. Nonetheless, first-arrival front-tracking continues to be popular for many seismological applications. Here we investigate the reversibility of first-arrivals using physics informed neural networks (PINNs) which once trained offer advantages in flexibility and speed in comparison to traditional numerical solutions. The occurrence of caustics, if not too densely occurring, can be identified from discontinuities in slope of the first-arrival fronts at the receivers. Once caustics have formed, reverse wavefront tracking can be thought of as finding a minimum-norm, initial wavefront solution. A general solution can then be obtained using prior information of L/a, the ratio of distance to heterogeneity scale, and heterogeneity strength to find an updated estimate of the initial wavefront while still using first-arrival tracking. Several tests are performed using forward and reverse propagation of corrugated wavefronts in laterally varying media. Further examples are then given of forward and reverse wavefront tracking from variable shaped earthquake faults.

POSTER 139

Methods for Preemptively Optimizing Geophone Array Size for Measurement of Subsurface Volumes using Machine Learning and Synthetic Data From Numerical Simulations

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Background. Acoustic measurement devices, such as geophones, can be used to image subsurface volumes. After acquiring electro-acoustic seismic data, or shot records, from the geophones, the data must be evaluated using computational methods, such as full-waveform inversion (FWI), to reconstruct the data as a usable image (velocity map). Geophone arrays, which can include thousands of sensors, can be very costly both in capital and operational costs. FWI (particularly in 3D) is computationally expensive and the calculation of residual minima is susceptible to error. Synthetik has developed methods to use machine learning (ML) and physics-based computational methods to identify the minimum hardware requirements to sufficiently image a subsurface volume and circumvent the high computational cost of FWI.

Methods. Synthetik uses a custom numerical solver to create 3D shot records from real or synthetic velocity maps. ML models are trained to perform inversion by using the shot records as input and the velocity maps as ground truths. For an initial pilot study, we evaluated a 39m x 39m x 35m deep volume of variable materials. We simulated 25 equidistant impact shots and a receiver array of 40 x 40 using 1m isometric spacing located at the surface. The mean absolute error (MAE) of the ML model trained and tested using the full recording field (all shots and receivers) was used as a baseline for comparing against field reductions. We then tested decreasing the recording field size by reducing each the sources and receivers fed into the ML model for both training and testing. *Abridged Results.* Using a trained ML model to solve for a velocity map from full field electrographic data takes >5 seconds each volume with an average MAE of 1.42 for the full field. Reducing the number of receivers in both the x and y planes by a factor of 2 decreased the MAE by 37%. Alternatively, decreasing the source counts by a factor of 5 decreased the MAE by only 35%. *Conclusion.* Using our methods to identify acceptable levels of accuracy may help reduce measurement and computational requirements, thus reducing imaging time and cost.

POSTER 140

Akinet: A Physics Informed Neural Network for Building a Short-period Global Dispersion Model

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Dispersion measurements from ambient noise correlations are essential for structural imaging at various scales, from reservoirs to continents. However, extracting these measurements requires computationally intensive signal processing of large waveform datasets. Existing neural network methods, such as Disper-Net and DC-Net, focus on time-domain ambient noise correlations but have not addressed frequency-domain cross-spectra, particularly in cases of multi-component seismograms obtained from spatially and temporally discontinuous seismic arrays. We introduce AkiNet, a physics-informed neural network (PINN) designed to estimate phase velocity through waveform fitting using linear combinations of Bessel functions. AkiNet currently employs unsupervised learning to extract phase dispersion from low-quality ambient noise cross-spectra. By incorporating physics, observational data, and prior Earth model constraints, AkiNet enhances global coverage of short-period dispersion measurements while ensuring computational speed, efficiency, and accuracy. In inference mode, AkiNet will act as a generative model, enabling rapid termination of waveform fitting or dispersion modeling, particularly for multi-component cross-spectra. Preliminary results are promising, and ongoing work focuses on benchmarking AkiNet using the Africa-wide ADAMA dataset, optimizing model architecture, different learning methods, and refining regularization strategies. We anticipate that AkiNet will contribute to the development of global dispersion models, improving structural understanding of the Earth's crust and upper mantle lithosphere.

Seismology for the Energy Transition

Oral Session • Wednesday 16 April • 4:30 PM Local

Conveners: Erkan Ay, Shell (Erkan.Ay@shell.com); Hiroshi Hiroshi, National Institute of Advanced Industrial Science and Technology (h.asanuma@aist.go.jp); Lianjie Huang, Los Alamos National Laboratory (ljh@lanl.gov); Yingcai Zheng, University of Houston (yzheng24@central.uh.edu)

De-risking Deep Geothermal Energy Projects: The Deep and GeoTwins Approach

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Enhanced Geothermal Systems (EGS), unlike conventional hydrothermal geothermal systems, exploit geothermal resources through hydraulic stimulation that improves the permeability of the reservoir to create a heat exchanger. Induced seismicity is, in EGS projects, not an undesired by-product but a necessary tool. The art of successful EGS stimulation lies in creating an economically viable heat exchanger in the deep underground while avoiding larger and potentially damaging earthquakes. Especially in urbanised areas, deep geothermal resources can only be exploited using EGS technology if induced seismicity is adequately managed and controlled. This talk will review the progress made in induced seismicity monitoring, forecasting, and mitigation strategies, showcasing the results of the ECfunded projects DEEP and GeoTwins (www.deepgeothermal.org) that demonstrated innovative induced seismicity monitoring and forecasting approaches combining conventional sensors, DAS and Deep Learning approaches. Our current aim is to build up digital twins of deep geothermal systems for reservoir optimisation, de-risking and risk mitigation. We show applications from the Utah FORGE site as well as the BedrettoLab in Switzerland, and an outlook to upcoming project and next frontiers.

Fiber Optic Seismic Vector, Acoustic, Pressure, Strain and Temperature Sensor Combinations Are Setting New Standards for Geothermal, CCUS, and UGS Reservoir Characterization and Monitoring

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Paulsson is inventing, designing, manufacturing, installing and operating large optical arrays with multiple sensors for the surveying and monitoring of Geothermal Reservoirs, Carbon Capture Utilization and Storage, Underground Gas Storage (UGS), including Hydrogen, and Natural Gas and Hydrogen Pipeline Monitoring. The pipelines we are monitoring include two pipelines that are crossing two major California faults, the Hayward Fault and the Calaveras Fault, a side fault to the San Andreas Fault. The Hayward Fault is now considered the most dangerous fault in North America capable of generating a M7-7.5 earthquake – besides having a constant creep of 1 mm per year which we captured with our fiber optic strain system. The Hayward Fault is dangerous because it is crossing 12 cities in the San Francisco East Bay. These projects are ongoing.

Our Fiber Optic Vector sensors have been tested at 320°C (608°F) for a week. Our 3C seismic vector sensor design can be extended to an operational temperature of 500°C by using metal coated fiber. Our Enhanced Distributed Acoustic Sensors (EDAS) have been installed together with our Distributed Temperature Sensors for the monitoring of an Underground Gas Storage (UGS) for a period of over three years, since 2021. We have recorded over 800 TB of data monitoring wells continuously, with real time processing, at the PG&E McDonald Island using 2,500 optical acoustic sensors and 1,800 optical temperature sensors installed to a depth of 5,500 ft. This project is also ongoing.

Paulsson has performed the largest 3D VSP surveys in the world using our pipe-based deployment system that allows our sensor arrays to be deployed into both vertical and horizontal wells to drilled depths of 23,000 ft. We have recorded over 70 Massive 3D VSP surveys with our sensor systems.

In addition to the instrument manufacturing and installation Paulsson is also processing, imaging and interpreting the optical sensor data. A 3D VSP typically records 5-10X higher frequencies compared with surface seismic and is producing accurate velocity and anisotropic models.

Our work has been funded by DOE, DOT and CEC.

Towards Thermo-hydro-mechanical Constitutive Models for Deep Geothermal Reservoirs: Experiments on Thermal Cracking Under Stress With Near-field Acoustic Sensing

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Deep geothermal heat mining at temperatures high enough for supercritical fluid extraction may become a significant source of carbon-free power generation. Thermal cracking may play an important role in the evolution of fracture networks that determine heat transfer and permeability in such reservoirs. During hydraulic stimulation, thermal cracking may couple strongly with hydraulic and background tectonic stresses to influence evolving fracture network characteristics.To better understand these couplings, we perform tri-axial laboratory experiments at 10 MPa, to produce thermal cracking in Westerly granite. We control stress buildup by ramping up temperature in stages under different mechanical boundary conditions. In some experiments, we lock the piston so that differential stress builds as the sample thermally expands, to reach failure that produces a rupture traversing the sample. We record continuous near-field acoustic data using novel high-temperature piezoelectric sensors stable up to about 500 C. Using the standard triggering method for detecting acoustic emissions (AEs), we find on the order of a hundred AEs per experiment. We then analyze continuous waveforms first using STA/LTA to build a catalog of template waveforms, and then perform matched filtering, which can detect tens of thousands of events, mostly below the noise level. Temporal clustering statistics identify multiple populations of events with burst-like and with random behavior. Finally, we perform unsupervised feature extraction (using SpecUFEx and hierarchical clustering) to discover temporal patterns in the spectral content of the signals, that evolve with increasing stress and temperature, providing potentially useful signatures of an evolving fracture network. As temperature increases towards and into brittle-ductile conditions, it is expected that the mean crack length scale decreases towards the grain scale, influenced by increasingly weak grain boundaries. Dense networks of grain-scale fractures may be essential for engineering geothermal reservoirs deep in the crust, potentially in conditions of brittle-ductile transitions.

Detectability of a CO2 Well Leakage using Amplitudes of Ambient Seismic Signals on DAS

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Well leakage is commonly recognized as one of the major environmental risks for Geological Carbon Storage (GCS). Previously, these concerns relied on abstract risk analysis and experience from underground gas storage. However, recently the Archer Daniels Midland CO2 storage site (ADM) reported a CO2 leakage through the corroded casing of a monitoring well, which extent remains highly uncertain. We present a novel monitoring technique for a well leakage, which detects the presence of CO2 using amplitudes of ambient seismic signals recorded by distributed acoustic sensors (DAS) cemented in the borehole annulus.

First, we describe a scattering-based approach to modeling the DAS amplitudes due to a small plume of supercritical CO2 around a leaky well. We validate the approach using earthquake signals and ocean-generated microseisms recorded in the injection well for CO2CRC Otway Project (Australia). Finally, we evaluate the feasibility of CO2 leakage detection in geological settings representing the ADM project site. Our results suggest that DAS amplitudes of ambient seismic wavefields could be a powerful tool for early leakage detection. They also may quantify the leakages if incidents occurred anyway.

Learning Permeability from Acoustic Emission with Distributed Acoustic Sensing

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The shallow crust holds essential natural resources, including water, energy storage or extraction reservoirs, and mineral deposits, making it essential to understand how fluids flow through near surface geologic formations. Rock permeability is a very important property because it measures the capacity and ability of the formation to transmit fluids and controls the directional movement and flow rate of reservoir fluids in the formation. Establishing reliable permeability estimates of subsurface fractured rock is remarkably challenging when considering the heterogeneous variations in rock composition, subsurface stress conditions, and the spatial variations of a fracture network through a large volume of bulk material. However, if the fluid flow rate can be reasonably approximated and the pressure differential in a system can be estimated using passive surface measurements, then the bulk permeability is obtainable with a few assumptions. These types of remote measurements to reliably estimate permeability are needed to optimize the production of natural resources that rely on knowing the hydraulic properties that control fluid flow and transport in rock formations.

Distributed Acoustic Sensing (DAS) technology is proven capable of capturing fracture displacements in boreholes with the potential to map the surrounding fracture networks. In this work, a laboratory experiment was designed to test the how well acoustic emission recorded with DAS sensors can be utilized to determine the flow characteristics. The experiment is comprised of a spherical bead pack in a pipe with fluid injected at one end and collected at the other. Optical fiber is wrapped around the pipe and is interrogated with a DAS instrument. Input and output pressure and flow velocity are measured so that permeability can be calculated directly. The results show consistent scaling characteristics that correspond well to the pressure drop across the porous media. Additionally, a machine learning model is developed that is capable of inputting features derived from the continuous noise and outputting an estimate of the bulk permeability.

Seismology for the Energy Transition [Poster]

Poster Session • Wednesday 16 April

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POSTER 127

Ambient Noise Tomography for Natural Hydrogen Exploration: A Case Study From the Gawler Craton, South Australia

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Natural hydrogen, also known as geologic or gold hydrogen, is rapidly gaining attention as a potentially inexpensive, clean, and renewable energy source for the future. However, standardized methods for exploring natural hydrogen are still lacking. Traditional exploration techniques used in sedimentary basins do not directly apply to natural hydrogen detection, which is often associated with non-sedimentary cratonic settings.

This study focuses on a 2,500 km2 area within the natural hydrogen exploration license (PEL 691) held by H2EX Ltd., located in the eastern Eyre Peninsula, South Australia. In 2024, two separate nodal arrays, each operating for one month, were deployed in this region, which overlies the Gawler Craton. A regional passive-seismic survey with 150 sensors achieved an average station spacing of 3-4 km, followed by an infill survey with 100 sensors targeting fault zones, that refined inter-station spacing to 1-1.5 km in these critical areas. An adaptive irregular grid tomography method based on the Poisson-Voronoi approach was developed to integrate these datasets. This technique enables multi-scale structural resolution while maintaining coverage in sparsely sampled areas, as confirmed through comprehensive tests. The resulting velocity model provides detailed structural insights from the surface down to a depth of 15 km, revealing features related to major fault zones, crystalline basement architectures, and sedimentary basins. These structures will be evaluated for their potential roles as migration pathways and storage sites for natural hydrogen. Our findings will advance exploration methods for natural hydrogen in complex geological settings.

POSTER 128

Improving Event Depth Constraint of a Local-scale Surface Seismic Network With Downhole DAS

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In recent years, distributed acoustic sensing (DAS) has garnered significant interest from the induced seismic monitoring community due to the potential for simultaneous improvements in earthquake monitoring, subsurface imaging, and reservoir characterization. Despite this interest, the practicality of using DAS as a means of real-time induced seismic monitoring remains unproven due to the large data volumes generated by DAS and the cost of providing adequate azimuthal coverage of the study area with downhole DAS alone. We propose an alternate approach wherein a real-time surface network of traditional wideband seismometers is enhanced by downhole DAS observations, providing dependable and efficient microseismic monitoring with improved depth constraint. First, we demonstrate that a targeted array of 9 surface stations with approximately 2 km spacing and pertinent noise-reduction techniques can sufficiently capture induced microseismicity to the extent that is required by governmental regulations. Next, we preprocess snippets of DAS data obtained from the lateral section of an injection well at 2 km depth for 114 microseismic events detected by the surface network during a one-week period of hydraulic fracturing. Leveraging the neural network model PhaseNet DAS (Zhu et al., 2023), we then generate P and S arrivals on all channels. To prevent these DAS observations from dominating relocations, we calculate average arrival times for different sections of the cable before relocating the events with NonLinLoc (Lomax et al., 2000) using both DAS and surface network observations as inputs. Comparing the resulting relocations to the original catalog, we find significant reductions in vertical uncertainty. Depth constraint is critical in the analysis of fracture networks and often seen as a weakness of surface networks. As a result, these results demonstrate the utility of a single downhole DAS cable when used in tandem with a robust surface array. Future developments of this workflow will explore potential improvements to cable orientation and the pre-trained model used in PhaseNet DAS.

POSTER 129

DAS-recorded Microseismic Monitoring in Geothermal Field Stimulation With Waveform Imaging and Deep Learning

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Enhanced Geothermal Systems (EGS) have the potential to provide clean energy on a large scale by amplifying the permeability of basement rocks through fracture stimulation. Accurate mapping of the stimulated fracture network is essential to optimize EGS efficiency. Microseismic events generated by the rupture of fractures provide the most reliable information for this purpose. The advent of distributed acoustic sensing (DAS) using fiber optic cables enables high-resolution recording of microseismic signals with improved signal-to-noise ratios. This advancement enhances the ability to map the finer details of fracture networks, necessitating the development of new algorithms to leverage the data provided by DAS technology. In this study, I propose a methodology to detect and locate microseismic events recorded by three DAS fibers installed in wells at a geothermal project near the FORGE site. The wells and corresponding fibers have varying geometries: horizontal, vertical, and deviated.

The proposed methodology combines waveform seismic imaging with deep learning to detect and locate seismic events. Sequential time-lapse images of potential microseismic sources are generated, and a deep convolutional neural network is trained to classify these images as containing a source or not. If a source is detected, another neural network determines its location and timing. This approach offers higher sensitivity by amplifying the seismic signal relative to background noise during imaging. Additionally, DAS-specific noise is attenuated, resulting in an improved signal-to-noise ratio and enhanced detectability. The imaging process produces point-like representations of sources at the time of microseismic triggering, facilitating accurate estimation of source location and time. The results demonstrate that the trained neural networks efficiently interpret these images, delivering reliable and precise source estimates. Overall, the methodology proves to be both robust and successful, highlighting its potential for advancing microseismic event detection and location in EGS applications.

