Seismic Tomography: What Comes Next?

Seismological Society of America
28–30 October | Toronto, Ontario

Technical Program

Friday, 28 October 2022

- Registration Open, 4–5 PM
- Opening Reception, 5–6 PM
- Opening Keynote, 6–7 PM

Saturday, 29 October and Sunday, 30 October 2022

- Posters & Breakfast, 7:30–9 AM
- Morning Plenary and Oral Session, 9–10:10 AM
- Oral Session, 10:45–11:45 AM
- Lunch, Noon–1 PM
- Afternoon Plenary and Oral Session, 1–2:30 PM
- Poster Session, 2:45–3:45 PM
- Panel Discussion, 3:45–4:45 PM
- Evening Plenary, 5–6 PM
- Reception, 6–7 PM

Keynote Speakers

- Sergei Lebedev, University of Cambridge and Dublin Institute for Advanced Studies: *"Increasing the Resolution of Global and Regional Tomography: Progress and Challenges"*
- Nicholas Rawlinson, University of Cambridge: *"From Traveltime to Adjoint Waveform Tomography in SE Asia"*
- Jeroen Ritsema, University of Michigan: *"Morning Keynote: Invited: Large Low-velocity Provinces (LLVPs) in the Lowermost Mantle"*
- Barbara Romanowicz, University of California, Berkeley and College de France: *"Forty Years of Global Mantle Tomography: Achievements and Challenges Ahead"*
- Carl Tape, University of Alaska Fairbanks: *"Seismic Imaging of Sedimentary Basins with Complex Seismic Wave Propagation"*
- Jeroen Tromp, Princeton University: *"Source Encoding and Uncertainty Quantification for Global Waveform Inversion"*

Meeting Co-Chairs

Andreas Fichtner of ETH Zürich and Clifford Thurber of the University of Wisconsin-Madison

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Friday, 28 October 2022

4–5 PM	Registration Open
5–6 PM	Reception
6–7 PM	Opening Keynote: Forty Years of Global Mantle Tomography: Achievements and Challenges Ahead. **Romanowicz, B.**

Saturday, 29 October 2022

7:30–9 AM	Posters & Breakfast
Morning Plenary and Oral Session	
9–9:30 AM	Morning Plenary: Large Low-velocity Provinces (LLVPs) in the Lowermost Mantle. **Ritsema, J.**
9:30–9:50 AM	Whole Earth Oscillations: The Key to Imaging Earth's Deep Interior. **Deuss, A.**, Jagt, L., van Tent, R., Talavera-Soza, S.
9:50–10:10 AM	Fast and Automated Global-scale Waveform Inversion. **Thrastarson, S.**, van Herwaarden, D., Fichtner, A.
Oral Session	
10:45–11:05 AM	Upper Mantle Anisotropy and Attenuation From Global Adjoint Tomography. **Bozdag, E.**, Orsvuran, R., Espindola, A., Peter, D.
11:05–11:25 AM	Radial Anisotropic Structure of the Upper Mantle. **Priestley, K.**, Ho, T., Debayle, E.
11:25–11:45 AM	Implications of General Viscoelastic Ray Theory for Anelastic Seismic Tomography. **Borcherdt, R. D.**
Noon–1 PM	Lunch
Afternoon Plenary and Oral Session	
1–1:30 PM	Afternoon Plenary: Increasing the Resolution of Global and Regional Tomography: Progress and Challenges. **Lebedev, S.**, Bonadio, R., Xu, Y., Fullea, J.
1:30–1:50 PM	Full-3D Inversion of Slowness Vectors Measured Across Seismic Arrays. **Vazquez, L.**, Jordan, T. H.
1:50–2:10 PM	Ambient Noise Tomography Across Dense Nodal Arrays. **Lin, F.**, Wu, S., Rabade, S., Liu, C., Farrell, J., *et al.*
2:10–2:30 PM	Complex Seismic Anisotropy Beneath the Central Appalachian Mountains from SKS-splitting Intensity Tomography. **Link, F.**, Long, M. D., Mondal, P.
2:45–3:45 PM	Poster Session
3:45–4:45 PM	Panel Discussion. Sergei Lebedev, Jeroen Ritsema, Jeroen Tromp
5–6 PM	Evening Plenary: Source Encoding and Uncertainty Quantification for Global Waveform Inversion. **Tromp, J.**
6–7 PM	Reception

