dicular and parallel to seismic reflectors, giving rise to oriented structure tensors. These oriented tensors enhance the representation of lateral velocity discontinuities, particularly those associated with features that align with dipping structures in the velocity model. The numerical experiments conducted using the well-established Marmousi model demonstrate better representations of discontinuous and stratigraphic velocity features compared to conventional FWI.

POSTER 101

Physics-Guided Unsupervised Deep Learning Approach for the Inversion of Receiver Functions in Dipping and Anisotropic Media

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The converted wave technique namely Receiver function (RF) has been utilized routinely for probing the crust and mantle structures. In the analysis of receiver functions, deterministic physical methods such as inversions are frequently employed to refine the estimations to image the subsurface realistic geological structure. Despite their utility, the presence of dipping and anisotropic geological structures very often complicates and can even hinder the inversion process. To address these complexities, here we introduce a Physics-Guided unsupervised deep learning approach for the inversion of receiver function data. We employ unsupervised deep learning, enhanced with implicit neural representations, allowing for the prediction of inverted Earth model parameters: thickness (H), S-wave velocity (Vs), anisotropy, trend, plunge, strike and dip without requiring any labeled data. For determining the optimal model parameters, the output parameters are used in a forward modeling scheme to simulate the receiver functions. During training, the model iteratively adjusts and improves these parameters based on discrepancies between the simulated and observed receiver functions. Inversion results from both synthetic and field examples from the Indian shield suggest that physics-guided unsupervised deep learning approach is effective in inversion tasks, particularly when dealing with intricate geological settings like dipping and anisotropic media. With its application aimed at understanding subsurface structures, we believe that this approach holds potential to broaden the capabilities of subsurface exploration.

POSTER 102

Towards a Practical Physics-Informed Neural Network Method for End-to-End Full Waveform Inversion

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Our aim is to explore the viability of end-to-end deep learning (DL) methods for full waveform inversion (FWI) towards practical use for active-source seismic data shot gathers, which may be able to overcome some of the challenges of traditional FWI. We developed a DL-based FWI method that inputs elastic full-waveform shot gathers along a seismic line and outputs a 2-D P-wave velocity model. We employ a physics-informed neural network (PINN) that solves the acoustic wave equation for enhanced generalizability and physics-based inverse solution. This method takes a starting velocity model guess and iterates over solving for the acoustic wave equation via PINN with boundary and initial condition constraints, including a point source location and source function, while fitting the input data for an updated velocity model that honors the physics. We generate a starting velocity model using a data-driven neural network trained on over three thousand velocity model and shot gather pairs. We explore multiple PINN architectures, including a physics-informed (PI)-DeepONet, which is a neural operator that allows for further generalizability and flexibility for enforcing boundary condition constraints (e.g., shot location and source function).

We find that our current methodology requires long training times for each inversion when incorporating a PINN and the solution struggles to converge for the source frequencies of interest. The S-wave energy in our elastic data further complicates our training and appears to confuse the NN and results in poorer solutions. Further research into PINN convergence for the wave equation, ways to limit frequency bias during learning, preprocessing techniques for sseismic data, and training strategies (e.g., domain decomposition, frequency staging), will pave the way for future end-to-end method that can compete with traditional or hybrid FWI methods at the scale and frequencies generally of interest for practical applications.

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POSTER 103

An Autoencoder-Based Prior for Bayesian Full Waveform Inversion

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To quantify the uncertainties of seismic full waveform inversion (FWI), one can solve FWI in Bayesian inference framework by estimating the posterior probability distribution (PPD) of subsurface model given seismic data. Sampling-based methods, e.g. Markov chain Monte Carlo (MCMC), draw samples from the PPD of the Bayesian inference problem and those samples can be used to estimate the PPD and make inference of the model. For Bayesian FWI problem, MCMC sampling suffers from low-convergence and inefficiency due to the high dimensionality of the model space.

In this abstract, we propose to train an autoencoder based on a subset of posterior samples and use it as prior for Bayesian FWI problem. We design a convolutional autoencoder (CAE) with a bottleneck latent layer with only a few variables. By training the CAE, the model space dimension can be reduced greatly. The proposed workflow starts with a short-run adaptive MCMC chain in physical domain model space for the FWI problem, generating a subset of posterior samples. Then the subset samples are used to train the CAE. Lastly, we run new MCMC chains in latent model space and use the decoder part of the CAE to transform the latent samples to physical domain samples. We verify the feasibility of the proposed method with Marmousi synthetic model example. Compared to physical domain MCMC chains, the proposed method improves the efficiency of MCMC in solving Bayesian FWI problem.