POSTER 130

The Problem of Uncontrolled Impacts on Natural Spheres

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In the previous 200 years, various degrees of disruption of natural processes caused by human activity were observed. In the so-called Pre-Industrial Period (before 1900), it was noted already that even weak impacts done hundreds of kilometers away affect the reaction of the geological environment, as demonstrated Shamakhi earthquakes in Azerbaijan. The earthquake in 09.08.1828 with a magnitude of M=5.7 followed the start of the oil producing in Absheron (50 km away from Shamakhi), in 11.06.1859 with M=5.9 followed their production intensification using oil rigs (20 000 tons per year) and in 28.01.1872 with M=5.7 occurred after the use of boreholes, which increased production to 100 000 of tons of oil per year! These coincidences are not accidental: in the previous 160 years, similar events were not observed. The so-called Industrial Period (1900-1950) was characterized by significant technological achievements, but did not cause much changes in the geological environment state.

Whereas during the period of Nuclear Explosions (1945-1992) in the atmosphere and then in the lithosphere, a surge of natural disasters (earthquakes, tectonic and volcanic activity, marine and atmospheric phenomena) occurred in a jumpy manner, which initiated disruptions in the energy exchange of the planet with its external environment - Space. Much more undesirable effects were accompanied by the start (1994) of the HAARP and colliders systems using, caused a continuously increasing the degradation of the ecological state of all natural spheres. As we first established, this led to an extremely dangerous tendency for the emergence of a certain higher-temperature region appearing on the Sun surface and to increase the flow of solar radiation falling on the Earth, which gradually began to take on a dangerous character. However, today the most threatening are the plans widely advertised by most countries of the world, the so-called "solar energy", without suspecting how much this process could be unpredictable for the life of the planet. In some case this process can take on a dangerous character.

POSTER 131

Find the Fluid: Using Cutting Edge-sensing to Track Geothermal Fluid and Gas Migration Underneath Sulfur Springs in the Valles Caldera

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Monitoring geologic leakage from pressurized subsurface reservoirs critical to the energy transition and climate mitigation remains a difficult task. Here, we present the outline and initial results of a project starting in 2025 with the goal of using three-dimensional Distributed Acoustic Sensing (DAS) array combined with Match Field Processing (MFP) to directly locate pressurized fracture flow that could indicate geologic leakage within test bed located in the Valles Caldera. We will use three-dimensional finite-element wavefield modelling to determine the optimal borehole and surface fiber array configuration and MFP workflow for detection of low SNR sources. Using these results, we will conduct an optimized field demonstration in a natural geothermal field in the Valles Caldera where pressurized near-surface fluid and gas migration through fractures is inferred from surface features. Because other sources of seismicity are limited, detected sources can be inferred related to fluid or gas migration and will be used to map near-surface flow pathways. Finally, we will use unsupervised learning to cluster the detected signals based on frequency content and use these properties to understand how fluid migration changes along detected flow pathways.

POSTER 132

Denoising Seismic Migration Images Using ConvNeXt-style Neural Networks

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The interpretation of seismic migration images is essential for fault and reservoir characterization in geological carbon storage and geothermal projects. However, migration images often contain random and migration-related image noise that is difficult and time-consuming to remove. Data-driven approaches, such as supervised training of convolutional neural networks (CNNs), have shown promising results but require large amounts of training data. Vision transformers (VTs) have also demonstrated comparable or superior performance to CNNs for computer vision tasks, though they require more data and longer training times because of their lack of implicit bias compared to CNNs. To address these challenges, we generate realistic synthetic seismic migration volumes that include random and migration-related noise. We use these images to train a ConvNeXt-style neural network, which incorporates modern, efficient VT-inspired convolutional blocks, improving both accuracy and training/inferencing speed. On migration images of field seismic data, we show that this ConvNeXt-style architecture outperforms traditional CNNs and VT networks with limited training data while maintaining the accuracy of VTs.

POSTER 133

Utah FORGE 2024 Stimulations: Improvement of Surface-based Microseismic Mapping of Fracture Zones via Nodal Geophone Patches

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The Utah Frontier Observatory for Research in Geothermal Energy (FORGE), the U.S. Department of Energy's field-scale enhanced geothermal system (EGS) laboratory, offers the unique opportunity to tackle research questions regarding techniques and strategies needed to develop economically viable EGS. Monitoring microseismic activity induced by the subsurface operation is crucial for the safe application of EGS. While deep borehole instrumentations (>1000m) can deliver very low detection thresholds, the installation is expensive. During the latest stimulation experiments at Utah FORGE in April 2024, we tested a cost-efficient way of improving the microseismic monitoring from the surface by deploying geophone patches in a radius of about 2km around the Utah FORGE site. The patches comprised nine colocated nodal geophones whose records were stacked for noise suppression. The stacked waveforms have similar or superior signal-to-noise ratios compared to permanently installed sensors at the surface or in shallow boreholes (~30m). Based on the enhanced temporary data from the nodal patches and the permanent stations at the surface, we successfully mapped the development of two isolated main fracture zones during the simulations in great detail. These two zones constitute efficient pathways for fluid to circulate between the injector and the producer. Spatial offsets between sealed-off injection intervals and the mapped microseismicity in the later part of the stimulations suggest that more complex interactions within the rock and aseismic process play an important role in the reservoir dynamics.

POSTER 134

Shear Wave Velocity Structure and Moho Depth Beneath the Virginia Coastal Plain (VCP) From Fundamental-mode Rayleigh-wave Group-velocity Measurements

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Deep fluid injections into the basement rock can alter its effective stress field (ss), leading to injection-induced seismic activity in the region. Monitoring induced seismicity requires a velocity model of the affected region. Given this, we investigate the crustal shear-velocity structure and estimate the Moho depth beneath the Virginia Coastal Plain (VCP) in southeastern Virginia by utilizing the fundamental-mode Rayleigh-wave group velocity and shear-wave velocity inversion. The seismic dataset is compiled using five-stations of the Hampton Roads Seismic Network (HRSN) operated by Virginia Tech between April 2022 and February 2024. We measure Rayleigh-wave group velocities of the vertical (Z-component) seismograms at periods of 6–50 s from five regional earthquakes with magnitudes between M_w 5.1 and M_w 6.2 respectively. The fundamental-mode Rayleigh-wave group velocities vary from 2.9 km/s at 6s to 3.8 km/s for 50 s period. Next, we invert these Rayleigh-wave group velocities to obtain an average 1-D shear-wave velocity-depth profile below all the five seismic stations in the array. The final resultant shear wave velocity model is a six-layer velocity model with the upper crustal velocity of 3.2 km/s, which gradually increases to 4.0 km/s for the crust-mantle boundary. The Moho depth from 1-D shear wave velocity inversion is estimated to be around ~ 35.0 km beneath the Virginia Coastal Plain.

POSTER 135

A Novel Passive Source Basin Scale Seismic Monitoring Approach of Carbon Storage Sites

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Large-scale geologic carbon storage (GCS) requires affordable geophysical tools for imaging and monitoring of subsurface CO2 plumes. Compared with active seismic methods, passive seismic surveys are low-cost but need enhanced resolution and event location precision. An improved passive seismic method and a high-resolution basin-scale earth model are crucial for cost-effective monitoring carbon storage. We will explore and test a novel passive seismic approach for basin scale GCS monitoring. This approach will also benefit source characterization by providing improved basin-scale earth models. Our technique uses adjoint waveform tomography, leveraging the long-lasting amplified seismic waves in the basin to passively image carbon plumes. The longer time windows selected for the adjoint waveform inversion contain information about the reverberating waves passing through the carbon plume, enabling high-resolution imaging of the carbon plume using only a few natural earthquakes. Our preliminary adjoint waveform tomography in Alaska's Nenana Basin, utilizing one seismic event and a single iteration, shows that shear wave sensitivity is significantly enhanced in the basin. This approach is expected to fill a critical technology gap in GCS monitoring, utilizing open source automated seismic adjoint tomography tool and data from existing CO2 storage sites.

POSTER 136

Using Machine Learning to Enhance Microseismicity Monitoring and Support Carbon Storage Initiatives in Oklahoma

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Induced seismicity in the southern midcontinent, primarily driven by human activities such as hydraulic fracturing and wastewater injection, presents significant challenges for monitoring due to the low signal-to-noise ratios of small-magnitude events. These conditions pose unique challenges to traditional analysis and detection efforts. To address this issue, we leveraged advanced machine learning techniques to enhance detection capabilities and improve seismic monitoring systems.

Using the PhaseNet framework, we adapted transfer learning to train models on a comprehensive, manually annotated dataset focused on microseismicity from Oklahoma and nearby regions. By applying fine-tuning and targeted preprocessing techniques, we demonstrated the effectiveness of this approach in detecting low-magnitude events. This work highlights the potential of transfer learning to better illuminate the complexities of anthropogenic seismicity.

We plan to publicly release this dataset, which spans from 2010 to 2024 and includes approximately 1.06 million traces of manually annotated seismic events. The dataset is predominantly events of magnitudes between 1 and 3 and depths ranging from 4 to 8 km. This makes it an ideal resource for microseismic research, benchmarking, and the development of advanced tools to support.

Looking forward, we aim to apply this machine learning-driven approach to support future carbon storage initiatives in Oklahoma. Effective microseismic detection and monitoring are critical for ensuring the safety and effectiveness of carbon sequestration efforts. Furthermore, this approach holds significant potential for monitoring other anthropogenic seismic events, advancing risk mitigation strategies, and contributing to the development of technologies needed for the energy transition.

POSTER 137

Seismic Monitoring Analogs for Hydrothermal Processes in Controlled Fracture Networks

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Characterizing and monitoring injection and production in fracture-dominated energy and storage reservoirs (such as for geothermal, hydrogen, carbon, critical minerals, etc) is a key scientific challenge for the energy transition and achieving climate goals. Seismic monitoring tools, especially ambient noise analysis, are one of the chief probes of coupled hydro-thermal-mechanical processes occurring within a volume of rock. The seismic wave features such as velocities and attenuation can capture and encode information about the effective properties of the reservoir, especially changes in the coda waves, which best probe the entire rock mass. However, the quantitative relationships between the fluid flow in a fractured rock volume, the effective transport properties of that volume along with the fluid saturation state, and the associated seismic wave characteristics have not been fully developed. To bridge this gap, we design a new experiment involving seismo-acoustic monitoring of a laboratory-scale hydrothermal flow system within a transparent, 3D-printed fracture network. Utilizing the ability to create controlled analog fracture networks, we inject cold fluids (at a range of inlet pressures/flow rates) into the system and use active acoustics, optical & thermal imagery to assess the seismic signatures of hydro-thermal-mechanical interactions as well as the saturation state of the fracture network. The fracture networks remain nominally static, while the fracture apertures may fluctuate in response to fluid pressure variations influenced by temperature changes. Our results provide both a physical understanding and seismo-acoustic calibration to monitor the interaction between hydrothermal flow and fracture networks during fluid circulation for the field seismic monitoring. These results will also serve as baselines for future studies on the brittle-ductile transition in analog fractured reservoirs.

Station Installations and Site Conditions, a Quest for Improved Strong Motion Database

Oral Session • Wednesday 16 April • 2:00 PM Local

Conveners: Fabrice Hollender, CEA Cadarache (fabrice.hollender@cea.fr); Vincent Perron, CEA Cadarache (vincent.perron@cea.fr); Zafeiria Roumelioti, University of Patras (zroumelioti@upatras.gr); Paola Traversa, Electricity of France (paola.traversa@edf.fr)

The Origin of Unusually High Earthquake Strong Motion Recordings at Three California Stations

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It is typically assumed that if a free-field strong motion station is properly installed on a concrete pad and the S-wave velocity profile including basin depth are measured using an acceptable method, there is enough information to assess response to the strong ground shaking. This work focuses on recordings from three California stations: Tarzana- Cedar Hill Nursery, Parkfield Fault Zone 16 and Carquinez bridge that demonstrate significantly higher earthquake responses compared to the surrounding stations. Shown examples indicate that assessing site amplification using standard methods may not be always adequate.

The Tarzana hill strong-motion station was installed near the crest of a low (< 20m) natural hill with gentle slopes. The hill is about 500m in length by 130m in width. Significantly amplified ground accelerations at the hill station were recorded during several events including 1.9g during the 1994 Mw 6.7 Northridge earthquake. It was suggested that the hill acts as a magnifying polarizing glass: It polarizes ground motion in the direction perpendicular to the strike of the hill and also amplifies ground motions that were also amplified by a low-velocity layer (Graizer, 2009).

A very high acceleration record was obtained at station Fault Zone 16 during the Mw 6.0 Parkfield earthquake of 2004. The accelerograph at Fault Zone 16 is deployed at a soil site in a fiberglass housing. Post earthquake instrument shake-table tests indicate that the recorded acceleration is relatively accurate even at the high accelerations involved in this record. Maximum estimated PGA exceeds 2.2g (Shakal et al., 2006).

The Carquinez Bridge geotechnical array #1 recorded PGA of approximately 1.0g at the ground surface during the Mw 6.0 2014 South Napa earthquake compared to 0.42g at a nearby station. The high-level shaking was attributed to the non-linear effect with a decrease of apparent shear-wave velocity during strong shaking (Kishida et al., 2018). The results showed that the apparent Vs in the upper 20m clearly decreased when the PGA was greater than 0.07g, confirming soil nonlinear behavior due to the strong shaking.

Site-specific Ground Motion Response Analysis for Bridges in Western Tennessee

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The AASHTO LRFD Bridge Design Specifications and the AASHTO Guide Specifications for LRFD Seismic Bridge Design generally provide adequate methods for determining seismic hazards and site response. However, site-specific hazard analyses may be necessary for unique scenarios, such as long-duration earthquakes, critical infrastructure, specific soil types, or near-fault conditions. These analyses can justify reductions in spectral acceleration compared to the uniform seismic hazard values derived from standard procedures, potentially reducing construction costs for bridges.

This study focuses on site-specific ground motion response analysis (SSGMRA) for 32 sites in Western Tennessee. Field tests, including Multi-channel Analysis of Surface Waves (MASW) and Refraction Microtremor (ReMi), were conducted at 12 sites, while data from a prior Tennessee Department of Transportation (TDOT) project was utilized for the remaining locations. Sites were selected based on the locations of existing TDOT bridges, ensuring the availability of at least one borehole dataset per site. To ensure comprehensive spatial coverage of the study area, a maximum Euclidean distance of 20 km between sites was maintained.

The seismic wave data process combines dispersion curves obtained from MASW and ReMi surveys. In some cases, low-frequency ReMi data is combined with MASW measurements to provide deeper subsurface insights. The combined dispersion curves are then inverted to derive detailed shear-wave velocity profiles for each tested site.

This phase of the project focuses on deriving accurate shear-wave velocity profiles through MASW and ReMi data integration, forming the foundation for subsequent phases, such as site response analysis and seismic hazard evaluation.

By incorporating the outcomes of SSGMRA into Geographic Information System (GIS) maps, engineers at TDOT will have access to cost-effective design tools that account for local site conditions, potentially reducing construction costs while enhancing seismic resilience.

Combining Empirical Approaches to Address the Site-specific Seismic Hazard Estimation: Application to Three Populated Cities and an Area of Two Nuclear Facilities in France

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Site-specific Seismic Hazard Estimates (SSHE) is a best practice for specific areas such as critical facilities or populated cities. SSHE involves taking into account the specific characteristics and seismic response behavior of the site under study as accurately as possible. However, assessing the site response over a broad frequency range and with high spatial resolution remains difficult.

We propose here a framework based on empirical approaches to estimate the site response to the spatial and frequency resolution required for SSHE. Our strategy is as follows : 1) Site response assessment for a few long-term stations with respect to the desired reference conditions using generalized GIT inversions on earthquakes. 2) Completion at low frequencies [0.05-1 Hz] by applying standard spectral ratios to the teleseism Coda SSRc. 3) Site response assessment at every station using the hybrid SSRh method on ambient noise.

In the framework of the EMISSER project, we apply it to three populated cities in France (Annecy, Grenoble and Nice) and to an industrial area in the Rhône Valley, home to two major French nuclear facilities. In each of these areas, dozens of earthquakes were recorded at a few long-term stations, and ambient noise was recorded for at least 12 hours at a dense network of dozens of seismic nodes. We report a good agreement between the GIT and SSRc site response estimates, similarly the SSRh method provides a good estimate of the site response obtained from earthquake observations. The strategy we have developed enables a coherent and high-resolution SSHE for sites of particular interest, marking a decisive first step towards mitigating seismic risks where they are prevalent.