Saturday Posters

1. New Imaging Strategies for Constraining Arbitrarily Oriented Upper Mantle Anisotropic Fabrics With Teleseismic P- and S-wave Delay Times. **VanderBeek, B. P.**, Faccenda, M.
3. Anisotropic Seismic Tomography with the Reversible Jump Markov Chain Monte Carlo. **Del Piccolo, G.**, VanderBeek, B. P.
5. Implementation of "Spherical Earth" for Box-tomography in Regional Scale. **Karakostas, F. G.**, Morelli, A., Molinari, I., VanderBeek, B. P., Faccenda, M.
7. 3D Anisotropic Transdimensional Seismic Tomography of the Inner Core Using Normal Mode and Body Wave Data. **Brett, H.**, Hawkins, R., Waszek, L., Lythgoe, K., Deuss, A.
9. Seismic Wave Modeling in Anisotropic Media With Fracture Sets Using the Finite-difference Rotated Staggered Grid. **Zhang, O.**, Schmitt, D. R.
11. Understanding Parameter Trade-offs in Anisotropic Inversion of Surface Wave Measurements. **Boyce, A.**, Bodin, T., Durand, S., Soergel, D.
13. Model Parameterization and Sensitivity Kernels in 3D Anisotropic Media. **Gupta, A.**, Chow, B., Tape, C., Modrak, R., Abers, G.
15. Global 3D Model of Mantle Attenuation Using Seismic Normal Modes. **Talavera-Soza, S.**, Jagt, L., Cobden, L., Faul, U. H., Dalton, C. A., *et al.*
17. Double-difference Seismic Attenuation Tomography. Guo, H., **Thurber, C. H.**
19. Resolution and Trade-offs in Anelastic Full-waveform Inversion for Global-scale Models. **Espindola, A.**, Peter, D., Orsvuran, R., Bozdag, E., Magnoni, F., *et al.*
21. Seismic Evidence of Slab Segmentation and Melt Focusing Atop the 410-Km Discontinuity in NE Asia. **Song, J.**, Rhie, J., Kim, S.
23. Bayesian Imaging of the Hawaiian ULVZ From Sdiff Postcursors. **Martin, C.**, Cottaar, S., Bodin, T.
25. New Global Models of 3D Mantle Density From Recent Normal Mode Measurements. **van Tent, R.**, Cobden, L., Deschamps, F., Fichtner, A., Gebraad, L., *et al.*
27. Normal Mode Constraints on Vs, Vp and Their Ratio in the Earth's Mantle. **Jagt, L.**, Koelemeijer, P., Cobden, L., Cottaar, S., Deuss, A.

29. Influence of Shear-wave Velocity Heterogeneity on SH Wave Reverberation Imaging of the Mantle Transition Zone. **Liu, M.**, Ritsema, J., Chaves, C.
31. Tomography for Plate Tectonics and Geodynamics: Advances, Open Questions, Future Opportunities. **Wu, J.**, Colli, L.
33. New Global and Tectonic-type 1D Models of the Upper Mantle. **Civiero, C.**, Lebedev, S., Xu, Y., Bonadio, R.
35. What Is "High Resolution" When It Comes to Continental Lithospheric Structure? **Bezada, M. J.**, Zhu, Z., Lee, H., Ford, H., Long, M.
37. Comparing Lithospheric Thickness From Sp Receiver Functions and Tomography in the Southwestern US. **Shallon, B.**, Ford, H. A.
39. Lithospheric Control on the Paleogene Uplift and Volcanism in Ireland and Britain: Insights From Optimal Resolution Tomography. **Bonadio, R.**, Lebedev, S., Chew, D.
43. WINTERC-G in Eastern North America: Local Control for a Global Multiparameter Model of the Mantle. **Levin, V.**, Lebedev, S., Fullea, J., Li, Y., Chen, X.
45. Off-great-circle Propagation of Earthquake Surface Waves in the NW Himalaya and Adjacent Areas. **Mir, R. R.**, Parvez, I. A.
47. Seismic Structure Beneath Mexico City: Linking the Spatial Correlation and Seismic-imaging Methods. **Aguilar-Velázquez, M.**, Pérez-Campos, X., Pita-Sllim, O., Gil-Vargas, N., Baena-Rivera, M., *et al.*
49. Fusion of Seismic Tomography Maps Using a Probability Graphical Model. **Gerstoft, P.**, Zhou, Z., Olsen, K. B.
51. Finite-frequency Kernels for Pg/Lg Phases. **Nelson, P.**, Modrak, R., Begnaud, M., Phillips, S.
53. SALSA3D: Updated Tomographic Velocity Models for Improved Travel-time Prediction and Uncertainty. **Conley, A. C.**, Porritt, R. W., Davenport, K., Begnaud, M., Rowe, C., *et al.*
55. Symplectic Geometry and Hamiltonian Monte Carlo Method. **Öztürk, F.**, Diner, Ç.
57. Earthquake Tomography Integrated With Gravity Data: An Application From NE-Italy. **Zampa, L. S.**, Magrin, A., Rossi, G., Bohm, G., Tondi, R., *et al.*
59. Seismotectonic Characteristics of the Taltal Segment in Northern Chile, Inferred Using Local Earthquake Tomography. **Leon-Rios, S.**, Calle-Gardella, D., Reyes-Wagner, V., Comte, D., Roecker, S.
61. Using a Consistent Travel-time Framework to Compare Three-dimensional Seismic Velocity Models for Location Accuracy. **Begnaud, M.**, Conley, A. C., Davenport, K., Porritt, R., Ballard, S., *et al.*
63. A Neural Network Travel Time Function for Direct Travel Time Tomography. **Taufik, M.**, Alkhalifah, T.
67. Finite-frequency Tomography in the Chile Triple Junction Region. **Kondo, Y.**, Obayashi, M., Sugioka, H., Ito, A., Shiobara, H., *et al.*
69. AI-enhanced Seismic Tomography for the Oklahoma Region. **Chai, C.**, Maceira, M.
71. Identification of the Meso-Kaynoy Complexes of the Earth's Crust of Azerbaijan by Seismic Tomography. Guliyev, I. G. I., **Yetirmishli, G. Y. G.**, Kazimova, S. S. K.
73. The Spiral Global Travel-time-based Model to Serve as a Starting Model for Global Adjoint Tomography. **Simmons, N. A.**, Morency, C., Chiang, A., Myers, S. C.
77. 3D Seismic Structure and Crustal Evolution of the South of Portugal Mainland (Preliminary Results). **Cavacundo, O. B. M.**, Dias, N. C. A., Matias, L. H. M., Rio, I.