Marine Seismoacoustics

Oral Session • Wednesday 1 May • 4:30 PM Pacific

Conveners: Kasey Aderhold, EarthScope Consortium (kasey.aderhold@earthscope.org); Helen Janiszewski, University of Hawaiʻi at Mānoa (hajanisz@hawaii.edu); Siobhan Niklasson, Los Alamos National Laboratory (sniklasson@lanl.gov); Charlotte Rowe, Los Alamos National Laboratory (char@lanl.gov)

Rupture Behavior of Large Strike-Slip Earthquakes at Equatorial Atlantic Oceanic Transform Faults: Constraints From Hydroacoustic Data

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Oceanic transform faults (OTFs) are tectonic strike-slip plate boundaries that offset mid-ocean ridges by tens to hundreds of kilometers, thus reaching the globally largest oceanic offset with up to 900 km in the equatorial Atlantic Ocean (EAO). Earthquakes along OTFs can produce moment magnitudes (Mw) of >7, with global networks monitoring in real time. Previous studies used teleseismic data, numerical modeling, and thermal constraints to yield characteristics of the seismic rupture behaviors along the OTFs. In this study, we take a different approach by using hydroacoustic T-waves arriving at the International Monitoring System hydrophone triplet deployed at Ascension Island and belonging to the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) to study the rupture of 43 strike-slip earthquakes in the EAO. The earthquakes occurred along nine OTFs in EAO with 5.6>Mw<7.1 reported by the Global Centroid Moment Tensor catalog. We use cross-correlation and arrival-time difference variations to identify the T-wave source directions (back-azimuth) and compare interceptions of the direc-

tions with mapped fault traces from multibeam bathymetric data to reveal the total rupture length of the earthquakes. Our technique is based on sound propagation through the ocean and provides a new alternative characterization of the rupture behavior of large strike-slip earthquakes. Our preliminary results show rupture lengths reaching from 5.34±1.0 to 101.98±12.8 km and rupture velocities between 0.83±0.29 and 4.5±0.8 km/s, with a well-correlated least-square regression between the rupture length and Mw. Most of the earthquakes show a unilateral rupture moving. Furthermore, we also identified a two-stage (eastward and westward) rupture propagation to the 2016 Mw 7.1 Romanche earthquake like results published by a recent study. This complex two-stage rupture style was similarly observed in the 2022 Mw 6.6 Vema earthquake. Therefore, we show that rupture parameters of large strike-slip earthquakes in OTFs can be revealed not just by commonly used teleseismic methods but also by solely using hydroacoustic data.

Waveform Modeling of Hydroacoustic Teleseismic Earthquake 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 deployed in the Pacific, 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 axisymmetric spectral-element simulations performed for moment-tensor earthquakes in a one-dimensional solid Earth to a two-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 applied our workflow to 1,129 seismograms for 682 earthquakes from 16 MERMAIDs owned by Princeton University that were deployed in the Southern Pacific as part of the South Pacific Plume Imaging and Modeling (SPPIM) project. We compare the modeled synthetic waveforms to the observed records in individually selected frequency bands aimed at reducing local noise levels while maximizing earthquake- generated signal content. The modeled waveforms match the observations very well, with a median correlation coefficient of 0.72, and some as high as 0.95. We compare our correlation-based travel-time measurements to measurements made on the same data sets determined by arrival-time picking and ray-traced travel-time predictions, with the aim of opening up the use of MERMAID records for global seismic tomography via full-waveform inversion.