Importance of Using 3-component F-K Methods for Processing Ambient Vibration Array (AVA) Measurements for Improved Site Characterization

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The characterization of sites hosting seismological stations is important for the optimal use of ground motion databases. Over the past decade, the use of non-invasive methods based on the recording and analysis of surface wave dispersion properties has imposed itself as an efficient, quick to implement and inexpensive approach for developing shear wave velocity (Vs) profiles. Several methods can be cited. One example is the MASW (Mutichannel Analysis of Surface Waves) method, which is an active-source method involving the use of a seismic source (often a sledgehammer) and several geophones (typically 24 to 48) placed on a line. This method is effective for characterizing the part of the soil column closest to the surface (typically the top 15 – 20 m). However, passive-source methods involving the use of sensors arranged in 2D arrays and recording ambient vibrations (e.g., 'Ambient Vibration Array' methods: AVA or 'Microtremor Array Methods': MAM) are necessary in order to estimate the properties of the subsurface at greater depth, which is often required if seismological bedrock is to be reached.

AVA data is often processed using the SPAC (Spatial Autocorrelation) method. The use of frequency-wavenumber (FK) methods (e.g., beamforming) is less widespread, although they do have certain advantages related to resolving the frequency-dependent direction of ambient noise propagation, among others. Recent developments in 3-component FK methods, such as the Rayleigh Three-component Beamforming (RTBF) method developed by Wathelet et al. (2018) and Wathelet (2024), present a real qualitative step forward in accurately resolving experimental dispersion data and a better separation of the different modes. We present characterization results obtained by 3-component FK analysis on complex sites. Examples of very large aperture networks (up to 10 km) will be discussed, enabling Vs profiles to be obtained at depths of up to several kilometers. We will also show how these methods can be used to highlight velocity anisotropies, and provide some recommendations on array geometry and minimum acquisition durations.

20 Years After the Sesame Guidelines: Should Anything Be Changed?

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Seismic methods based on surface waves established in use about 25 years ago. 20 years ago, the European project SESAME (Site Effects assessment with AMbient Excitation, 2005) had the great merit of standardizing processing and interpretation of the single-station microtremor data. The project ended with the formulation of 9 criteria that established the reliability of an H/V curve and the clarity of a possible peak in the same curve. However, much time has passed since then and new knowledge has been added, to the point that some of the SESAME criteria could be reformulated today.

SURVEY PLANNING & SITE SELECTION. Before any interpretation of an H/V peak, it is necessary to understand the nature of the H/V peak itself, i.e. whether it is linked to surface waves or a true resonance. The two cases are easily distinguished in the microtremor spectra; however, this determines a different approach in the interpretation of H/V peaks.

SITE SELECTION & SENSOR INSTALLATION. Contrary to what the SESAME guidelines suggested, it has been shown that the measurement point influences the output. Rigid artificial layers break down the horizontal spectral components of motion, leading to H/V ratios < 1 even up to disappearance of H/V peaks.

Tremor measurements are easily affected by structures surrounding the investigated site. It is not difficult to distinguish H/V peaks related to nearby buildings from should be introduced in an ideally renewed set of guidelines.

DATA ANALYSIS. Data analysis always requires the removal of spurious measurements (outliers). This is traditionally carried out based on STA/LTA algorithms, but these end up removing too much of the signal than necessary.

DATA INTERPRETATION AND CONCLUSIONS. We will review the issues above and show that there is more information in the individual component spectra (H & V) than in the H/V spectral ratio, to the point that while the former can be interpreted without the latter, the latter is almost not interpretable without the first. We will review the 9 SESAME criteria, suggesting those that can still be considered valid today and those that could be modified.

Geologically Informed Non-ergodic Site Effects Model for California Enhanced With Geotechnical Measurements

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This work presents a non-ergodic site term model for California for use with the Boore et al. (2014) (BSSA14) NGA-West2 ground-motion model. The developed model uses continuous geospatial parameters, along with correction factors for geotechnical measurements (HVSR and V_{S30}) where available. Recent growth in ground-motion databases has enabled more accurate spatial quantification of repeatable site effects on ground-motion intensity. This work uses recordings from 3,099 stations in the Ji et al. (2022) DesignSafe database paired with geospatial variables (e.g., elevation, soil thickness, and surficial geology). These geospatial parameters serve as primary site terms, offering an alternative to proxy-based V_{S30} and $Z_{1.0}$. Mixed-effects regression is performed using the geospatial explanatory variables to estimate site response (derived from the BSSA14 site terms and residuals) for PGA, PGV, and PSA at 21 spectral periods. Compared to V_{S30}-based site terms, the non-ergodic geospatial site terms are found to reduce inter-site variability. The reduction is most significant (an average of 6.6%) when the novel regional geologic unit site parameter (defined by surficial geology and geomorphic province) is used. Correction factors are then developed using HVSR-derived parameters and V_{S30} for sites where these measurements are available to further reduce inter-site variability at the sites with site-specific seismic characterizations. We demonstrate the benefit of using HVSR, an inexpensive geotechnical measurement, to enhance ground-motion models by analyzing multiple HVSR parameters (from both earthquake HVSR and microtremor HVSR) and the categorical classification of sites with clear HVSR peaks and those without. The addition of geotechnical correction factors further reduces the inter-site variability by 5.6% using HVSR, 4.5% using V_{S30}, and 9.9% using both sets of data. The development of a non-ergodic site term for use in California using geospatial variables highlights the predictive power of continuously available non-proxy-based parameters and accounts for their impacts on ground motion intensity.

Temporal and Directional Variations in Shallow Seismic Velocities and Vp/Vs Ratio: Insights From a Borehole Array

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Shallow seismic wave velocity variations are finding new applications in environmental seismology, while remaining important in classical and engineering seismology. From monitoring hydrological processes to landslide stability and accurate site characterization for seismic hazard, it is important to understand and prioritize the natural processes and factors that shape these variations. We contribute to this direction by studying the acceleration data of the ARGONET vertical array (Cephalonia Island, Greece). Our dataset covers the period from July 2015 to May 2024 and includes 1347 earthquake records. Both vertical and horizontal accelerograms are analyzed using the method of seismic interferometry by deconvolution to compute P- and S-wave velocities, respectively. Variations of V_P and V_S are then examined in terms of time and azimuth, both separately and in the form of their ratio, V_P/V_S. Several possible factors contributing to the observed variations, i.e., soil moisture, ground shaking level and possible nonlinear soil behavior, earthquake magnitude, back-azimuth and distance, and soil anisotropy are examined. To disentangle the coupled signature of these factors, we apply the method of Generalized Additive Models (GAMs), in which the relationships between independent and dependent variables need not be described a priori as linear or nonlinear. This is particularly powerful in the context of complex relationships between predictors and a response variable. For the soil moisture description, we test both in-situ and modified Copernicus Climate Change Service (ERA5-Land) data. GAMs identify which of the considered predictors contribute with statistical significance to the observed velocity variations and quantify the individual contributions, providing a justified hierarchy for future modeling. At the ARGONET site, the most important factors contributing to the seismic wave variations are the seasonal changes in groundwater, expressed in our analysis through soil moisture, and the nonlinear behavior of the soil.

Are Seismological Signals Recorded at Free-field? Recommendations for Taking Better Account of Installation Conditions When Using Existing Databases and for Installing New Stations

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Accurate and reliable ground motion records are essential for accurate assessment of seismicity and seismic hazard. Current ground motion databases used to develop ground motion models (GMM) rarely provide information on sensor installation conditions, and are often regarded as free-field measurements. However, the various seismological networks use a wide variety of sensor installation methods. These different installation conditions have a significant impact on the recorded motion (amplification or deamplification, the amount of which depends on frequency). We will show, on the basis of real cases, how these installation conditions impact recorded signals, and how these differ from signals recorded in "true free field" conditions. These examples will be taken from experiments carried out in Greece. We'll look at the effects of sensor installation depth (e.g. sensors located in post-holes, manholes or tunnels), the effects of soil-structure interaction (e.g. sensors located in the foundation slab or basement of buildings), the effects of seismic slabs or pillars sometimes used to couple sensors to the ground, and the effects of short-wavelength topography.

Beyond this inventory of disturbing phenomena, we will present the international effort initiated to 1/ better document the installation conditions of existing stations in the metadata of seismic motion databases, so that users can more effectively take into account (and if necessary correct) these installation effects, and 2/ draw up a best practice guide for the installation of seismological stations (in the context of deploying new stations or updating existing ones) to minimize the effects of external disturbances. This work is being carried out in coordination with the "Site Characterization" working group of the Consortium of Organizations for Strong Motion Observation Systems (COSMOS).

Ground Motion Models Uncertainties and Variability: The Impact of Seismic Station Installation Conditions

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In the framework of ground motion and seismic hazard assessment in low to moderate seismic activity regions, the use of locally recorded ground motions has grown in popularity in these last years. Such ground motions allow for example to adjust to the local context existing Ground Motion Models (GMMs) developed in active regions of the world, to develop specific non-ergodic GMM or to perform Generalized Inversions (GIT) and assess seismological models.

When developing GMMs, it is generally assumed that ground motions are recorded in free-field condition, i.e. at the ground surface and far enough from any structure or construction that could interact with and affect the

motion. However, when looking closer, there is a wide variety of sensor installation configurations and conditions worldwide. Nonetheless, information about seismic station installation conditions (housing, type of soil-sensor coupling…) is most often lacking in ground motion databases.

In this context, with the objectives of identifying possible biases and robustly characterizing variabilities associated to GMMs, this work illustrates the impact of the "free-filed assumption" on site-to-site variability and the benefit of accounting for the information about seismic station installation conditions in the development of empirical GMMs. For this, a simple GMM based on EPOS-France ground motion dataset (Buscetti et al., 2024) is developed, accounting for available information on the sensor installation conditions. The results highlight that a significant portion of the site-related variability in the GMM is due to the variety of sensor installation modalities and conditions inventoried in France. Accounting for these metadata allows to improve the description of the GMM variability by an enhanced separation of repeatable and aleatoric effects. Overall, this contributes to the improvement of seismic hazard studies accuracy.

Site Amplification and Crustal Attenuation in the CEUS: Joint Tomographic Models for Ground Motion Analysis

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The amplification of earthquake shaking by local geologic structures presents significant seismic hazards, particularly in sediment-rich regions like the Gulf and Atlantic Coastal Plains and Illinois Basin of the central and eastern United States (CEUS). This study employs tomographic joint inversions to separate the overlapping and frequency-dependent contributions of crustal attenuation (1/Q), source characteristics, and site amplification in the CEUS. Using Lg wave amplitudes recorded over long raypaths (~200–1500+ km), we image crustal Q in seismically quiet yet densely populated areas such as the Coastal Plains while simultaneously accounting for sedimentary basin and coastal plain amplification effects. Seismic data from over 1400 events (Mw > 3.5) recorded by the EarthScope Transportable Array (TA), the newly deployed N4 network, and other broadband stations enable robust analyses of both vertical and horizontal Lg wave amplitudes, producing the first comprehensive CEUS attenuation maps since the TA's deployment.

Preliminary results reveal significant spatial variations in crustal Q across the CEUS. Attenuation is highest in Yellowstone, the Basin and Range, Southern Rockies, and Oklahoma Aulacogen; intermediate in the Gulf and Atlantic Coastal Plains, Midcontinent and St. Lawrence Rifts, and intraplate uplifts (e.g., Black Hills, Adirondacks); and low in the Colorado Plateau, Wyoming Craton, and broadly across the Great Plains to the Grenville Front. By contrast, mountainous areas of the western U.S. have the lowest site amplifications, cratonic basins the highest, and coastal plains appear intermediate. These maps will support the development of improved nonergodic ground motion models by incorporating frequency-dependent site amplification terms for vertical and horizontal motions. This project will quantify seismic attenuation, validate coastal plain amplification models, and assess sedimentary effects, delivering attenuation maps across eight frequency bands (~10–0.1 s) and frequency-dependent amplification factors critical for seismic hazard assessment.

Station Installations and Site Conditions, a Quest for Improved Strong Motion Database [Poster]

Poster Session • Wednesday 16 April

Conveners: Fabrice Hollender, CEA Cadarache (fabrice.hollender@cea.fr); Vincent Perron, CEA Cadarache (vincent.perron@cea.fr); Zafeiria Roumelioti, University of Patras (zroumelioti@upatras.gr); Paola Traversa, Electricity of France (paola.traversa@edf.fr)

POSTER 60

Identifying Site Resonance in the Central and Eastern U.S. Using HVSR: Insights From Ambient-noise and Earthquake S-wave Energy Sources and Implications for Site Characterizations

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Earthquake S waves can become trapped, or resonate, between the free surface and high-impedance basal layers, strongly contributing to site response at site-specific frequencies. Strong S-wave resonances have been observed in the central and eastern United States (CEUS), where *Vs30* has been shown to be an unreliable proxy for site effects and where stiff bedrock layers underlie slow, unlithified sediments at many locations. We evaluated the ability of single-station horizontal-to-vertical spectral ratios (*HVSR*) to estimate fundamental-mode site resonance frequencies (f_0) and amplifications (A_0) by comparison with the amplifications and frequencies of the first peaks calculated using 1D linear analyses. Our analyses relied on S-wave velocity profiles and recordings of ambient noise and earthquakes from more than 20 seismic stations and borehole arrays in the CEUS, with site conditions ranging from bedrock to thick (>100 m) soils. Consistent with previous studies, we found that f_0 is estimated well by *HVSR*s produced from both earthquake S-wave and ambient-noise energy sources. In contrast, *HVSR* estimates A_0 less reliably, although the empirical measurements derived from both energy sources correlate positively with the predicted values. Improved site characterizations, particularly of the bedrock S-wave velocities, may yield improved correlations. At stations in sedimentary basins, many *HVSR* curves reveal resonance frequencies much lower than those predicted by the 1D analyses, indicating both that deeper sedimentary layers influence *HVSR*s and that *HVSR*s developed in such geological settings must be interpreted with care for engineering use. We also found that although both types of *HVSR*s record peaks from multiple strong impedance contrasts, S-wave *HVSR*s reveal higher-mode resonance peaks, which are absent from the ambient-noise *HVSR*s. Thus, we encourage simultaneously interpreting site *HVSR*s from both earthquakes and ambient noise to identify site resonances and to gain additional insights into the subsurface structures that bear on site response.

POSTER 61

Vertical Arrays Drilled Passing Through an Active Fault With Very Short Recurrence Interval – Investigations and Preliminary Observations

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Two seismic vertical arrays have been installed at the hanging wall and footwall of the Milun Fault, which caused the 2018 Hualien, Taiwan earthquake with a M_W of 6.4 and ruptured through downtown Hualien city. The Milun Fault is an active fault that has a very short recurrence interval. The previous rupturing occurred in 1951 with an earthquake of magnitude 7.1. To understand the local structure, microtremor array measurements were adopted to investigate S-wave velocities at the two vertical array sites before the drilling. Velocity logging was then used to measure P-wave velocities after drilling. Short-period and strong motion sensors are equipment at the surface and different depths of the two arrays. The measured V_P and V_S profiles are validated to be reliable using the observed ground motion data. The M_W 7.4 earthquake that occurred on April 3rd, 2024, which was caused by an unknown blind fault, was recorded by the two vertical arrays. The highest intensity was 6-strong during this event according to the intensity scale in Taiwan. Results of the investigations, preliminary observations of ground motions, and site amplification behaviors are studied and introduced.

POSTER 62

Estimation of Vs Profiles from Strongmotion Records

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In recent years, a large number of strongmotion stations have been deployed all over the world, enabling the recording of large numbers of strongmotion records. While being a source of significant information for the community, this data losses significance if the site are not properly caracterized. Usually, a small percentage of strngmotion site have been properly characterized. In this study, we proposed to retrieve 1D S wave velocity (Vs) profile using only strongmotion records from the respective station. We analyse data from moderate earthquakes, retrieving parameters such as horizontal-to-vertical vertically incident S waves and Rayleigh wave's ellipticity and group velocity; that can be used to estimate the corresponding Vs profile. Preliminary results shows a better performance for lower frequencies (< 1 Hz), hindering our analysis of higer frequencies. In turn, this produces lower resolution in the upper part of the obtained Vs profiles. Currently, we are addressing the significance of this reduced resolution of the shallow part of the Vs profile. This methodology will enable the caracterization of strongmotion sites considering only records from registered data, providing usefull information for its appropiriate analysis.