Sunday, 30 October 2022

7:30–9 AM	Posters & Breakfast
Morning Plenary and Oral Session	
9–9:30 AM	Morning Plenary: Seismic Imaging of Sedimentary Basins with Complex Seismic Wave Propagation. **Tape, C.**, Tian, Y., Chow, B., Smith, K.
9:30–9:50 AM	Towards the Geologic Parameterization of Seismic Tomography. **Tsai, V. C.**
9:50–10:10 AM	Lithospheric Thermochemical Heterogeneity in the Continental United States From Seismic Tomography. **Golos, E.**, Shinevar, W. J., Jagoutz, O., Behn, M., van der Hilst, R. D.
Oral Session	
10:45–11:05 AM	Improving Results and Interpretation in Time-dependent Tomography and Between Temporal Campaigns. **Hobé, A.**, Tryggvason, A.
11:05–11:25 AM	Data Assimilated Full Waveform Inversion of Continuous Seismic Monitoring Data for Tracking the Evolution of CO_2 Plumes. **Zhu, T.**, Huang, C.
11:25–11:45 AM	Seismoelectric Effects for Subsurface Characterization. **Morency, C.**, Matzel, E.
Noon–1 PM	Lunch
Afternoon Plenary and Oral Session	
1–1:30 PM	Afternoon Plenary: From Travel-time to Adjoint Waveform Tomography in SE Asia. **Rawlinson, N.**, Wehner, D., Zenonos, A., Widiyantoro, S.
1:30–1:50 PM	Adjoint Waveform Tomography of the Western US for Improved Waveform Simulations and Source Characterization. **Rodgers, A. J.**, Krischer, L., Afanasiev, M., Boehm, C., Doody, C., *et al.*
1:50–2:10 PM	Structure and Evolution of the Australian Plate and Underlying Upper Mantle From Waveform Tomography With Massive Datasets. **de Laat, J. I.**, Lebedev, S., Celli, N., Chagas de Melo, B., Bonadio, R.
2:10–2:30 PM	Lithospheric Structures of Western Mid-continent Rift Revealed by Full-waveform Joint Inversion of Ambient-noise Data and Teleseismic P Waves. **Liu, Q.**, He, B., Liu, T., Lei, T., van der Lee, S.
2:45–3:45 PM	Poster Session
3:45–4:45 PM	Panel Discussion. Nicholas Rawlinson, Barbara Romanowicz, Carl Tape.
5–6 PM	Closing Lecture: Cliff Thurber and Andreas Fichtner
6–7 PM	Closing Reception

Sunday Posters

2. Shear Velocity Structure of Northeastern India From Ambient Seismic Noise Tomography. **Singh, D. K.**
6. Imaging the Lithospheric Structure Beneath Portugal With Seismic Ambient Noise. **Silveira, G.**, Dias, N., Kiselev, S., Stutzmann, E., Custódio, S., *et al.*
8. Imaging the Crustal Velocity Structure Beneath Sikkim Himalaya Using Ambient Noise Tomography. **Uthaman, M.**, Singh, A., Singh, C., Kumar, G., Dubey, A. K.
10. High-resolution Imaging of the Shallow Subsurface and Relationship With Site Responses Using Joint Nodal and DAS Arrays Near Enid, Oklahoma. **Dangwal, D. S.**, Chen, X., Behm, M., Ng, R., Zhan, Z., *et al.*
12. Submarine Distributed Acoustic Sensing for Crustal Imaging in the Cascadia Forearc. **Fang, J.**, Yang, Y., Biondi, E., Williams, E. F., Zhan, Z.
16. Fiberoptic Versus Geophone / Accelerometer Data in Elastic Full Waveform Inversion of Borehole Seismic Data. Eaid, M. V., Keating, S. D., **Innanen, K. A.**, Macquet, M., Lawton, D. C.
18. Crustal Structure of Terceira Island (Azores): Sampling a Volcanic Island With a Dense Network. **Dias, N. A.**, Fontiela, J., Matias, L. M., Silveira, G., Veludo, I., *et al.*
20. Spectral-infinite-element Simulations of Seismic Wave Propagation in Self-gravitating 3D Earth Models. **Gharti, H.**, Eaton, W. P., Tromp, J.
22. Validating Tomographic Models of Alaska Using Seismic Wavefield Simulations. **McPherson, A.**, Chow, B., Tape, C.
24. Central Italy High-resolution Model for Accurate Ground Motion Simulation. **Stallone, A.**, Krischer, L., Magnoni, F., Casarotti, E., Fichtner, A.
28. Modeling and Observation of Train Signals in the Urban Environment. **Lapietra Garcia, P.**, Gharti, H., Bucciarelli, D., Reed, M.
30. Understanding Subsurface Fracture Evolution Dynamics Using Time-lapse Full Waveform Inversion of Continuous Active-source Seismic Monitoring Data. **Liu, X.**, Zhu, T.
36. CANVAS: An Adjoint Waveform Tomography Model of California and Nevada. **Doody, C.**, Rodgers, A. J., Chiang, A., Afanasiev, M., Boehm, C., *et al.*
38. Viscoacoustic Full-waveform Inversion: Theory and Application to Critical Zone. **Zhu, T.**, Xing, G.
40. Adjoint Seismic Tomography of the Antarctic Continent Incorporating Both Earthquake Waveforms and Green's