Decoding the Submarine Ambient Noise Field with Distributed Acoustic Sensing

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Microseism constitutes a major component of seismic ambient noise on Earth. However, a comprehensive understanding of its generation and propagation were limited by sparse seismic instrumentations in the ocean. Distributed acoustic sensing (DAS) is bridging this gap by enabling direct measurements of microseism sources and seafloor sedimentary structures that host the resulting noise field. In this study, we use DAS data from offshore Oregon to analyze the principal factors that modulate these vibrations, sources and site amplification. With ambient noise tomography, we obtain the subsurface velocity structures and can then calculate the relative surface wave amplification along the DAS array. The microseism source distribution can be inverted from the directional asymmetry of noise cross-correlation signal amplitudes, which determines the energy received by each DAS channel. The integration of these two effects satisfactorily predicts the power spectral density (PSD) observations. At low frequencies, the source heterogeneity is mitigated by minimal attenuation and the site amplification is dominant. Conversely, at high frequencies, the contribution from local sources becomes crucial as well, and the PSD is a composite outcome of both site and source effects. The spatial variations of noise can be explained by the interplay between the bathymetry, sedimentary structures and frequency-dependent ocean wave properties. Consequently, we demonstrate that the ambient noise field on the seafloor is shaped by both geological features below and ocean activities above. Our approach also permits a quantitative evaluation of microseism excitation and offshore site amplification at a local scale, which provides vital insight for harnessing ocean energy and assessing undersea natural hazards.

Ocean Bottom Turbulence Evolution Observed by Arrayed Obs, Dpg, and a Temperature String

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Turbulent mixing in the deep sea is not well understood due to lack of long-term in-situ observation. The breaking of internal waves on sloped seafloor topography can generate turbulence that is difficult to measure comprehensively due to its multi-scale processes, in addition to the flow-flow, and flow-topography interactions. Here we deploy a high-resolution spatiotemporal array of four ocean bottom seismometers (OBS) and a 200-m vertical temperature string at 3000-meter water depth in a footprint of 1 X 1 km, in order to characterize turbulence induced by internal waves. Each OBS is also equipped with a differential pressure gauge (DPG). We found that the OBS has recorded signals induced by near-seafloor turbulence, particularly during typhoon periods. We propose that large-scale inertial breaking has occurred with upslope transport speeds of 0.2 to 0.5 m s^{-1}. We also found evidence of small-scale bathymetry causing localized wave breaking. Data from the DPG and the temperature string also document internal waves and turbulent motions, with a frequency of 0.002 to 0.1 mHz. Applying beamforming-frequency-wavenumber analysis and linear regress to the arrayed Temperature sensor and DPG, we estimated a transport speed similar to that derived from the OBS. Arrayed OBS can provide complementary observations to characterize deep-sea turbulence.

Searching for Low-Amplitude Shallow Tectonic Tremor in Cascadia Using Buried Ocean Bottom Seismometers

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Tectonic tremor is an indicator of slow slip in the shallow portions of subduction zones, which typically lie offshore. Constraining the extent of shallow tremor is important for earthquake and tsunami hazard assessment, but offshore tremor detection is complicated by emergent oceanic signals such as T-phases, ship noise, and tremor-like signals from bottom currents. In the Cascadia subduction zone, shallow tremor has not been conclusively observed. However, offshore seismic data is limited and noisy, and previous investigations have only applied traditional land-based network methods. We explore new techniques to detect low-amplitude tremor signals using a limited ocean bottom seismometer (OBS) network. We analyze seismic data from 2014-2023 for two broadband OBS spaced 20 km apart near the deformation front at ~45.5°N on the Ocean Observatories Initiative Regional Cabled Array. The OBS are buried and collocated with bottom current meters. We find no relationship between seismic noise and bottom current speeds at either OBS, suggesting that the burial of the instruments successfully eliminates current-generated noise. We do find that background noise on both OBS is linearly related to wind speeds. We use this relationship to flag time periods with increased amplitudes in the frequency band of interest (3-10 Hz for tectonic tremor) that cannot be attributed to heightened wind speeds. Within flagged periods, we identify individual emergent signals as tremor candidates. For a test window from July 2018-July 2019, we find > 1,000 candidate 300-s detections present on both stations within flagged periods, most of which are visually assessed as T-phases. We will extend this approach to the full time period and systematically classify all candidate signals as T-phases, ship noise, or potential tremor on the basis of signal characteristics, hydrophone recordings, and comparison to regional earthquake catalogs. In addition to investigating tremor in shallow Cascadia, this will produce a labeled dataset of emergent oceanic seismic signals that can be used for detection at other offshore sites and with future networks.

Marine Seismoacoustics [Poster Session]

Poster Session • Wednesday 1 May

Conveners: Kasey Aderhold, EarthScope Consortium (kasey.aderhold@earthscope.org); Helen Janiszewski, University of Hawaiʻi at Mānoa (hajanisz@hawaii.edu); Siobhan Niklasson,