POSTER 63

Development of a Linear Site Amplification Model for the CEUS based on Physiographic Province and Sediment Thickness: Incorporating Lessons from Station Placement Biases

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Understanding site amplification effects in the Central and Eastern United States (CEUS) enables more accurate seismic hazard assessments, informing building codes and land-use planning to mitigate earthquake risks effectively. Most current CEUS ground-motion models (GMMs) rely on the average shear-wave velocity in the upper 30 meters of the subsurface (V_{S30}) as the primary site parameter and lack other site parameters, despite the observed and simulated influences of sediment thickness, impedance contrasts, and basin effects on ground-motion amplification. We complete residual analyses using mixed-effects regression to calculate site-to-site (S2S) residual terms from ground-motion predictions using the CEUS NGA-East GMMs. This analysis reveals strong S2S dependence on geographically defined regions within the CEUS, with additional dependence on sediment thickness. In this study, we develop a new two-parameter linear site amplification term, based on adjusted physiographic province and sediment thickness, for use with the NGA-East GMMs. When evaluated using all ground motions from earthquakes with M > 4 against the current linear amplification term, we see an average reduction in the standard deviation of site-to-site terms across all periods of 25.3%. This study also evaluates the effect of station location bias in CEUS on the site terms, first by documenting the extent of station location bias, and then by exploring sampling techniques to reduce the impact on the site amplification term. Current strong-motion station placement in the CEUS is biased toward stiffer sites with higher V_{S30} values, largely comprised of bedrock or shallow sediment. We hypothesize that using different sampling techniques for use in building empirical site amplification terms will aid in developing models that more accurately quantify seismic hazards at sites with higher risks of amplification.

POSTER 64

Geologically Informed Non-ergodic Site Effects Model for the Western US Outside of California

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This work presents a non-ergodic site term model for the Western U.S. outside of California for use with the Boore et al. (2014) (BSSA14) NGA-West2 ground-motion model. This work builds on a similar effort undertaken for California. The developed model uses continuous geospatial parameters to predict the site term, and quantifies repeatable site effects on ground motion intensity in a continuous spatial manner. This approach results in a non-ergodic site term without the need for interpolation, which is beneficial due to the limited spatial coverage of seismic stations in the Western U.S. outside of California. This project uses the Ji et al. (2022) DesignSafe database containing over 14,000 recordings at 669 stations across Oregon, Utah, Nevada, and Arizona, and the Moschetti et al. (2021) database for Utah earthquakes from 2010 to 2020 that contains over 3,000 recordings at 201 stations. Each station is paired with its corresponding geospatial parameters (e.g., elevation, soil thickness, surficial geology, and geomorphic province), which serve as the primary variables in the site terms, offering an alternative to proxy-based variables V_{S30} and $Z_{1.0}$. When site-specific measurements are available, a V_{S30}-based correction is added to further reduce the ground-motion residuals. Mixed-effects regression is performed using geospatial explanatory variables to estimate site response (derived from the BSSA14 site terms and residuals) for PGA, PGV, and PSA at 21 periods. Compared to the conventional V_{S30}-based site terms, the non-ergodic geospatial site terms reduce the inter-site variability. The development of a non-ergodic site term for use in the Western U.S. outside of California highlights the predictive power of continuously available non-proxy-based parameters and accounts for their impact on ground motion intensity. Furthermore, this work demonstrates how we can leverage geologic data in areas of low station density to accurately predict site terms, and how a V_{S30} correction can be applied to further reduce the ground motion residuals where site-specific measurements are available.

POSTER 65

100m-Resolution Site Condition Map of China

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The updating of seismic ground motion parameter zoning map requires more accurate site classification maps to account for adjustments related to site conditions. When site investigations are not feasible, proxy-based estimations of V_{S30} are typically used to evaluate site conditions. We compiled a nationwide borehole database from research documents and technical reports, with approximately 82.02% of the profiles having depths greater than 20m. Unlike traditional approaches that primarily consider surface characteristics, we developed a hybrid V_{S30} model considering both surface and subsurface site information. Our new model uses surface geology category and subsurface bedrock depth as indicators. The geological units across China were classified into 33 Quaternary deposit units and 5 rock units according to geological age and genesis. Combined with 1:500,000 geological maps and a 100-m resolution depth-to-bedrock map, we generated a nationwide V_{S30} map. We made regional adjustments based on the geological environmental zoning and developed a 100-m resolution Chinese site classification map. Validation through borehole data and comparisons with previous models demonstrated that the V_{S30} results and Chinese site classification derived from our model effectively classify site conditions on a national scale. Additionally, in plain areas, our model outperforms slope-based ones in distinguishing between Chinese site classes II and III, as well as NEHRP classes C and D.

Temporally Variable Records of Earthquake Behavior and Considerations for Seismic Hazard Analyses [Poster]

Poster Session • Thursday 17 April

Conveners: Alexandra E. Hatem, U.S. Geological Survey (ahatem@usgs.gov); Belle Philibosian, U.S. Geological Survey (bphilibosian@usgs.gov); Ashley Streig, Portland State University (streig@pdx.edu)

POSTER 30

Disentangling Slip-rate Variability in Time and Space at the Cucamonga Fault, Southern California, USA

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Fault-slip rates are often interpreted in terms of fault structure and earthquake processes. For example, temporal variability may reflect earthquake super-cycles, which are relevant to time-dependent seismic hazard analyses. However, measuring slip rates at multiple time intervals frequently requires measurements at multiple points in space because piercing points of multiple ages rarely occur in the same landform. As a result, it may be difficult to disentangle temporal variability (from earthquake to earthquake) from spatial variability (along strike). Here, we review recent efforts to characterize both temporal and spatial variability of slip rate on the Cucamonga fault, located in greater Los Angeles at an intersection of the Transverse Range reverse-fault system and the San Jacinto-San Andreas plate boundary fault system. Multi-fault ruptures on these systems potentially allow larger magnitude (M >7) earthquakes near the urban center and potentially occur with periodicity akin to super-cycles. First, we show that cumulative fault displacement is variable along strike at many length scales, using lidar mapping. Next, we measure slip rate at different time intervals using cosmogenic radionuclide-dated alluvial surface offsets. We then apply calibrated geomorphic models of scarp diffusion and stream-channel incision to characterize the sources of along-strike variability and measure long-term (10^5 yr) slip rates. We identify fault geometry and erosive scarp modification as two important sources of real and apparent spatial variability, respectively. Slip rates are constant at ~1 mm/yr at intervals of 20, 30, and 40 ka. Real, long-wavelength spatial variability also appears stationary in time. If multi-fault ruptures include the Cucamonga fault, these ruptures likely span the entire fault and produce similar, long-wavelength spatial patterns of displacement. On other fault systems, where spatial variability is not necessarily stationary in time, efforts to measure temporal variability to improve hazard analysis should consider ruling out contributions from real and apparent spatial slip-rate variability.

POSTER 31

Wasatch Fault Zone Paleoseismic Rupture Models

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The Wasatch fault zone (WFZ), which forms the approximate eastern limit of Basin and Range Province extension in Utah, has long been evaluated through the lens of fault segmentation, which impacts estimates of earthquake rupture length, recurrence, magnitude, and probability. We evaluate this assumption using WFZ paleoseismic data, including 87 earthquakes younger than 7 ka identified at 28 sites along the 290-km-long Holocene trace. Using the temporal overlap of these earthquakes, we generate four non-unique rupture models that capture a range of plausible rupture behavior. Two end-member modes use overlapping site earthquakes to generate (1) minimum-length (≤50-km) and (2) maximum-length rupture models, which include the most spatially limited (n=30) and longest-possible (n=22) ruptures, respectively. (3) A structural model is similar to (2) but with ruptures trimmed or extended to geometric complexities (n=26). (4) A segmented model includes ruptures that are largely restricted to the most prominent structural complexities along strike (n=26). These models yield consistent rupture extents in the youngest portion of the paleoseismic record (<1ka) and diverge with age as timing uncertainty increases and the completeness of the record decreases. Across the models, rupture lengths vary from 12 to 154 km (mean of 45 ± 20 km). Although some ruptures appear to terminate at or near structural complexities, spatially variable ruptures that cross typical segmentation boundaries are the norm. We evaluate seismic moment release over time, spatial and temporal patterns of recurrence, and aperiodicity implied by these rupture models. We also compare our results with an inversion-based rupture forecast using geometric plausibility filters to determine multi-fault ruptures. Our results improve understanding of how earthquake cycles manifest on long normal faults and will inform time-dependent earthquake probability calculations for the Wasatch Front region.

POSTER 32

Earthquake and Slip-rate History of the Middle Branch of the Northern Anatolian Fault, Türkiye

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We present results from paleoseismic trenching and geomorphic mapping on the middle branch of the Northern Anatolian Fault (MNAF) in Türkiye. A recent geodetic study indicates lower slip rates (~2.5 mm/yr) on the MNAF relative to the more seismically active northern branch. However, historical, archeological, and paleoseismic studies show the MNAF has hosted several damaging earthquakes in the last two millennia and indicate right-lateral slip rates of up to ~5.3 mm/yr. Whether geodesy represents a present-day reduction in slip rates along this branch of the Northern Anatolian fault and/or earthquake clustering is not clear. We conducted geomorphic mapping and paleoseismic trenching along the understudied easternmost section of the MNAF to determine slip rates over different temporal scales and to understand its earthquake history. Our paleoseismic trench suggests up to four surface rupturing earthquakes on this section of the MNAF and our geomorphic mapping indicates variable offsets of river terraces and channels. By dating the paleo-earthquakes and the different offset geomorphic features, we will determine slip rates over variable temporal scales and an earthquake record for this segment of the MNAF. These data will help confirm if there is an observed reduction in slip rates at present day. Conversely, we may see that the reduction in slip rate is apparent and due to earthquake clustering. This result could indicate that longer term geologic slip rates that average out earthquake clusters are more appropriate inputs for time-independent seismic hazard models of MNAF.

POSTER 33

Assessment of Legacy Fault Studies and New Geological Mapping: Towards Improving Seismic Hazard Models at Yucca Mountain, Nevada

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Yucca Mountain is a potential geological repository for spent nuclear fuel and other high-level radioactive waste in Nye County, Nevada. Strong ground motions and surface rupture generated by earthquakes are hazards that have the potential to affect the suitability of nuclear waste storage at the site. Due to these hazards, investigations of active faulting were conducted from the late 1970's to the mid 1990's by multiple Federal (DOE; USGS) and State (NBMG; NSL) agencies to better characterize seismic sources and define fault rupture parameters necessary for probabilistic seismic hazard assessments. These legacy studies determined that at least eight faults in the immediate vicinity of Yucca Mountain are clearly active seismic sources. However, the experimental age dating techniques and poor quality of imagery available at the time of the studies resulted in large uncertainties in the assessment of fault parameters including the timing of events, slip rates, recurrence intervals, and maximum displacements.

Funded by the Nevada Agency for Nuclear Projects, this 4-year project aims to critically evaluate previous geological mapping and trenching studies at Yucca Mountain based on interpretation of modern satellite and aerial imagery, digital elevation models (DEMs), and lidar (pending). The evaluation will independently assess and critique the data quality and provide potential improvements. Data products will include new Quaternary geologic mapping at 25 previous fault trenching study sites and a quality ranking of the sites. We present the initial geodatabase compilation (legacy maps, imagery, topographic models, etc.) and preliminary mapping at several sites. Later phases of the project will include field verification of the mapping and collection of geochronologic samples to constrain the ages of faulted deposits. The products will be used to prioritize sites for detailed study that will help plan a long-term paleoseismic assessment program aimed at improving seismic hazard models at Yucca Mountain.

POSTER 34

Reconstructing Vertical Deformation Using Stratigraphy and Microfossils to Infer Megathrust Rupture History on Sitkinak Island, Alaska

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Historical records of great (Mw>8.0) earthquakes and tsunamis along the Alaska-Aleutian Subduction Zone (AASZ) are too short to forecast future events. Does the recent tectonic history of the subduction zone reflect long-term rupture patterns? Coastal marsh stratigraphy can provide centennial to millennial-scale archives of abrupt coseismic vertical deformation from past earthquakes and give clues about long-term rupture patterns. Quantitative estimates of coseismic vertical deformation can be obtained using diatom-based transfer functions (TFs). Diatoms are siliceous, unicellular algae that are sensitive to salinity, restricting species to vertical elevation zones. TFs statistically relate modern diatom assemblages to tidal elevation and can be applied to fossil diatom assemblages within the sedimentary record to reconstruct paleo-elevations. Recent work on Sitkinak Island, located at the western limit of the 1964 CE rupture boundary in southwest Kodiak Island, utilized qualitative diatom analyses and indicated a mixed record of coseismic uplift and subsidence suggesting a non-persistent rupture boundary. Here, we present additional stratigraphic and microfossil evidence of a series of great earthquakes on Sitkinak Island. We described stratigraphy from a low-energy coastal marsh to the east of the previous Sitkinak lagoon study site. We collected a 130 cm-long sediment core that was representative of the site stratigraphy. We identified two peat-mud contacts indicating subsidence, and three mud-peat contacts indicating uplift, that radiocarbon and Cs137 analyses suggest are consistent with previously identified earthquakes at Sitkinak dated to 1964 CE and 640-510 cal yrs BP (subsidence), and 290-0, 520-300, and 1050-790 cal yrs BP (uplift). Ongoing work will apply the diatom-based TF across each of the earthquake contacts to generate quantitative estimates of vertical deformation. Our data will be used to help constrain past rupture models and improve our knowledge of slip variability along the AASZ over time.

POSTER 35

Short-term Variations in Earthquake Production in the Southern San Andreas Fault System Due to Lake Level Variations in Lake Cahuilla, Salton Trough, California: Implications for Short-term Slip Rate Variability

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Paleoseismic data collected over the past several decades from among the major elements of the southern San Andreas fault (sSAF) system in the Salton Trough, southern California, show significant variability in earthquake production resulting from the presence or absence of the regional Lake Cahuilla. Modeling by Hill et al. (2023) demonstrate that ~100 m of water load effect the strength of the southern SAF due to variations in pore water pressure, and Rockwell et al. (2023) show that this effect also applies to the Imperial fault (IF) and elements of the southern San Jacinto fault. M7 and larger earthquakes account for most of the moment release in the sSAF system, with the majority of these larger earthquakes having occurred during periods of high lake stand on the southernmost SAF and SJF, sometimes resulting in periods of higher moment release (clusters).

The Salton Trough was dry or mostly so for at least 1 ka between about 100 BCE and 950 CE during which the system equilibrated to lower pore pressure conditions. When lakes again repeatedly filled the Salton Trough between about 950 and 1250 CE, earthquake production on the Imperial fault increased by a factor of 2 to 3 suggesting that its slip rate also increased by this magnitude. A similar burst of activity is seen on the sSAF based on reanalysis of paleoseismic data. These observations indicate that relatively small changes in water depth, such as lake level variations, seemingly innocuous differences in the water table, or the result of sea level rise from the late Pleistocene to the Holocene, can dramatically affect earthquake production on faults that are directly connect to a fluctuating water system in a fluid saturated crust.

POSTER 36

The Secondary Zone of Subsidence (SZS) During Subduction Zone Interseismic Deformation and Its Implications for Megathrust Earthquake Potential

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Understanding interseismic vertical deformation helps to evaluate the potential of megathrust earthquakes, especially in areas where horizontal constraints are inadequate. In a viscoelastic Earth, a fundamental component of this deformation is the development of a Secondary Zone of Subsidence (SZS) around the volcanic arc, in addition to the Primary Zone of Subsidence (PSZ) above the locked zone of the megathrust. To explain the physics of the SZS, we construct finite element models of repeating megathrust earthquakes. We show that the near-arc area initially undergoes uplift during postseismic stress relaxation but changes to subsidence about halfway into the interseismic period. The late-interseismic subsidence rate of the SZS is higher for a longer earthquake recurrence interval or lower mantle viscosity but is of the order of 10% of the subduction rate. In contrast, the commonly used elastic locking models fail to predict the presence of the SZS and thus can lead to incorrect understanding of earthquake potential.

Our models are validated by a comparison with geodetic observations at various subduction zones that are presently at different stages of their earthquake cycles, including southern Chile (early interseismic), Nankai (mid interseismic), and Japan Trench prior to 2011 (late interseismic). The importance of understanding SZS is demonstrated by examining the Lesser Antilles subduction zone, where the forearc is submarine, and GNSS measurements along the volcanic island arc cannot tell whether there is contractile strain associated with megathrust locking. However, the GNSS measurements indicate that the arc area is subsiding at about 2 mm/yr, 10% of the subduction rate. We propose that the ongoing arc subsidence is evidence for SZS which indicates that the megathrust is locked in a late stage of interseismic deformation. The implication is that this subduction zone is prone to megathrust rupture in the future, requiring a revision of seismic and tsunami hazard assessment in this region.