Functions From Ambient Noise Correlation. **Zhou, Z.**, Wiens, D. A., Lloyd, A. J.

42. Full-waveform Tomography of the African Continent. **van Herwaarden, D.**, Thrastarson, S., Afanasiev, M., Trampert, J., Fichtner, A.
44. Seismic Imaging Reveals a Melt-rich Storage Zone Below Yellowstone Caldera. **Maguire, R.**, Schmandt, B., Li, J., Jiang, C., Li, G., *et al.*
46. Source Encoding for Ultrasound Full Waveform Inversion. **Bachmann, E.**
48. Imaging the Alaskan Lithosphere Using Full-waveform Seismic Inversion. **Liu, T.**, Wang, K., Tape, C., He, B., Yang, Y., *et al.*
50. Pyatoa and SeisFlows: Automated Workflow Tools for Adjoint Tomography. **Chow, B.**, Modrak, R., Tape, C.
52. An Overview of Full-waveform Inversion Workflows to Image the Deep Earth. **Riaño, A. C.**, Orsvuran, R., Espindola, A., Huang, Q., Bozdag, E., *et al.*
54. Modernized Adjoint Tomography Workflow Applied to the South California Earthquake Center Community Velocity Models. **Thurin, J.**, Chow, B., Tape, C.
56. Lithospheric Imaging of the Cascadia Subduction Zone Based on Full-waveform Inversion. **Du, N.**, He, B., Lei, T., Liu, Q.
58. Optimal Transport for Elastic Source Full Waveform Inversion. **Masthay, T.**, Engquist, B.
60. On the Sensitivity of Local-scale Full-waveform Ambient Noise Inversion to Global Noise Sources. **Valero Cano, E.**, Peter, D.
62. Breaking Adria: Adjoint Tomography of a Disappearing Continental Microplate. **Casarotti, E.**, Magnoni, F., Stallone, A., Ciaccio, M., Di Stefano, R.
64. The Remnants of Continental Collision in Southern Appalachians: Constraints From Joint Full-waveform Inversion. **Lei, T.**, He, B., Wang, K., Du, N., Liu, Q.
66. Adjoint Tomography of the Middle East. **Orsvuran, R.**, Bozdag, E., Gok, R., Peter, D., Alotaibi, Z., *et al.*
68. Exploring the Outermost Outer Core With Full-waveform Modeling. **Vite Sanchez, R.**, Frost, D., Riaño, A., Creasy, N., Huang, Q., *et al.*
70. Adjoint Tomography of an Accretionary Wedge and Shallow Slow-slip Regions in the North Island of New Zealand. Adachi, S., Chow, B., **Kaneko, Y.**
72. Towards Box Tomography of the Root of the Iceland Plume at the Base of the Earth's Mantle. **Lyu, C.**, Su, H., Martin, C., Masson, Y., Romanowicz, B.
74. The Collaborative Seismic Earth Model: Generation 2. **Noe, S.**, van Herwaarden, D., Thrastarson, S., Gao, Y., Tilmann, F., *et al.*
76. Imaging of the Yellowstone Plume Using Box Tomography. **Kumar, U.**, Munch, F., Adourian, S., Lyu, C., Maurya, S., *et al.*
78. Hamiltonian Monte Carlo Sampling for Uncertainty Quantification in Real-world Tomography. **Gebraad, L.**, Zunino, A., Boehm, C., Fichtner, A.

Abstracts

Alphabetized by presenting author (underlined).

Seismic Structure Beneath Mexico City: Linking the Spatial Correlation and Seismic-imaging Methods

Poster 47, presented Saturday, 29 October

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For years, seismic-imaging techniques have been used to characterize the Earth's structure and knowing their resolution is a crucial step for the interpretation. In this work, we present two seismic images: a shallow Rayleigh-wave group-velocity tomography inside the lake-sediment zone in Mexico City and a crustal high-resolution *S*-wave velocity model beneath Mexico City. The evidence suggests a relationship between the resolution and the spatial correlation in both cases. For the shallow tomography, the spatial correlation was quantified using the range of a short-period dispersion-curves similarity-function semivariogram. We performed a checkerboard test and confirmed that a cell-size value of 400 m, obtained as the semivariogram range value, was adequate to recover the tomography's resolution. Taking advantage of this finding, we present a high-resolution crustal model beneath Mexico City retrieved from joint-inversion of receiver functions and long-period dispersion curves. The spatial correlation was quantified using the *S*-wave velocity retrieved from the joint inversion at different depths. We obtained an average range for the *S*-wave velocity semivariograms per depth of 7.5 km. Using cell sizes of 7.5 km revealed a good resolution beneath Mexico City but poor at the boundaries. Instead, we used two times the range value as a cell size; we confirmed that the 15.0 km cell size allowed us to interpret the whole study area. We present the retrieved crustal velocity model (we named it: VMRDFC), the followed methodology to infer the composition that better fits the *S*-wave velocity estimations as a function of the pressure-temperature conditions and the validation of these interpretations in terms of geological and geophysical features reported in the literature.

Source Encoding for Ultrasound Full Waveform Inversion

Poster 46, presented Sunday, 30 October

BACHMANN, E., Princeton University, New Jersey, USA, etienneb@princeton.edu

Ultrasound computed tomography (USCT) is a noninvasive imaging modality that has shown its clinical relevance for breast cancer diagnostics. As opposed to travel-time inversions, waveform-based inversions can exploit the full content of ultrasound data, thereby providing increased resolution. However, this is only feasible when modeling the full physics of wave propagation, accounting for 3D effects such as refraction and diffraction, and this comes at a significant computational cost. To mitigate this cost, a crosstalk-free source encoding method for explicit time-domain solvers is proposed. The gradient computation is performed with only two numerical "super" wave simulations, independent of the number of sources and receivers. Absence of crosstalk is achieved by considering orthogonal frequencies attributed to each source. By considering "double-difference" measurements, no *a priori* knowledge of the source time function is required. With this method, full-physics based 3D waveform inversions can be performed within minutes using reasonable computational resources, fitting clinical requirements.

Using a Consistent Travel-time Framework to Compare Three-dimensional Seismic Velocity Models for Location Accuracy

Poster 61, presented Saturday, 29 October

BEGNAUD, M., Los Alamos National Laboratory, New Mexico, USA, mbegnaud@lanl.gov; CONLEY, A. C., Sandia National Laboratories, New Mexico, USA, acconle@sandia.gov; DAVENPORT, K., Sandia National Laboratories, New Mexico, USA, kdavenp@sandia.gov; PORRITT, R., Sandia National Laboratories, New Mexico, USA, rwporri@sandia.gov; BALLARD, S., Sandia National Laboratories, New Mexico, USA, sballar@sandia.gov; GAMMANS, C., Los Alamos National Laboratory, New Mexico, USA, cgammans@lanl.gov

Location algorithms have relied on one-dimensional (1D) velocity models for fast, seismic event locations. The fast computational speed of these models made them the preferred type of velocity model for operational needs. 3D seismic velocity models are becoming readily available and usually provide more accurate event locations over 1D models. The computational requirements of 3D models tend to make their operational use prohibitive. Comparing location accuracy for 3D seismic velocity models tends to be problematic as each model is determined using different ray-tracing algorithms. Attempting to use a different algorithm than used to develop a model usually results in poor travel-time prediction. We have previously demonstrated and validated the ability to quickly create 3D travel-time correction surfaces using an open-source framework (PCalc+GeoTess, www.sandia.gov/salsa3d, www.sandia.gov/geotess) that easily stores spatially-varying data, including 3D travel-time data. This framework overcomes the ray-tracing algorithm hurdle because the lookup tables can be generated using the exact ray-tracing algorithm that is preferred. We have created first-P 3D travel-time correction surfaces for several publicly available 3D models (e.g., RSTT, SALSA3D, G3D, DETOX-P2, etc.). We demonstrate using these correction surfaces to compare models fairly and consistently for seismic location accuracy via a set of validation events and International Monitoring System (IMS) stations.

What Is "High Resolution" When It Comes to Continental Lithospheric Structure?