POSTER 37

Non-ergodic Probabilistic Fault-displacement Hazard Analysis

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The two main methods used for probabilistic fault-displacement hazard analysis (PFDHA) are the earthquake-based and displacement-based approaches. The earthquake-based approach is similar to ergodic probabilistic seismic hazard analysis used for ground motion, but the ground-motion model (GMM) is replaced by a global fault-displacement model FDM. In contrast, the displacement-based approach relies on empirical data of fault-specific displacement observations instead of using global FDMs, which is related to a non-ergodic approach. An issue is that the variability of the observed displacements at a site includes the effect of variability of the magnitude (M) and site distance from the end of the rupture (X) normalized by the rupture length (L) values. We do not know the M and X/L for paleoseismic displacement data, so we cannot directly compute the residuals as done for ground-motion data. To identify aleatory and epistemic components for the FDMs, we use the displacement hazard for generic source models to remove the effect of the M and X/L variability from the standard deviations of the observed slip at a point data sets. Using this formulation, we develop the first non-ergodic FDM, which results in a large reduction in the aleatory variability of displacement. Example PFDHA calculations using ergodic and non-ergodic approaches are shown for three cases: (1) without displacement data for the fault, (2) with displacement data at the site, and (3) with displacement data observed on the fault but a distance down strike from the site. With no data, the epistemic uncertainty is extremely large, but even a few data points provide significant constraints on the hazard with much narrower epistemic fractiles. Because the ergodic and non-ergodic approaches represent very different levels of simplification, the epistemic fractiles have different meanings for the two approaches. Therefore, the earthquake-based and displacement-based approaches should not be included as alternative branches on the logic tree.

Testing, Testing 1 2 3: Appropriate Evaluation of New Seismic Hazard and Risk Models

Oral Session • Tuesday 15 April • 8:00 AM Local

Conveners: Kirsty Bayliss, GEM Foundation, (kirsty.bayliss@globalquakemodel.org); Bill Fry, GNS Science, (b.fry@gns.cri.nz); Matthew Gerstenberger, GNS Science, (m.gerstenberger@gns.cri.nz); Andrew Nicol, University of Canterbury(andy.nicol@canterbury.ac.nz); Bruno Pace, Gabriele d'Annunzio University Chieti-Pescara (bruno.pace@unich.it); Camilla Penney, University of Canterbury(camilla.penney@canterbury.ac.nz)

Testing and Evaluation of Earthquake Simulations for Natural Hazards and Risk Modelling

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Numerical earthquake simulators are being widely developed, primarily to address questions of geophysical interest. At the same time, these models have the potential to supplement established hazard models. Before these new methods are adopted for hazard assessment and life-safety decisions, their usefulness and appropriateness for such decisions needs to be critically evaluated. In this talk we examine a number of key questions that must be addressed as part of this critical evaluation. These questions include: i) what are the minimum requirements for testing and evaluation before earthquake simulations are included in hazard analysis? ii) As a community, how do we reach agreement about the testing and evaluation required before earthquake simulations are included in hazard models? And iii) given the incompleteness and short duration of existing earthquake data, can earthquake simulations improve constraints on uncertainties and/or estimates of time-dependent hazard? Answering these questions will require input from a diverse cross-disciplinary group of researchers and end-user stakeholders. When assessing the utility of earthquake simulators, we must consider statistical rigour of testing, informativeness of the chosen test and value added by the new modelling. At a minimum, models should be consistent with, and explain, existing observations, while allowing for physically credible events which have not (yet) been observed. The level of testing and evaluation will vary dependent on the purpose of hazard models and the tolerance for uncertainty. This talk is designed to promote discussion and collaboration across the hazard community.

Evaluating the Impact of 3D Fault Geometry on Surface Rupture Probabilities Using Earthquake-cycle Simulations

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Surface rupture and deformation are common processes during large earthquakes, often worsening damage caused by ground shaking. The ongoing growth of urban areas and the expansion of critical infrastructure—such as dams, power plants, and lifelines—near seismically active faults increase exposure to earthquake ruptures and amplify seismic risk. Consequently, quantifying surface rupture probabilities and related hazard in active regions has become a key focus in fault displacement hazard analyses (FDHA). Despite this, a primary challenge for FDHA, especially in slower deforming regions, is the limited availability of surface rupture records needed for robust statistical analyses. These records are often insufficient to characterize the long-term, seismic cycle-scale behavior of fault systems, ultimately limiting forecasting capabilities.

In this study, we adopt a novel approach to estimate surface rupture probabilities by analyzing simulated earthquake ruptures generated with the RSQSim earthquake cycle simulator at the Monte Vettore Fault System (MVFS) in Central Italy. Following benchmarking tests to select rate-and-state parameters that best match empirical relationships, we simulate 100 kyr-long earthquake catalogs using three distinct 3D fault geometry models for the MVFS. These models incorporate variations in fault dip—constant and listric—and segment connectivity at depth, employing a detailed fault discretization (~150 m elements) to capture the complexity of mapped fault traces. We evaluate the impact of these geometries on surface fault rupture probabilities, and we discuss their feasibility by comparing simulated cumulative throw and earthquake recurrence intervals at surface locations against geomorphic and paleoseismic records, as well as empirical regressions of rupture probabilities from the literature. This approach highlights the potential of earthquake cycle simulations to improve FDHA and provides insights into the long-term behavior of geometrically complex fault systems and their surface rupturing potential.

At the Testing Frontier

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For earthquake forecast models that generate synthetic catalogs down to small magnitudes, there are many ways in which they can be tested rigorously. One can look for systematic differences that distinguish stacked features of observed and synthetic catalogs ("seismological Turing tests") and evaluate the likelihood that the model would produce different aspects of observations (as many Collaboratory for the Study of Earthquake Predictability (CSEP) tests do). Many of the more controversial aspects of fault-based earthquake rupture forecasts, however, such as large earthquake rates and their variability, remain largely untestable on short time scales. This limitation hampers the ability to validate the very elements of earthquake forecast models that have the greatest societal importance.

There are several paths forward from this testing dilemma. One can, when possible, obtain more data by enlarging the testing region, effectively trading space for time. The underlying hypotheses used in models can also be tested directly. When testing the model is not possible, we can choose the simplest model consistent with observations, or sample over modeling uncertainties, including different models entirely. I will discuss these different testing paths in the context of fault-based seismic hazard models in California and the Western U.S.

Modeling Synthetic Catalogues of Earthquake Ruptures in Complex Interacting Fault Systems: A Case Study in Central Apennines, Italy

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Seismology and paleoseismology are crucial for collecting data on earthquakes and assessing seismic hazards. However, earthquake catalogues are often too short and uncertain, especially in areas with low-to-moderate seismicity, making accurate seismic risk evaluation challenging. Physics-based earthquake simulators offer a solution by generating long, synthetic earthquake sequences.

This study uses MCQsim (Zielke & Mai, 2023) to create synthetic earthquake catalogues for Central Italy, a region with moderate seismic activity and an extensional tectonic regime. Data from the Fault2SHA database (Walker et al., 2021) help model key faults to produce earthquake sequences that realistically reflect the region's tectonics.

Initial results match known earthquake-scaling relationships, magnitude-frequency distributions, and fault slip rates. Further refinements will focus on adding fault details and refining depth characteristics to enhance simulation accuracy.

Part of the MSCA-DN TREAD project (https://tread-horizon.eu/), this work aims to improve probabilistic seismic hazard analysis (PSHA) and overcome limitations of traditional earthquake catalogues, enabling better seismic hazard assessments.

Zielke O. and Mai M. (2023) – MCQsim: a multicycle earthquake simulator, Bulletin of the Seismological Society of America, 113-3, 889-908.

Faure Walker, J., Boncio, P., Pace, B.et al.Fault2SHA Central Apennines database and structuring active fault data for seismic hazard assessment.Sci Data8, 87 (2021).

Guidelines for the Evaluation Process of a NSHM: The Italian MPS19 Legacy

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In numerous countries, the acceptance of a new National Seismic Hazard Model (NSHM) for risk reduction strategies typically follows thorough scrutiny and comparative analysis with previous models, focusing on scientific reliability and practical applicability for building codes. While these two criteria are both valid, they represent distinct concepts that are often conflated in scientific and public discourse. We recognize that the implementation of an NSHM in risk reduction strategies involves several non-scientific challenges; however, it is essential to emphasize that NSHM is fundamentally a scientific model, and its credibility hinges solely on its scientific reliability.

Inspired by the evaluation process of the most recent NSHM in Italy, here we delve into how to effectively assess the reliability of an NSHM and its limitations using available data, as well as the implications of comparing outcomes between new and previous models. Lastly, we offer recommendations to assist scientists in navigating the complex process of evaluating the scientific reliability of NSHMs and meaningfully comparing the results of different models.

Testing, Testing 1 2 3: Appropriate Evaluation of New Seismic Hazard and Risk Models [Poster]

Poster Session • Tuesday 15 April

Conveners: Kirsty Bayliss, GEM Foundation, (kirsty.bayliss@globalquakemodel.org); Bill Fry, GNS Science, (b.fry@gns.cri.nz); Matthew Gerstenberger, GNS Science, (m.gerstenberger@gns.cri.nz); Andrew Nicol, University of Canterbury(andy.nicol@canterbury.ac.nz); Bruno Pace, Gabriele d'Annunzio University Chieti-Pescara (bruno.pace@unich.it); Camilla Penney, University of Canterbury(camilla.penney@canterbury.ac.nz)

POSTER 66

A New Empirical Probability Model for Surface Faulting Utilizing Width-rupture Ratio for Crustal Earthquakes

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Models for the probability of surface rupture are used in probabilistic fault displacement hazard analyses (PFDHA). Most existing empirical modelsfor the probability of surface rupture (PSR) are based on a magnitude and style of faulting. An advantage of empirical models is that they need fewer assumptions about the depth distribution of the top of rupture of large-magnitude earthquakes, but a disadvantage is they do not account for the differences in the seismogenic thickness. Faultswith down-dip widths that are much thinner than average (e.g., 5 km), have a larger chance of surface rupture from small-magnitude earthquakes. Notable examples include the 2010 Mw 5.0 earthquake in Ecuador and the 2019 Mw 4.9 quake in France. Mammarella et al. (2024) proposed a PSR model utilizing a numerical approach that accounts for the seismogenic thickness and dip of the fault. This model has the advantage that it uses the fault-specific hypocenter depth distribution and seismogenic thickness, but it has the disadvantage that it assumes that the depth distribution of the top of rupture can be computed from the distribution of hypocenters from all magnitudes. In this study, we adopted an approach that uses the strengths of the empirical and numerical approaches. An empirical model is developed using the width-rupture ratio (WRR) in place of magnitude for the logistic regression. The WRR is the rupture width divided by the fault width. We compiled an empirical dataset of crustal earthquakes that occurred between 1970 and 2023 with a magnitude greater than 6. About half of the events have fault rupture information from finite-fault inversion. In cases where fault rupture widths were not available, we utilized the source scaling model from Huang et al. (2024) to estimate the rupture widths. By using the WRR, the proposed model accounts for the fault-specific seismogenic thickness and dip, but with empirical constraints on the PSR, avoiding the key assumptions in the numerical approach. This model successfully accommodates both large-and small-magnitude cases, facilitating fault-specific evaluations of the PSR.

POSTER 67

Refining Seismogenic Source Models: Revisiting the Alboran Sea for an Updated Zesis Framework

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The Iberian Peninsula's seismogenic source model (ZESIS), first published in 2015, has served as a cornerstone for seismic hazard assessment in the region, encompassing the peninsula and adjacent offshore areas (http://info.igme.es/zesis/). However, the past decade has seen significant advancements in geophysical data acquisition and seismic studies, providing crucial insights into the region's tectonic framework. These developments present an opportunity to refine the ZESIS model, particularly in the geologically complex Alboran Sea. The study here presented focuses on updating the seismogenic source zones within the Alboran Sea using an enhanced dataset and methodologies consistent with those employed in the original ZESIS framework. In addition to previously utilized datasets such as crustal thickness, heat flow, horizontal stress, and the Quaternary Active Faults Database of Iberia (QAFI), we integrate new resources including GNSS velocity fields, a revised earthquake catalog, detailed mappings of active faults, crustal domain boundaries, and newly constructed Moho depth map. These inputs enable a more precise delineation of seismogenic boundaries and a deeper understanding of the region's tectonic dynamics. The updated seismogenic zones in the Alboran Sea reveal significant changes, ranging from minor adjustments to the boundaries to major reconfigurations, reflecting the improved resolution and scope of the current dataset. This refined model not only enhances the accuracy of seismic hazard assessments for the Alboran Sea but also provides a robust foundation for future updates to the ZESIS model, ensuring its continued relevance and utility in seismic risk mitigation efforts.

POSTER 68

Earthquake Source Modelling for Hazard Assessment of the Tonga and Vanuatu Subduction Zones

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Understanding the complexity of earthquake source parameters, including coseismic slip distribution and rupture dimensions, is essential for local-scale seismic and tsunami hazard assessments. One effective approach is to use earthquake source models generated from synthetic earthquake catalogues via physics-based generators like RSQSim. A key factor influencing the characteristics of a synthetic earthquake catalogue is the tectonic stressing rate, calculated from the slip-deficit rate using a back-slip loading method. The slip-deficit rate can be calculated by integrating the geodetically-inferred convergence rate from Euler Pole rotations with seismic coupling models. Unfortunately, some of the world's subduction zones have insufficient geodetic data to significantly constrain coupling models. Such is the case with our focus area in the southwest Pacific. To overcome this challenge, we estimate coupling factors on subduction interfaces by adjusting them according to the seismicity rate ratios between the instrumental and synthetic earthquake catalogues of the baseline models. The subduction interfaces are divided into several segments for calculating the seismicity rate ratios along strike. To incorporate sufficient instrumental earthquakes for seismicity rate estimates and to avoid artificial segmentation, we test the segment window lengths and shifting distance. Our new method is applied to the Tonga and Vanuatu subduction zones, which exhibit the highest convergence rates among subduction zones worldwide of approximately 240 mm/year. The coupling factor in this area was poorly defined in previous studies, leading to debates about whether the coupling was weak or strong in each segment. The ideal coupling distribution occurs when adjusted by seismicity rate ratios calculated with a 500 km moving window shifted 50 km along the strike for the Tonga and Vanuatu subduction zones, showing weak coupling at northern Tonga and strong coupling at northern Vanuatu interfaces. We use this model to develop a synthetic catalogue of finite fault earthquakes spanning ~60,000 years.

POSTER 69

Significance of Non-ergodic Ground Motion Models in Seismic Loss Assessment

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The substantial increase in ground motion records in California over the past decades has enabled the development of non-ergodic ground motion models (NEGMMs). However, the implications of NEGMMs for structural and infrastructural loss assessment have not yet been thoroughly examined. This study is among the first to investigate the impact of NEGMMs on site-specific seismic hazard and losses due to scenario earthquakes in California. Two sets of ground motion models are employed: a state-of-the-art NEGMM and a conventional ergodic model. Response spectra for scenario earthquakes are generated for two hypothetical assets—a bridge and a building—located at distinct sites in the San Francisco Bay Area, with expected loss ratios calculated using the HAZUS estimation methodology. By accounting for systematic variations in source, path, and site effects, non-ergodic response spectra exhibit reduced aleatory variability compared to their ergodic counterparts, while median ground motions can either increase or decrease relative to the ergodic model. As a result, the adoption of NEGMMs may increase or decrease site-specific hazard and loss. Furthermore, our preliminary loss evaluation results indicate that incorporating the non-ergodic model moderately increases bridge losses but significantly decreases building losses. These findings underscore the potential for NEGMMs to enhance seismic hazard and risk assessments. Further work should explore their implications at the portfolio level, particularly for stochastic event sets.

POSTER 70

SIGMA3: A Further Step for the Reduction of Epistemic Uncertainties in PSHA

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Today, the evaluation of seismic hazard and risk at critical facilities, such as nuclear installations, often relies on probabilistic site-specific approaches for return periods of 10,000 years, or more. In this context, this type of results is very dependent on the knowledge of local site conditions (i.e., geology, soil response) and on the level of uncertainties in the components of the seismic source model (SSM) and in the ground-motion model (GMM). This situation is heightened in low-to-moderate seismicity areas due to data scarcity or to large uncertainties in the models.

The research program SIGMA3 has been launched in 2024 over a period of 5 years to overcome such difficulties by developing data, methods and models that will contribute to the reduction of epistemic uncertainties in seismic hazard assessment (SHA). We aim at working with the largest international community of researchers and to improve our practices for hazard assessment and safety demonstration based on consensus.

Our poster will introduce the main technical orientations of the program, which are also grounded on the results of the two previous SIGMA and SIGMA2 programs. Work Package (WP) 1 will coordinate research actions (RA) to improve the quality of earthquake catalogues and active faults databases. WP 2 will organize RA for the modelling of ground-motion (GM) and to pursue the quest for reference GMM, devoid of any spurious (de-)amplification effects. WP 3 will organize RA on soil dynamics and non-linear site response. WP 4 will conduct RA to improve the PSHA methodology, both for calculation efficiency and for the propagation of uncertainties. Frameworks for the introduction of all available information will also be developed to enable to obtain better informed hazard models (e.g., instrumental, historical, paleo-seismological…). Finally, WP 5 will develop a virtual simulation platform for the generation of synthetic seismicity and ground-motion data for PSHA purposes. By simulating reality, we want to better understand what we observe in the models and in PSHA outcomes.

Unusual Earthquakes and Their Implications

Oral Session • Wednesday 16 April • 2:00 PM Local

Conveners: Zhe Jia, University of Texas at Austin (zjia@ig.utexas.edu); Chris Rollins, GNS Science (c.rollins@gns.cri.nz); Alice R. Turner, University of Texas at Austin (alice.turner@jsg.utexas.edu)

Challenges Created by Unusual Earthquakes for Operational Tsunami Assessment and Response

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As cascading hazards resulting from other geohazards, tsunami events are challenging to communicate as they unfold. Tsunami warning centers must issue initial alerts based on rapid preliminary assessments long before full characterization of a source is possible, and usually also before the tsunami itself is even observed. Accordingly, alerts are typically issued following predetermined procedures based on preliminary earthquake parameters, and initial tsunami forecasts are based on worst-case scenarios and simplifying assumptions. Earthquake characteristics that violate these assumptions can create profound differences between default estimates and actual tsunami characteristics, including estimated tsunami arrival times and the geographical distribution of expected impacts. This effort reviews the assumptions currently used by the U.S. Tsunami Warning Centers in the early stages of tsunami response, highlighting the implications of those assumptions for case studies of real and hypothetical earthquakes with particular rupture properties and triggered secondary hazards.

Characteristics of Intermediate and Deep-focus Earthquakes Along the Tonga Subduction Zone Revealed by Cross-correlation Earthquake Relocation

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The mechanisms underlying the genesis of intermediate and deep-focus earthquakes remain a topic of debate, with dehydration embrittlement, thermal runaway, and phase transformational faulting proposed as leading hypotheses. The Tonga Wadati-Benioff Zone, which is characterized by (1) seismicity gaps, (2) a transition between single and double seismic zones, and (3) dense deep earthquake clusters, provides a unique setting for examining these hypotheses. We explore the variations in seismicity along the Tonga subduction zone using high-precision earthquake relocations, incorporating waveform cross-correlation differential times. We take advantage of a regional machine learning catalog including ocean bottom seismometers in the study region from 2009 to 2010 and a temporary land-based network from 1993 to 1995. We relocated over 10,000 earthquakes that reveal linear trends missing from the original catalog. We provide a more detailed examination of the high intermediate-depth seismicity belt, which, as identified by Wei et al. (2017), becomes shallower with increasing slab temperature. Double seismic zones, where present, converge at varying depth (250 – 350 km) whereas seismicity branches into multiple segments at depths greater than 400 km. The spatial correlation of these intricate seismicity patterns along the Tonga seismic zone with seismic velocity structure, temperature, slab age, b-value, convergence rate, and local stress regimes can advance our understanding of the processes governing intermediate and deep-focus earthquakes.

Low Aftershock Productivity of the 2017 Delaware Earthquake

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The Mw 4.2 earthquake near Dover, Delaware, in November 2017 represented an opportunity to evaluate seismicity in a passive margin setting, motivating a rapid deployment of temporary instruments to record aftershocks.

Within 24 hours of the main shock, personnel from the Department of Terrestrial Magnetism of the Carnegie Institution for Science, the University of Maryland, and the USGS mobilized to install a mix of instruments in the epicentral area for one month.

Using template matching, we detect several dozen aftershocks with magnitudes ≤ 2.0 and locate a subset of them using a site-specific 1D velocity model. The local magnitudes reveal unusually low aftershock productivity, with a notable departure from Båth's Law for the typical magnitude of the largest aftershock. We investigate stress drop and fault orientation with respect to the regional tectonic stress as potential explanations for the earthquake's unusually low aftershock activity. We then place the event in the context of other low magnitude events across the stable United States in order to better understand potential drivers of aftershock productivity. Finally, we discuss implications for predictions of aftershock productivity and largest aftershock magnitude based on the earthquake location and mechanism.

Satellite Optical Image Correlation Measurements for a Moderate Magnitude Thrust Earthquake: The January 2024 Wushi (Aykol), China Mw 5.7 Aftershock

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Sub-pixel optical image correlation has become a standard tool in earthquake deformation studies, filling key spatial and temporal gaps in data coverage for large magnitude events. The method, however, has rarely been employed to document small to moderate magnitude earthquake deformation. On January 22nd, 2024, a blind Mw 7.0 rangefront thrust earthquake occurred in the southern Tian Shan of China on the northwest-dipping Maidan fault. Although the mainshock did not rupture to the surface, a Mw 5.7 aftershock on January 29th, 2024 ruptured an oppositely-dipping thrust fault, yielding a NE-trending ~4.8-km-long surface rupture with vertical displacements high enough to temporarily pond the Qialemati River. High-resolution (0.5 m) satellite optical imagery available within the month following the aftershock presents an opportunity to remotely derive near-fault three-dimensional kinematic information via pre- and post-earthquake sub-pixel image correlation and digital elevation model differencing. This study is particularly challenging and atypical in the context of previous imagery-based three-dimensional displacement analyses because of the relatively small displacements (<2 m) that were primarily vertical rather than horizontal. Additional epistemic uncertainties enter our analyses due to sub-optimal image quality, including oblique image capture in a non-stereo configuration, different sensor platforms, cloud cover, and intervening snow cover. Field measurements collected along the surface rupture immediately following the event provide ground-truth comparison for the remotely derived kinematics. Together, the two datasets complement each other for both earthquake response and discerning displacement characteristics of a surprising surface rupture from a moderate magnitude aftershock.

Revisiting an Enigma on California's North Coast: The Seismotectonics of the M6.5 Fickle Hill Earthquake of December 1954

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Many earthquakes occur along the North Coast of California around the Mendocino Triple Junction (MTJ). There the Pacific, Gorda and North American (NA) plates meet, forming the Mendocino and San Andreas faults and the Cascadia subduction zone (CSZ). Historically, the majority of large earthquakes around the MTJ have been intraplate – within the Gorda plate offshore and in its subducted portion beneath the NA plate. On land north of the MTJ, many active faults mapped in the NA plate are interpreted as part of the CSZ fold and thrust belt. While some events have been detected in the NA plate, no large historic events have been clearly identified as associated with mapped surface faults with one possible exception, the M6.5 earthquake of 21 Dec 1954 near Fickle Hill, CA, in Humboldt County. The location and seismotectonics of this event remain enigmatic, as it occurred well before the present era of broadly available, digital seismic data. It was well recorded for the time, by two nearby accelerometers and other stations of the US Coast and Geodetic Survey (USCGS), on seismographs operated by UC Berkeley and the California Seismological Lab in Pasadena, CA, and at other regional and teleseismic sites. The 14 epicenters given in the literature cluster between 40.78N and 124.17W in the SW and 40.94N and 124.0W in the NE. Using published catalog data, unpublished data from Berkeley's archives, and digitized accelerometer records, we redetermine the earthquake's hypocenter. Its most likely location is just east of Arcata at 40.87N, 124.03W, at ~11 km depth. P-wave polarities read from Berkeley station records and the digitized waveforms from the two accelerometer stations are consistent with a reverse mechanism. With the depth uncertainties, this implies that the source is more likely to be the subduction interface or the NW-SE trending crustal Mad River Fault zone. We update the ShakeMap using reinterpreted detailed felt/damage reports from the USCGS, newspaper archives and eyewitness accounts. The intensity distribution also supports a relatively shallow location beneath Fickle Hill, to the east of Arcata.

Unusual Earthquakes and Their Implications [Poster]

Poster Session • Wednesday 16 April

Conveners: Zhe Jia, University of Texas at Austin (zjia@ig.utexas.edu); Chris Rollins, GNS Science (c.rollins@gns.cri.nz); Alice R. Turner, University of Texas at Austin (alice.turner@jsg.utexas.edu)

POSTER 14

Surface Rupture From an Aftershock: Remote Observations From the January 2024 Wushi (Aykol) Earthquakes, China

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On January 22, 2024, a moment magnitude (Mw) 7.0 earthquake occurred in the southern Tian Shan region of western China, followed by a Mw 5.7 aftershock on January 29. Interferometric synthetic aperture radar (InSAR) observations and a lack of observed surface rupture in optical satellite imagery between January 22 and 26 indicated the Mw 7.0 rupture was blind. The location and depth of the Mw 7.0 mainshock is consistent with southeast-vergent thrust motion on the mapped range-front Maidan fault along the southern Tian Shan. However, sub-pixel correlation of independent high-resolution optical satellite imagery and post-mainshock InSAR observations spanning the Mw 5.7 aftershock shows ~4.8 km of discontinuous surface rupture with a south-side-up sense of motion. The trend of the surface rupture is north-east-southwest, similar to that of the bedding orientation within the limb of a previously mapped syncline. Sub-pixel image correlation and digital elevation model differencing show mean surface displacements of 0.6 m, with a peak of ~1 m, along the fault near the center of the mapped surface rupture trace. Given these observations, we interpret the Mw 5.7 aftershock produced surface rupture on an unmapped flexural slip fault within a syncline in the hanging wall of the Maidan fault or on a backthrust associated with the Maidan fault. Importantly, this difference in observed surface rupture between the larger magnitude mainshock and smaller magnitude aftershock is a critical observation that highlights the need to understand secondary or distributed faulting associated with larger earthquakes that rupture either coseismically with the mainshock or during an aftershock. Such secondary faults may represent potentially poorly constrained hazards that should be considered during seismic and fault displacement hazard analysis and earthquake response.

POSTER 15

Deciphering the Multi-fault System of the 2024 Mw 7.4 Hualien, Taiwan Earthquake Using Combined Seismic, Geodetic and Insar Datasets

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The April 3, 2024 Mw 7.4 Hualien earthquake was the largest earthquake in Taiwan in almost 25 years, and it has resulted in thousands of aftershocks so far. The intricate fault distribution in eastern Taiwan adds challenges to determining the fault geometry and slip distribution associated with this event. The USGS finite-fault solution indicates an overall east-dipping fault rupture, but inversions based on geodetic observations suggest a west-dipping thrust fault. To better constrain the fault geometry and slip distribution of the Hualien earthquake, we combine strong motion seismic, GPS, and InSAR datasets for joint inversions. We first use a Bayesian inversion scheme to constrain the most probable fault parameters, including source location, depth, strike, dip, rake, and slip with the coseismic GPS displacement solutions from the Nevada Geodetic Laboratory. We then use a finite fault inversion method to estimate slip distribution on this fault geometry with a 3 km sub-fault patch size. For the seismic dataset operated by the Taiwan Strong Motion Instrumentation Program network (TSMIP), we first explore the fault parameters by random search for a half-million parameter combinations. The results from individual GPS and seismic inversions prefer two main slip patches on two different fault planes, suggesting that a deeper west-dipping fault plane around 35 km depth may have triggered a shallower west-dipping fault around 20 km depth. A joint inversion with all 3 datasets and these two fault planes can yield a total variance reduction over 75%. The total seismic moment of the two faults is equivalent to Mw 7.39. This multi-fault geometry is also in good agreement with the aftershocks. Additionally, preliminary Coulomb stress change analysis indicates better consistency between Coulomb stress increase and aftershock locations. Our analysis supports a multi-fault system that caused the Mw 7.4 Hualien earthquake. It also highlights the value of leveraging dynamic seismic as well as static geodetic measurements such as GPS and InSAR for earthquake source inversions.

POSTER 16

Deep Lithospheric Rupture and Dual-mechanism Transition During the 2024 Mw 7.4 Calama Earthquake, Chile

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The mechanism of intermediate depth earthquakes (70-300 km depth) remains enigmatic, with leading hypotheses attributing rock failure to either dehydration embrittlement or thermal runaway instabilities. Here, we estimate the rupture details of the 2024 Calama Mw 7.4 intermediate-depth earthquake using a dense local network of seismometers, accelerometers and cGNSS stations deployed in tNorthern Chile, and teleseismic seismograms, and compare the rupture extent with the temperature environment resolved from thermo-mechanical simulations. Time series reveal several short-duration pulses of P and S waves, along with coseismic displacements that extended over 300 km from the epicenter and exceeded 10 mm. These observations indicate a maximum slip of approximately 1 meter, concentrated within a vertical rupture plane characterized by five distinct subevents inside the slab. Rupture of the vertical plane is consistent with the location of aftershocks. The subevent and slip models suggest that the rupture nucleated within the cold core of the subducting slab, likely driven by dehydration embrittlement mechanism, before propagating deeper and engaging multiple asperities. Remarkably, the rupture extended into warmer regions, well beyond the serpentine dehydration isotherms, suggesting that a transition to shear thermal instability likely facilitated the later stages of rupture propagation. This is the first time an intermediate-depth earthquake in Chile has been characterized in such detail, including regional deformation and high resolution seismicity. The dual-mechanism transition extends the potential rupture zones beyond recognized seismogenic boundaries, which emphasizes the need to consider the complex interactions between rupture mechanisms and slab thermal and compositional structures for understanding large intermediate-depth earthquakes.

POSTER 17

A New Perspective on the Origin of Seismic and Tectonic Activity of the Sichuan Basin, Central China

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The Sichuan Basin, adjacent to the eastern margin of the Tibetan Plateau, has long intrigued geologists and seismologists due to its complex tectonic and seismic activity. While existing models, such as upper crustal thickening and low-to-middle crust channel flow, explain aspects of plateau growth and tectonic extrusion, they fail to fully account for the internal seismicity of the basin and the weak tectonic activity preceding major earthquakes like the 2008 Mw 7.9 Wenchuan event. To address these gaps, we present a novel framework for understanding the tectonic and seismic dynamics of the Sichuan Basin.

Integrating geological evidence, focal mechanism solutions, GPS measurements, and geomorphic analyses, we identify a counterclockwise rotation of the basin's crystalline basement—initiated ~12 million years ago—driven by the lateral extrusion of the Chuan-Dian fragment at the southeastern margin of the Tibetan Plateau. This rotation is facilitated by interactions between two dominant fault systems: the left-lateral Xianshuihe fault, which accommodates southeastward motion, and the Longmenshan fault belt, responsible for oblique compression and thrusting. These processes lead to strain partitioning, reactivation of NE-SW transpressional faults, and decoupling of the sedimentary cover from the crystalline basement.

Earthquakes predominantly occur at depths of 8–25 km within the rigid basement, as demonstrated by events like the 2008 Wenchuan earthquake. This highlights the role of fault discontinuities and rotational dynamics in accommodating strain. Our findings enhance the understanding of the occurrence of right-lateral shearing during the Wenchuan earthquake and the high frequency of seismic events within the rigid Sichuan Basin block, thereby contributing to the development of improved seismic risk models and early warning systems for tectonically active regions worldwide.

POSTER 18

Tidally Modulated Icequakes Along a Ross Ice Shelf Rift in Antarctica

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The Ross Ice Shelf (RIS) in Antarctica is the largest ice shelf on Earth. There are multiple periodically spaced rifts spanning ~100 km. They were formed due to a buildup of tensile stress as the ice shelf flows toward the Ross Sea. Previous work established that these rifts are seismically active, with seismicity modulated by tidal stresses. Here we present high quality seismic results from the NASA-supported Antarctic Rift Research for Ocean Worlds (ARROW) project which deployed 16 seismometers and 12 GPS stations across the east portion of the rift Western Ross 4 (WR4) between December 2022 and January 2023. The ARROW array recorded over 6000 seismic events (i.e. icequakes) and measured surface strain across WR4 from the GPS data. To locate the icequakes, we first hand-picked the P- and S-wave arrivals from each seismic station of an event. We then used a layered velocity structure derived from the active source experiments to locate each icequake and their depth. For events with higher signal-to-noise ratio, we additionally computed their moment tensor solutions. Our results indicate that most icequakes were located along both sides of the WR4 rift, and their distribution appears to represent several major en echelon fractures that can be observed from optical satellite imagery. Additionally, ~73% of the icequakes occurred during the extensional phase of the strain rates. For the moment tensor solutions, the Variance Reduction (VR) of most events are greater than 20% with their major tension-axis nearly parallel to the main ice flow direction. About 80% icequakes are located at a shallow depth (≤ 50 m), and 40% of them are shallower than 20 m depth, implying events occur within the shallow mélange within the rift or shallow marginal crevasses. Our measurements of deformation across the WR4 rift provide new constraints on the material strength and properties of both the ice shelf and rift mélange. Our results have implications for the ongoing deformation of ice shelf structures which affect the stability of the RIS in the future under a changing climate.

POSTER 19

3D Dynamic Rupture Modeling of the 2021 Haiti Earthquake Used to Constrain Stress Conditions and Fault System Complexity

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The 2021 Mw7.2 Haiti earthquake was a devastating event which occurred within the Enriquillo Plantain Garden Fault Zone (EPGFZ). It is not well-understood why neither the 2021 nor the prior 2010 Mw7.0 earthquake were simple strike slip events and, instead, ruptured with distinct patches of dip slip and strike slip motion on largely separate fault planes. We develop several 3D dynamic rupture simulations of the 2021 earthquake to analyze which conditions may have controlled the complex rupture. The major characteristics of the earthquake rupture include: the characteristic spatial and temporal separation of strike-slip and dip-slip motion, rupture transfer to the Ravine du Sud Fault (RSF), and a multi-peak source time function. We construct a detailed fault system geometry comprising 17 fault segments, which includes a north-dipping Thrust Fault (TF) and near-vertical RSF, along with surrounding regional and secondary faults. We find that along-strike changes to the frictional strength of the TF are needed to focus the slip to reproduce the scale and pattern of deformation observed with InSAR. Lateral changes in the regional stress shape and orientation are key to reproducing the observed rupture transfer from the TF to the RSF while maintaining the rake required to reproduce the broad InSAR surface deformation pattern and multi-peak source time function. The dynamic rupture modeling results suggest that significant variability in fault stress and strength as well as complexities of the subsurface geometry may have been key controlling factors on the dynamics of the 2021 rupture.