Poster 35, presented Saturday, 29 October

BEZADA, M. J., University of Minnesota, Minnesota, USA, mbezada@umn.edu; ZHU, Z., University of Minnesota, Minnesota, USA, zhu00064@umn.edu; LEE, H., Seoul National University, Seoul, South Korea, leex8217@umn.edu; FORD, H., University of California, Riverside, California, USA, heather.ford@ucr.edu; LONG, M., Yale University, Connecticut, USA, maureen.long@yale.edu

The definition of "high resolution" is, of course, relative. Resolution is sufficiently high when the spatially smallest anomalies of interest are well-resolved, at which point better resolution provides little additional information. When it comes to continental lithospheric structure, and North American lithosphere in particular, our view has evolved substantially in the last two decades. Thanks to the EarthScope Transportable Array (TA), the classic view that divided North America into two broad regions ("tectonic" and "stable") thousands of kms across was replaced by one where there are significant anomalies within these regions with length scales of only 100s of km. However, can we say that tomography models based on TA data are "high resolution"? Do they capture the smallest significant anomalies? We present examples from regional models that include FlexArray-type deployments along with TA data to show that there are velocity anomalies that can impact our understanding of the lithosphere-asthenosphere system with spatial length scales of only ~100 km that can be missed or improperly imaged by TA-like station density. We focus on the Central Appalachian Anomaly and the Black Hills anomaly. The Central Appalachian anomaly is well known from TA models; we show however, that when including data from the MAGIC deployment the geometry of the anomaly at 100-200 km depth is constrained to a narrower region beneath the Appalachian Mountains and corresponds very closely to an attenuation anomaly imaged with data from the same stations. Similarly, using data from the CIELO and

BASE deployments, we image a low-velocity anomaly that is ~100 km across and corresponds very closely to the Black Hills. Such an anomaly is not conspicuous in models built from TA data. We conclude that current-generation continent-scale velocity models do not adequately image all geologically significant anomalies in the lithosphere-asthenosphere system and that higher resolution is necessary.

Lithospheric Control on the Paleogene Uplift and Volcanism in Ireland and Britain: Insights From Optimal Resolution Tomography

Poster 39, presented Saturday, 29 October

BONADIO, R., Dublin Institute For Advanced Study, Dublin, Ireland, raffaelebonadio@gmail.com; LEBEDEV, S., University of Cambridge, Cambridge, United Kingdom, sl2072@cam.ac.uk; CHEW, D., Trinity College Dublin, Dublin, Ireland, chewd@tcd.ie

Optimal resolution tomography, a new method for finding the optimal resolving length at every point of a tomographic model grid, yields exciting new insights into the structure and evolution of the Ireland–Britain region.

The approach utilizes a direct, empirical evaluation of the posterior model error at a point. In our surface wave tomography, we estimate the error by isolating the roughness of the phase-velocity curve that cannot be explained by any Earth structure and determine the optimal resolving length at each knot such that the error of the local phase-velocity curve is below a specified threshold.

We apply this method to over 11,000 interstation phase-velocity curves measured at station pairs recording simultaneously and image the lithosphere and underlying mantle beneath Ireland and Britain. The very large dataset has a broad period range, produces an unprecedented data coverage of the region and constrains detailed structure from the crust to the deep asthenosphere.

The composite, optimal resolution phase-velocity maps are inverted for a 3D V_S model, which reveals pronounced, previously unknown variations in the lithospheric thickness beneath the area. The model shows evidence of a robust, low-velocity anomaly beneath the Irish Sea and its surroundings that persists in the models from ~60 to at least 140 km depth, indicating an anomalously thin lithosphere and demonstrating that the assumption of a nearly constant lithospheric thickness across the area, previously adopted, is not valid. This anomaly matches the region of the Paleogene uplift previously suggested to be caused by a lateral branch of the Iceland mantle plume, which played a fundamental role in the evolution of the North Atlantic Ocean over the past 60 M.y. The anomalies in our model exhibit a marked correlation with proposed underplating thickness, denudation, thermochronological measurements and the locations of the intraplate volcanism of the enigmatic North Atlantic Igneous Province.

Implications of General Viscoelastic Ray Theory for Anelastic Seismic Tomography

Oral Presentation, Saturday, 29 October, 11:25 AM

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Recent advances in general viscoelastic ray theory provide a rigorous mathematical framework for purposes of anelastic seismic tomography. They provide closed-form solutions of forward ray-tracing and simple inverse problems for horizontal and spherical anelastic media. These solutions provide a number of insights regarding the characteristics of anelastic seismic waves and their ray paths not provided by conventional Q models. They account for changes in velocity and attenuation of anelastic P and S body waves associated with changes in inhomogeneity of the waves induced by anelastic material boundaries and gradients along the ray path. These changes, which are not induced at elastic boundaries, manifest themselves as variations in ray-path location, travel time and amplitude attenuation as inferred at the surface of an anelastic Earth.

The forward ray-tracing solutions provide computation algorithms for general viscoelastic ray-tracing computer codes that can be used to exactly account for these variations in a variety of tomography-inferred anelastic geophysical models, such as those used to delineate the anelastic properties of the mantle and near-surface petroleum reserves. Numerical models indicate these distinctions increase with inhomogeneity of the waves and are more significant for some ray tracing problems than others. The solutions of inverse problems including that involving the viscoelastic solution of the Herglotz-Wiechert integral permit simultaneous inference of intrinsic-material seismic absorption and material wave speed from empirical travel-time and amplitude-attenuation curves. Application of these recent advances in general viscoelastic ray theory to large empirical teleseismic and exploration data sets will provide a host of research opportunities for the younger generation to advance our understanding of the anelastic properties of the Earth's interior (Borcherdt, 2020, pp. 430-32, isbn=9781108495691).

Understanding Parameter Trade-offs in Anisotropic Inversion of Surface Wave Measurements

Poster 11, presented Saturday, 29 October

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Measurements of seismic anisotropy are important to constrain active and ancient geological processes, often concerning crustal and mantle deformation. However existing radial anisotropic models lack consensus at upper mantle depths when compared to their isotropic counterparts.

Radial anisotropy is usually constrained by jointly inverting Rayleigh and Love measurements. However, a significant challenge is their differing sensitivities to elastic parameters. Rayleigh waves are sensitive to Vsv and Vp, whereas Love waves are sensitive to Vsv and Vsh. Rayleigh wave dispersion curves are insufficient to constrain Vp alone meaning Vp perturbations are often tied to Vs perturbations in classical inverse approaches, leaving little room for these parameters (i.e., Vp/Vs ratio) to vary. This assumption presents an unwanted constraint in geologically complex environments and remains relatively untested. However, Vp can be uniquely constrained by widely-available body wave data sets, so is a clear candidate for investigation combined with Bayesian techniques for joint inversion.

We conduct a series of tests initially using synthetic dispersion data to highlight the impact of variable parameterization choices on radial anisotropic images. Our results show substantial spurious radial anisotropy is produced when Rayleigh and Love dispersion curves are inverted separately using classical optimization approaches for starting models between which only Vp varies. We also perform directly comparable tests where Rayleigh and Love dispersion curves are inverted jointly using both LSQR and Bayesian frameworks. The Bayesian framework allows us to easily incorporate independent and complementary body-wave data into our joint inversion while quantifying the reduction in model uncertainties when doing so. We offer recommendations for the community to improve agreement between future constraints on Earth's upper mantle radial anisotropic structure.

Upper Mantle Anisotropy and Attenuation From Global Adjoint Tomography

Oral Presentation, Saturday, 29 October, 10:45 AM

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The first-generation global adjoint models are isotropic or transversely isotropic constructed using travel times only to tackle the elastic structure perturbed around 1D Q models. While full 3D complexity of wave propagation is captured by numerical simulations we also need to address better physics in inversions through appropriate model parameterizations. In this study, we address the azimuthal anisotropy and anelasticity in global adjoint inversions.

Starting from GLAD-M25, we have so far performed 21 conjugate-gradient iterations to construct an azimuthally anisotropic upper-mantel model using minor and major-arc surface waves down to 40 s from a dataset of ~300 earthquakes. During the first 12 iterations, we used double-difference multitaper phase measurements. We continue our iterations with the exponentiated-phase misfit to better capture higher-mode surface waves and increase the resolution in the mantle transition zone. Our initial large-scale results are consistent with previous global azimuthally anisotropic models and plate motions. We also approach continental-scale resolution in densely covered regions in our global inversion.

Meanwhile, we explore the effect of anelastic structure on waveforms which is most pronounced on surface waves. Our ultimate goal is to construct an anelastic mantle model by simultaneously updating elastic and anelastic parameters by assimilating both the phase and amplitude information to perform exact FWI. We started global FWI from GLAD-M25 and its 1D Q model QL6. After combining multitaper phase and amplitude misfits during the first two iterations we continue with an envelope misfit. In a complementary study, we perform 3D global synthetic FWI with the same measurements used in FWI with real data to assess the trade-off between elastic and anelastic parameters. We perform our simulations on TACC's Frontera and PRACE's Marconi100. We will present our results with future directions in constraining the mantle structure.

3D Anisotropic Transdimensional Seismic Tomography of the Inner Core Using Normal Mode and Body Wave Data

Poster 7, presented Saturday, 29 October

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The Earth's inner core displays strong seismic heterogeneity, which is most likely formed as a result of growth processes and post solidification deformation. Accurately resolving seismic anomalies is therefore key to understanding the dynamic mechanisms of the inner core. However, being the deepest region of our planet, the inner core presents a unique challenge in seismic tomography, as the amount of good quality data is relatively low compared to the mantle/crust of the Earth.

To overcome this challenge, we have applied a transdimensional methodology to our body wave data producing a high resolution 3D model. In the transdimensional approach, the inversion itself determines the parameterization. We recover many well known features, such as the hemispherical difference between a slow and strongly anisotropic western region and a fast and only weakly anisotropic eastern hemisphere, without a priori imposing those in our parameterization. We have also identified new features using this methodology, such as a better resolved innermost inner core, which we find is in fact restricted to the eastern hemisphere. We also find an anisotropic western zone which is isolated to the northern hemisphere of the inner core. These features would have been more challenging to observe using a traditional tomographic method.

Given the limited resolution of body waves we have started including normal mode data into our transdimensional inversions. Normal modes are whole Earth oscillations which provide long wavelength information on seismic anisotropy in the inner core. We have measured inner core sensitive normal modes using the splitting function approximation in a way which explores the splitting function measurement model space. From this we quantify the uncertainty in individual splitting function coefficients for each mode. We have combined these new normal mode measurements with our body wave data in a transdimensional inversion for seismic structure in the inner core. This is the first time a transdimensional method has been used jointly with both normal mode and body wave data.