POSTER 20

Implications of a Reverse Polarity Earthquake Pair on Fault Friction and Stress Heterogeneity Near Ridgecrest, California

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Earthquake focal mechanisms are estimated from seismic observations and provide valuable information on fault geometry and crustal stress orientation at depth. Most focal mechanisms are spatially correlated, that is, mechanisms tend to be similar to those of neighboring earthquakes. However, on rare occasions earthquake pairs are observed that appear nearly opposite in orientation, as evidenced by seismograms that are flipped in polarity. These extreme examples of focal mechanism diversity are valuable because they provide strong constraints on fault and stress properties at depth. Here we apply the Matrix Profile algorithm to 100 days of continuous data from the 2019 Ridgecrest, California, sequence and find many examples of reversely polarized waveforms. We focus our analysis on a particularly well-recorded reverse-polarity earthquake pair among the Ridgecrest aftershocks. Our analysis shows that the two events in the pair are at 10 km depth in the crust but only 115 m apart and that their fault planes differ in orientation by less than 20 degrees. This implies either unusually low values of fault friction, which permit faults to slip even when they are far from their optimal faulting orientation, or strong changes in stress orientation at depth, perhaps caused by residual stresses from prior earthquakes.

Visualization and Sonification in Solid Earth Geosciences, What's Next?

Oral Session • Thursday 17 April • 10:30 AM Local

Conveners: Julien Chaput, University of Texas, El Paso (jachaput@utep.edu); Debi Kilb, University of California, San Diego (dkilb@ucsd.edu); Leif Karlstrom, University of Oregon (leif@uoregon.edu); Zhigang Peng, Georgia Institute of Technology (zpeng@gatech.edu)

Shakemovie: Rapid Post-earthquake Animation of Near-fault Ground Shaking

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Earthquakes are known to generate complex near-fault ground shaking effects such as rupture directivity and amplification of waves in sedimentary basins. Verbally describing these features can be cumbersome and time consuming especially within an event-specific context. An alternate way to efficiently convey this information is with visualizations. ShakeMovie (patterned after Princeton's *Global-ShakeMovie*) is a recently developed resource that quickly produces a computer-generated animation of earthquake rupture and ground shaking effects throughout the near-fault region.

The ShakeMovie workflow consists of five main modules: 1) 3D velocity mesh creation, 2) kinematic rupture specification, 3) 3D wave-propagation, 4) graphics rendering, and 5) video generation. Required inputs are a general description of the earthquake and its location, i.e., magnitude, hypocenter, slip mechanism and faulting information. Then, the Graves-Pitarka kinematic rupture generator is used to create the full source parameterization needed for the computation. The current implementation covers most of California using the SCEC 3D Community Velocity Model, the USGS SF Bay Region 3D Velocity Model and the Cape Mendocino Region 3D Velocity Model. The wave-simulation code uses a grid spacing of 100 meters and minimum shear wave velocity of 500 m/s, yielding results at shaking periods of one second and longer. Graphics rendering and video generation are done using *Generic Mapping Tools* and *FFmpeg* software packages, respectively. To produce the animation in a timely manner, parallel coding coupled with High Performance Computing (HPC) resources are utilized. The goal is to have the animation available within one hour following the occurrence of the earthquake. The ShakeMovie workflow has been successfully implemented on several HPC platforms and currently is being run on Frontera at the Texas Advanced Computing Center under an allocation to SCEC. In my presentation, in addition to describing the workflow elements, I will also show examples of recent ShakeMovies and discuss strategies on possible future improvements.

Optimizing Earthquake Ground Motion Visualizations to Enhance Public Understanding and Preparedness

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Creating engaging and informative visualizations of earthquake ground motion can improve public understanding of seismic hazards, reduce anxiety, and enhance preparedness. Educating the public about earthquakes also increases the acceptance of scientific findings and helps to justify allotted research funding. In this social science study, we evaluate the effectiveness of user-centered computational earthquake ground motion visualizations, accompanied by voice-overs explaining key concepts. We survey the general public to assess how these visualizations can enhance the public's understanding of scientific facts and comprehension of seismic hazards and address common misconceptions about earthquakes, which prior studies have shown are problematic (e.g., Karjack et al., 2022).

We designed an online survey containing 25 questions and three animations that provide an avenue to pre-test the public's understanding of these products, evaluate at what point and through which channels these visualizations should be distributed following a notable earthquake, which design format is preferred, and to what extent the information conveyed is actually understood. We gather quantitative feedback from participants recruited via social media platforms (e.g., LinkedIn and BlueSky) and direct emails. We aim to obtain feedback from ~200 survey participants. In the questionnaire, the participants can share their opinions about the three visualizations, and survey questions are used to assess their understanding of the science concepts. Participants have the opportunity to provide socio-demographic information to help us assess potential correlations between demographics and survey results. Our overall goal is to evaluate what earthquake ground motion visualizations are the most useful, what aspects need improvement, and how to iteratively improve these visualizations to increase the public's understanding of seismic hazards and earthquake preparedness.

Sonic and Visual Representations of Seismic Data, Coupled to Machine Listening and Pattern Discovery

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Since about 2005, participants in the Seismic Sound Lab activities have been exploring the use of sonification and synchronized data animations ("data-movies") to convey a wide range of aspects of earthquake physics and other natural signals beyond our normal perceptual reach, from laboratory acoustic emissions to decades of earthquakes. We also explore the use of multi-modal data sonifications: data representing different, coupled expressions of a complex process, such as seismicity and ground deformation in Kilauea (Karlstrom et al, "Earth is Noisy. Why should its data be silent?" EOS, 2024), geysers and geothermal reservoirs. Multi-modal data sonification requires a range of methods that span from "direct sonification" to "tonal representation," with an increasing need for aesthetic choices from the former to the latter. Tonal representation is required for non-oscillatory signals, using a broad range of methods from simple beeps to granular synthesis. Our sonification work also has a close and growing connection to unsupervised machine learning methods aimed at pattern discovery, loosely called machine listening. Our seismic catalog sonifications and listening experiments led to a collaboration with John Paisley, a data scientist, who had previously worked on feature extraction methods for speech and audio analysis. He developed what we now call SpecUFEx, to detect subtle variations in the spectral-temporal content of microseismicity and ambient noise, first applied to a catalog from The Geysers (Holtzman et al, Science Advances, 2018). In this talk, we will show data-movies from that paper, that illustrate the patterns detectable by human listening and then those that emerge with machine listening. We will discuss some current work on detection of multi-scale patterns in acoustic emissions in laboratory experiments. We will discuss the similarities between speech/audio and seismic data as they pertain to the feature extraction methods, and some perspectives on the benefits of iterating between human and machine listening.

Sonifying Seismic Data on the Go, for Research and STEM Engagement

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Seismic waveforms are perfect candidates for data sonification as they merely need to be squeezed in time. Most existing applications of seismogram sonification adjust the output volume to the maximum amplitude of the input waveform, which is helpful in cases where a waveform's characteristics matter more than its amplitude. The smart phone app "Earthtunes" allows users to fix the volume setting, so the waveform's output volume is proportional to signal power on an absolute scale, which allows users to compare signal strength across time and space. This sonification algorithm was used in a research project, called Earthquake Detective, where volunteers ("citizen scientists") helped researchers classify high-frequency seismic signals coincident with low-frequency surface waves into one of four categories, including dynamically triggered earthquakes and tremor. This helped researchers comb through vast amounts of data in ways machine learning algorithms were not ready for. The infrastructure of this highly accessible and mobile Zooniverse project is available to any seismologist needing this kind of help in data analysis or monitoring. While Earthtunes also helps researchers with data exploration, especially when in the field or otherwise on the go, it is an excellent engagement tool as well. The ability to listen to seismic events in near real-time fosters a deeper appreciation for our planet. Listening to earthquakes and other events as they happen enhances users' awareness of geological activity and its impact on the world around them. Pre-programmed Earthtunes challenges include sonified earthquake signals, close and far away, induced and tectonic, as well as sonified seismic noise on an island, Antarctica, planet Mars, pre- and during a COVID-19 lockdown, and on quiet and stormy days. Sonified swarms of earthquakes in the Reykjanes peninsula were shared widely when volcanic fissures opened there late in 2023.

Sonification and Visualization of High-resolution Earthquake and Tremor Catalogs

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Recently, template matching and machine-learning methods have been applied to detect regular microearthquakes and low-frequency earthquakes in tectonically active regions, resulting in a significant increase in the number of events listed in these high-resolution catalogs. These catalogs can be used to delineate subtle fault structures and reveal hidden patterns in their space-time evolutions. In a 2D plot those events are projected along a certain fault plane or the distances with respect to a certain point are calculated. In some cases, a 2D-map view or 3D-projected animation is generated but without any sound effects. In this study, we explore the possibility of including sounds in the 2D or 3D animations of high-resolution catalogs. We shape the amplitude and frequency content of the sounds to represent earthquake magnitudes, depth and other spatial features. This allows us to take advantage of the human auditory pattern recognition system, unearthing patterns that can't be intuited from visual animations. Our target regions are the Parkfield-Cholame section of the San Andreas Faults in Central California, where millions of low-frequency earthquakes have been detected since 2001, and the Noto Peninsula region in Western Japan, where an intensive earthquake swarm started near the end of 2020, and was followed by a magnitude 7.5 earthquake on Jan 1st 2024. We plan to use these animations to demonstrate the unique spatial-temporal migrations of tremor and earthquake swarms in these regions. Updated results will be presented at the meeting.

Why Ignore the Structure? Soil-structure Interaction and Site Response at Local and Regional Scales

Oral Session • Thursday 17 April • 10:30 AM Local

Conveners: Sean K. Ahdi, ARUP US, Inc., (sean.ahdi@arup.com); Mohammad Yazdi, Mott MacDonald, (m_yazdi@nevada.unr.edu); Peiman Zogh, ARUP US, Inc. (peiman.zogh@arup.com)

Vs30-Fd Relationship for Measured-Vs30 Stations in the Western United States

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Two important ground motion modeling parameters have been used to account for seismic site effects at network seismic monitoring stations: 1) the time-averaged shear-wave velocity (V_S) of the upper 30 m from the ground surface (V_{S30}), derived through V_S profiles determined from in situ measurements; and 2) the dominant site frequency (f_d), derived from the horizontal-to-vertical spectral ratio of earthquake (eHVSR) or microtremor (mHVSR) ground motions recorded by the single-station method. Using f_d from mHVSR as an independent parameter for characterizing site effects in ground motion models (GMMs) is important because—when f_d is derived from eHVSR—its use in GMMs may introduce circularity, making the eHVSR-based f_d less suitable as an independent parameter. These two indices characterize different aspects of site effects and the effectiveness of using either (or the combination of) indices as site terms is an ongoing research topic; f_d, particularly when based on microtremor sources is substantially less costly to determine than in situ V_{S30}. As both indices are known to fundamentally represent seismic site conditions, we regress measured V_{S30} against f_d using available data recorded by stations in the western U.S. The many different methods for computing HVSR may result in varying f_d estimates, whereas V_{S30} methods are relatively better established. We examine possible f_d-related biases by using a common set of recordings from each network station and by computing their Fourier amplitude spectrum (FAS), power spectral density (PSD), and response spectrum (RS) based HVSRs. We discuss the pros and cons of the FAS, PSD, and

RS approaches to computing f_d, then present a relationship between V_{S30} and f_d, and compare the relationship to those proposed in recent studies.

Probabilistic Seismic Assessment of Nuclear Power Plants

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The seismic performance of nuclear power plants is critical for the safety operation of nuclear infrastructure given the catastrophic consequence if reactors are damaged by earthquakes. The soil exhibits significant spatial variability, which has important impact on evaluating the seismic performance of nuclear power plants under earthquake hazard conditions. The paper aims to present a probabilistic scheme to evaluate the reliability of nuclear power plants considering soil spatial variability in the face of earthquake hazards using the random finite difference method. A 3D soil-foundation-structure numerical model will be established to evaluate the seismic performance of nuclear power plants. A case study is utilized to demonstrate the effectiveness of the proposed framework for the probabilistic seismic assessment of nuclear power plants under earthquake hazards. The results from this paper can provide useful insights for practitioners to evaluate the seismic risk of nuclear power plants and make an informed decision in the face of earthquake hazards.

Sub-regional Site Response for the San Francisco Bay Area

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This study aims to develop a site response model specific to Northern California, focusing on the San Francisco Bay Area (SFBA). Whereas current NGA-West2 ground motion models, such as Boore et al. (2014; BSSA14), were developed for application across broad regions (such as California), they may be biased for application in particular sub-regions. We investigate whether the unique geology in the SFBA contribute to sub-regional site response features that can be modelled conditional on V_{S30}, 1.0 km/s isosurface depths ($z_{1.0}$), and broad geologic descriptors.

Typical site conditions in the SFBA include Quaternary sediments of variable thicknesses over Franciscan Complex bedrock west of the Hayward Fault, whereas east of the Hayward fault outcropping bedrock includes Late Jurassic through Cretaceous Great Valley Sequence formations and Tertiary sedimentary rock such as the Orinda formation. In contrast to the deep sedimentary basins that inhabit large areas in Southern California, the SFBA Quaternary sediments are generally characterized by smaller basins (e.g., San Jose, Livermore) and shallow sedimentary-shelf deposits, typically with $z_{1.0} <$ 200 m. Based on these observations, we classify major site types, from rock to soil as: Franciscan and Great Valley Sequence rock, Tertiary rock, shelf deposits, valleys, and basins. These distinct geological provinces provide a basis for investigating systematic variations of site response across the region.

Preliminary findings suggest that the ergodic V_{S30}-based site response model in BSSA14 generally performs well across the region as a whole, but that adjustments are needed for soft and stiff sites and stiff sites (> 760 m/s). Specifically, the data support V_{S30}-scaling saturation for low-velocity sites (< 200 m/s), small adjustments to V_{S30}-scaling for moderate site conditions, and reduced de-amplification for V_{S30} > 760 m/s. Ongoing work is underway to examine depth effects, which will be conditioned on type of geologic province.

City-scale Assessment of Site and Basin Effects in Selected CEUS Sedimentary Basins: Memphis and New York City

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Many cities in the central and eastern United States (CEUS) are located in sedimentary basins with strong potential for soil amplification and earthquake-induced damage. As part of this study, we examine city-scale site response in two CEUS cities that reside within basin structures: Memphis, TN, and New York City, NY. We develop shear-wave velocity models from available data and perform theoretical linear one-dimensional site response analyses to estimate site response at multiple ground-motion stations within these cities. We compare the theoretical site response predictions with those from the NGA-East V_{S30}-based linear amplification model (Stewart et al., 2020) and a linear amplification model proposed in a companion study (Meyer et al., 2025) that is based on geospatial predictor variables (adjusted physiographic province and sediment thickness) rather than V_{S30}. We also compare the results to observed amplifications from recent earthquakes recorded at ground-motion stations in each city. In Memphis, which is located on deep sediment within the Mississippi Embayment, our proposed model accurately predicts long-period amplification but overestimates short-period amplification compared to the NGA-East model. In New York City, which is located on the edge of the Atlantic Coastal Plain, there are significant variations in sediment thickness. Both linear site amplification models perform better at deep sites than shallow sites, highlighting the difficulty in modeling site response at shallow sediment sites with strong impedance contrasts and the need for higher-resolution sediment thickness data in the entire CEUS. The improved performance of our model in Memphis at longer periods indicates that the explanatory variables of sediment thickness and adjusted physiographic province are useful for estimating site amplifications in regions with deep sediments in the CEUS. This study also highlights the limitations of ergodic ground-motion modeling and the benefits of site-specific or city-scale ground response analysis within vulnerable cities, especially in capturing changing behavior at a smaller spatial scale.

Investigation of Basin Effects in Po Plain in Italy: A Case Study From 2012 Emilia Earthquake Sequence

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In this case study, we evaluated site amplification observed during the 2012 Emilia earthquake sequence in the Po Plain, Northern Italy. This research not only delves into the amplification characteristics but also assesses the performance of two recently published ground motion models (GMMs) in capturing basin effects in the region. We compiled a comprehensive strong motion flatfile for all of Europe, which includes over 50,000 recordings from at least 6500 earthquakes between 1969 and 2023. Using this flatfile, we extracted approximately 650 strong ground motion records from 99 stations, both inside and along the basin edges of the Po Plain. A significant portion of these records originates from the 2012 Emilia sequence. To estimate single-station ground motion amplification, we utilized three reference rock stations located outside the Po Plain. Our key findings include: 1) significant difference in rock stations response spectra at the north and south edge of Po Plain, due to underlying complex geologic structure; 2) peak amplification generally occurs between spectral periods of 0.7 to 3.0 seconds; and 3) interestingly, the stations along the southern edge exhibited more significant amplification beyond spectral periods of 0.5 seconds relative to northern edge, likely due to basin edge effects. For qualitative isolation of basin edge effect, we performed 1D nonlinear site response analysis using DEEPSOIL at the two stations along southern edge. Results of 1D site response analysis showed peak amplification near the resonance frequency followed by de-amplification, whereas GM records showed sustained amplification. Further, we assessed the performance of two GMMs widely used in the region: the Italian regional model by Lanzano et al. (2019) and the pan-European model by Kotha et al. (2022). The results of robust residual analyses, which utilized all ground motion recording within the Po Plain, indicated that both models tend to underpredict the amplification. However, the regional model demonstrated better performance in capturing part of basin edge amplification compared to the pan-European model.

Why Ignore the Structure? Soil-structure Interaction and Site Response at Local and Regional Scales [Poster]

Poster Session • Thursday 17 April

Conveners: Sean K. Ahdi, ARUP US, Inc., (sean.ahdi@arup.com); Mohammad Yazdi, Mott MacDonald, (m_yazdi@nevada.unr.edu); Peiman Zogh, ARUP US, Inc. (peiman.zogh@arup.com)

POSTER 7

Evaluating Soil-structure Interaction and Site Response in Urban Excavation: Insights From the I-495 Project Next

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The interaction between soil and structural systems is crucial for ensuring stability and performance in urban excavation projects. This study examines the design, installation, and monitoring of a multi-phase soil nail wall reinforced with temporary and permanent shotcrete, constructed as part of the I-495 Project Next in McLean, Virginia. The project involved installing 70 soil nails and applying shotcrete over a total area of approximately 3,270 sq. ft., with temporary shotcrete providing immediate stability and permanent shotcrete ensuring long-term stability, durability, and aesthetic requirements. A comprehensive monitoring plan was implemented to evaluate soil-structure interaction and site response. The monitoring system, utilizing methodologies such as differential leveling for vertical settlement and lateral displacement monitoring, employed Total Station equipment (LEICA TS-16) and adhesive reflective targets to track movements of both the existing abutment and the newly constructed soil nail wall. By comparing baseline pre-construction data to real-time monitoring results, potential perpendicular, lateral, and vertical displacements were accurately identified, confirming minimal displacements within design tolerances. This study highlights the importance of a well-integrated soil nail and shotcrete system in managing soil-structure interaction and site response in complex urban excavation projects. The findings emphasize the importance of integrating monitoring systems into excavation projects to evaluate ground motion, site response, and soil-structure interaction. This study contributes practical insights to geotechnical engineering practices, particularly in urban and regional settings, and highlights the significance role of monitoring in mitigating risks associated with ground movement in complex infrastructure projects.

Keywords: Soil-structure interaction, soil nail wall, shotcrete, site response, ground motion, monitoring, geotechnical engineering, structural stability.

POSTER 8

Nonlinear Dynamic Analysis of RC Structures and Soil Structure Interaction Effects

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In seismically prone areas, when a severe earthquake occurs, it can cause significant damage to structures, leading to economic losses and a threat to human safety. Therefore, increasing the reliability and resilience of structures against seismic events is essential to reduce the destructive effects. One way to achieve this goal is through advanced analysis methods such as nonlinear dynamic analysis. This analysis allows for a more realistic assessment of the behavior of structures by considering the nonlinearity of materials, large deformations, and damage mechanisms that occur under severe earthquake forces. As well as the dynamic interactions between structural components and underlying soil layers, known as soil-structure interaction (SSI), which affect the overall seismic performance and safety of structures. The combination of these methods ensures a comprehensive understanding of how structures behave during earthquakes, leading to improved design strategies.

In this analysis, modeling using numerical methods has been performed on RC frames to evaluate their dynamic response under seismic loading. The results were compared using different values of Rayleigh damping and ductile and brittle modeling of failures to determine the most efficient results in terms of peak ground acceleration (PGA) and peak ground velocity (PGV) over time. Next, we will evaluate the soil-structure interaction (SSI), which plays an important role in the overall response of buildings, using numerical methods and laboratory tests. The flexibility and deformation of the soil can affect the movement of the structure and lead to changes in its dynamic behavior. By integrating SSI with nonlinear dynamic analysis and time history, we aim to provide a more realistic and comprehensive assessment of the structure's performance during seismic events. This combined approach will help develop more accurate design recommendations for earthquake-resistant buildings, ultimately increasing their reliability and resilience.

POSTER 9

Application of Bayesian SPAC to Estimate Vs30 and Classify Soils in Ponce, Puerto Rico

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The city of Ponce, one of Puerto Rico's largest urban centers, is characterized by significant variations in topography and soil conditions, which result in differences in seismic wave amplification across the area. To address these variations, seismic design standards such as ASCE 7-22 recommend adjusting seismic design spectra based on local soil characteristics. Accurate estimation of the average shear-wave velocity in the upper 30 meters of soil (Vs30) is crucial for ensuring resilient infrastructure and promoting sustainable urban development. In line with the United Nations' Sustainable Development Goal No. 9, which advocates for resilient infrastructure, the Spatial Autocorrelation (SPAC) method provides a non-invasive, Cost-effective way to estimate Vs30, making it ideal for densely populated cities like Ponce.

This study applied the SPAC method at 10 locations across Ponce, utilizing three concentric circular arrays (or three common-base nested triangle arrays), with the largest circle having a radius of at least 30 meters. Data were recorded over a minimum of four days to capture dynamic variations in ground behavior at different times of day and week. Hierarchical Transdimensional Bayesian Inversion was then employed to analyze the coherence curves derived from the SPAC data, enabling the calculation of shear-wave velocity profiles and Vs30 values at each site. These Vs30 values were subsequently used to classify the soils according to the National Earthquake Hazards Reduction Program (NEHRP) standards.

The results revealed that most of the studied sites in Ponce are classified as soil type C or worse, indicating soils with limited energy dissipation capacity that are likely to amplify seismic waves. Interestingly, the coherency curves at bedrock sites displayed unexpected behavior, that's why the model fits were more accurate for sites with soil layers than for bedrock, where the SPAC-derived shear-wave velocity profiles closely matched the observed data. These findings contribute to a more precise characterization of Vs30, A key parameter for estimating seismic loads buildings must withstand.

POSTER 10

Toward Neural Network Based Automated Structural Health Monitoring With MyShake Smartphones

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Effective Structural Health Monitoring (SHM) is crucial for maintaining the safety, resilience, and integrity of buildings and infrastructure. However, traditional SHM methods often rely on costly, labor-intensive sensor installations, limiting scalability. The widespread availability of smartphones with built-in accelerometers offers an innovative, cost-effective alternative for SHM. The MyShake smartphone app, developed at UC Berkeley, harnesses this potential by collecting acceleration waveforms during seismic events and ambient vibrations to monitor the dynamic properties of buildings.

MyShake, part of California's Earthquake Early Warning initiative, has been downloaded over 2.9 million times globally. It delivers earthquake early warnings and autonomously records three-component waveforms during significant shaking or ambient vibrations. Since smartphones are often stationary within buildings, these recordings provide critical insights into ground motion and structural behavior. Previous research has shown MyShake's ability to capture natural frequencies of buildings during seismic and wind loading events, proving its viability for SHM.

To scale this approach, we developed an artificial neural network (ANN)-based automated workflow for analyzing natural frequencies and damping properties of buildings. We curated a dataset of 3,000 ambient vibration records, manually labeled for measurement quality, to train the ANN. This workflow automates the association of smartphones with buildings, evaluates waveform quality using statistical parameters, and applies power spectral density (PSD) analysis to compute dynamic building properties.

Controlled deployments in the San Francisco Bay Area validated the method's accuracy across structural types.

Our results confirm the feasibility of using MyShake-enabled smartphones for reliable SHM under strong and ambient dynamic loading conditions. This integration of crowdsourced smartphone data and machine learning provides a scalable, efficient solution for global SHM, paving the way for proactive maintenance and improved infrastructure safety.

POSTER 11

Incorporating Uncertainties Into Vs-delta Kappa_0 Corrections

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Relevant characteristics of recorded earthquake ground motions reflect the contributions of shallow and deep geologic structures at the recording station. Instrumented infrastructure (e.g., bridges or buildings) are still not common, and when available, records at these sites of interest may not correspond to desired design levels. Hence, adjustments of recorded ground motions are necessary to obtain hazard-compatible ground motions at the site of interest. While corrections for impedance and attenuation properties of near-surface materials have been proposed, uncertainty in those properties has not been explicitly quantified. The Vs-delta kappa_0 correction framework is used here to modify recorded ground motions at the ground surface and derive ground motions at the assumed reference condition at a nearby site of interest (i.e., simplified deconvolution process). This study incorporates uncertainties in shear wave velocity (Vs) and delta kappa_0 into the modification of recorded ground motions. To demonstrate our proposed approach, we use a case study based on recorded ground motions from the 2018 Anchorage earthquake and measured Vs profiles in Anchorage, Alaska. The Toro's (1995) randomization model (i.e., Monte Carlo simulations) is applied to generate multiple synthetic Vs profiles and assess uncertainties in Vs values. A range of delta kappa_0 is also considered. The multiple synthetic Vs profiles help obtaining multiple modified ground motions using the Vs-delta kappa_0 correction framework. We find that adjusted median spectral values, in terms of spectral accelerations and displacements, at the assumed reference conditions are in agreement with recorded ground motions at a nearby downhole array and they fall within one standard deviation from median predictions from suitable ground-motion models. The proposed framework to incorporate uncertainty in Vs and delta kappa_0 provide a simplified alternative to deconvolution techniques and can expand the catalog of suitable recordings at a given site of interest.

POSTER 12

Nonlinear Site Response Observed by the NDHU Downhole Array During the April 2, 2024 Taiwan M7.4 Earthquake

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At the end of April 2nd, 2024, an earthquake with a magnitude of 7.4 occurred in Hualien County in eastern Taiwan. The largest earthquake in Taiwan in a quarter century induces extremely strong ground motion with a maximum PGA of 1.5 g and PGV over 80 cm/sec in the nearfield. In two months after the mainshock, thousands of aftershocks, including seven earthquakes larger than M_L 6.0, occurred in a northeast-striking linear region of about 70 km. The NDHU downhole array consisted of four accelerometers installed at depths of 0, 20, 30, and 70 meters. It is just 5.2 km from the epicenter of the M7.4 earthquake and observed a PGA of 271 gal. This study used a large number of downhole records during the earthquake sequence to analyze the local nonlinear site responses of the ground motion. For small input ground motions with peak acceleration lower than 10 gal, the PGA observed at the ground surface is about twice that observed at the depth of 70 meters. Based on the spectral ratio of surface to downhole horizontal accelerations, the predominant frequency of the soil amplification is at 2.0 Hz, which agrees with the theoretical transfer function of the soil profile. The second and third modes of soil amplification also obviously appear at 5.5 Hz and 8.4 Hz, respectively. As the input ground motion increases, the amplification of peak acceleration from downhole to surface gradually decreases, and the dominant frequencies also become lower. For the M 7.4 mainshock, the peak acceleration at the ground surface is 1.5 times the downhole input ground motion of 181 gal. The predominant frequency of the soil amplification moves to 1.5 Hz. The nonlinear site responses depressed the peak acceleration and predominant frequency of ground motions observed at the NDHU downhole array. The significant nonlinearity allows us to conduct further research on soil behavior.

POSTER 13

Willamette Valley Site Characterization With HVSR

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Oregon's population density is mostly concentrated within the Willamette Valley, a foreland basin with sedimentary cover. Sedimentary fill in basins or valleys will amplify ground motion at frequencies related to regional structure, a key component of accurately assessing hazard and understanding the impacts on the built environment. One methodology to constrain spectral site response and amplification is from horizontal-to-vertical spectral ratios (HVSR). This relies on sufficient seismic activity and instrumentation, which have both been low historically in the Willamette Valley. Recently, instrumentation has increased due to the buildout of the Pacific Northwest Seismic Network, providing additional constraints to use in the region.

We present our analysis of earthquake HVSR (eHVSR) data on permanent broadband (BB) and strong motion (SM) instrument recordings within the Willamette Valley, following the SESAME criteria for identifying fundamental site frequencies. We found that, of the 17 fundamental peak frequencies (f0) identified throughout the Willamette Valley, 82% were < 3 Hz, 76% were < 2 Hz, and 47% were < 1 Hz, and SM instruments were less reliable than BB in detecting f0 < 1 Hz due to their corner frequency (fc) limits. Some sites had just a few reliable and clear peaks, however others were affected by basin effects, which produced a significant number of qualifying peaks across a large range of frequencies due to trapped waves within the sediments. Our ability to fully characterize site response is still affected by limited permanent instrumentation in the center of the Willamette Valley. Future HVSR studies of this region should consider a higher density placement of BB seismic instruments, microtremor inclusion, and azimuthal processing to observe true fundamental frequencies on a microzonation-scale in order to gain a better understanding of expected ground motion across Oregon's most densely populated areas.

POSTER 14

Cosmos Site Characterization Working Group: Achievements and Perspectives, From the Determination of Soil Properties to the Consideration of Topography and Installation Effects

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We present the results and perspectives of the "Site Characterization" working group of the Consortium of Organizations for Strong Motion Observation Systems (COSMOS). The group's leaders see the project as an interdisciplinary means of bringing together the engineering and earth science aspects associated with site characterization. Since 2015, implementation recommendations of non-invasive and passive site characterization methods have been issued. The main outcomes of these efforts was the publication of articles in a special issue of the Journal of Seismology in 2022. In parallel, a series of international online and face-to-face workshops, meetings and a training course have been organized from 2022 to 2024 and additional user-specific workshops are scheduled for future conferences. The working group is also planning to develop an Internet forum to bring together users and experts in the field of site characterization. In the coming years, in addition to the site characterization, the working group aims to broaden the range of topics covered by considering all the phenomena that impact the representativeness of recorded signals. One example is topographical site effects, on which we propose to contribute to the organization of a numerical simulation benchmark within the framework of the ESG 2026 conference. It is also important to address the "installation effects", i.e. the impact of the practical installation choices of seismological stations (coupling using concrete slabs or pillars, etc.; installation on the surface, manholes, or at greater depth; installation in larger or smaller buildings). With this in mind, we would like to establish a consensus on the additional metadata required to fully describe a station. In the long term, we plan to propose a best practice guide for installing seismological stations, to minimize external perturbation effects.

POSTER 15

Shear-wave Velocities in the Bellingham and Everett Basins, Washington State: Insights From Multimethod Characterization With krSPAC and Active-source Linear Arrays

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Characterizing earthquake ground motions through three-dimensional simulations has become an important focus for seismic hazard assessment in urbanized sedimentary basins. However, realistic ground motion prediction requires shear-wave velocity (Vs) at depths that capture the extent of the sedimentary column (i.e., usually >30 m), which is often poorly constrained. We acquired microtremor array data at 19 sites throughout the Everett and Bellingham basins in the Puget Lowland, Washington State, and applied the wavenumber-normalized spatial autocorrelation method (krSPAC) to characterize Vs at depths capable of delineating the Quaternary and upper Tertiary deposits, possibly >1000 m at some sites. In contrast to a traditional SPAC approach, where modeling high wavenumbers within the SPAC spectrum requires array symmetry, in the krSPAC approach we interpolate observed coherency-versus-frequency spectrum to coherency-versus-kr (where k and r are wavenumber and averaged interstation spacing, respectively), prior to Vs modeling in the kr domain. We deployed ten-sensor nested asymmetric triangular arrays with nominal interstation spacings that varied from ~100 m to 1000 m. We complement the krSPAC microtremor data with two colinear active-source, 72-sensor linear array seismic datasets (1.5 m sensor spacing) at the center of each site: one with single-component (1C) 4.5 Hz vertical and one with 1C 4.5 Hz horizontal sensors. We analyze the active-source horizontal-component data for both SH-wave refraction traveltimes and Love wave dispersion, and the vertical-component data for Rayleigh wave dispersion and P-wave refraction traveltimes. For modeling, we first use the active-source dispersion and traveltime datasets in an iterative least-squares joint inversion to constrain Vs in the upper ~50 m; these shallow profiles then constrain the krSPAC microtremor modeling, which resolves Vs to greater depths. Preliminary Vs profiles in both basins are generally consistent with those observed farther south in the Seattle and Tacoma basins, with Vs ranging from ~200 m/s to ~900 m/s in the upper 600 m at the deeper basin sites.

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