Breaking Adria: Adjoint Tomography of a Disappearing Continental Microplate

Poster 62, presented Sunday, 30 October

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The Adria plate plays a peculiar role in the geodynamics of the Central Mediterranean. It is the foreland of non-coeval mountain ranges and its margins are consumed in the process by subduction systems under the Alps to the north, the Apennines to the west and the Dinarides to the east.

The complex behavior of this system and the large heterogeneity in data availability lead to a fragmented understanding of the Adria plate. In particular, its lithospheric structure, in terms of Vp and Vs profiles, is poorly known due to a lack of seismic stations, poor earthquake location quality (large observational gaps) and the consequent lack of coverage by classical seismic tomography methods. The uncertainties increase the difficulty of correctly assessing the seismic hazard along the Adriatic coasts (including tsunami hazard).

Recently, we have proposed IMAGINE_IT, a reference 3D high-resolution seismic tomography of the Italian lithosphere. Enhanced accuracy is enabled by three-dimensional wavefield simulations based on SPECFEM3D in combination with an adjoint-state method. The Adria plate is located at the eastern border of the volume considered in the simulations, nevertheless, our tomography is able to image this plate with an unprecedented resolution and supports the idea that it is made of two distinct microplates having different fabric and behavior and separated by the Gargano deformation zone.

We have highlighted a northern portion with more complex wavespeed anomalies and a thinner crust, and a southern part with a more regularly layered wavespeed structure and a thicker crust. Here, we focus on additional details of those images, such as the mid-Adriatic ridge and a new set of iterations that exploit 7 years of additional data (IMAGINE_IT was limited to data until 2015) and the 2016-2019 AlpArray very dense regional arrays of broadband seismic stations which provide a new opportunity to improve our comprehension of the area.

3D Seismic Structure and Crustal Evolution of the South of Portugal Mainland (Preliminary Results)

Poster 77, presented Saturday, 29 October

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This work aims to derive an improved 3D tomographic crustal velocity model for Vp and Vs for southern Portugal, to better understand the inland seismicity distribution, especially around the Monchique igneous intrusion, elucidating the causes of seismic anisotropy reported by active seismic profiles of previous studies and to correlate the observed seismic heterogeneities with the tectonic evolution of the crust. We will present the preliminary results of the passive data modeling of P-wave and S-wave refracted phases, but P and S Moho reflections are to be included at a later stage.

We collected all data from previous passive and active seismic campaigns in the region; active data coming from 1970's and 1990's wide-angle refraction/reflection seismic profiles, whereas passive data provided by recent temporary deployments plus 2000-2021 data from the permanent network of the Instituto Português do Mar e da Atmosfera. The new passive dataset comprises 62 seismic stations and 4338 seismic events located in SW Iberia. The initial 1D velocity model was obtained using VELEST, from a combination of previous models, using a subset of 827 events distributed throughout the region, with 49267 P and S readings. The 3D Vp model was inverted using FMTOMO, the 3D grid with 15 km horizontal and 5 km vertical spacing, mapping the entire Crust. The results show that the main seismic anomalies are compatible with previous results. We hope that the joint inclusion of P- and S- reflected waves will significantly improve the final 3D model and retrieve smaller scale crustal heterogeneities.

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AI-enhanced Seismic Tomography for the Oklahoma Region

Poster 69, presented Saturday, 29 October

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Seismic signal arrival times are fundamental to seismic events, locations and images of subsurface geophysical structures. Improvements in the volume or accuracy of seismic arrival times usually lead to better subsurface images and an improved seismic catalog. Measuring seismic signal arrival times with AI algorithms has shown rapid progress. Many of these AI applications have improved the volume and accuracy of the seismic arrival time measurements as well as processing speed. We have designed a workflow that combines a deep learning algorithm with an advanced seismic imaging technique for a 10-meter scale site. The integrated workflow resulted in better subsurface images and a higher-precision seismic event catalog. We are applying a similar workflow to the Oklahoma region. With both natural and induced seismic events and a large number of recorded signals, the Oklahoma region serves as a nice testbed for the workflow. We utilize a deep learning model, PhaseNet, to measure body-wave arrival times. A 3D velocity model from our previous efforts is used as the starting point. The AI-derived arrival times are used together with a double-difference tomography package to improve seismic event locations and images of the subsurface structure simultaneously. We will compare the seismic catalog and the seismic velocity model obtained with AI-derived arrival times against the earthquake catalog maintained by the United States Geological Survey for the region and the results constrained by traditional arrival times measurements. Checkerboard tests will be performed to validate the results.

Pyatoa and SeisFlows: Automated Workflow Tools for Adjoint Tomography

Poster 50, presented Sunday, 30 October

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Adjoint tomography is a computationally and algorithmically complex technique. Many research codes and software libraries that tackle the adjoint tomography workflow are designed to reduce the amount of human effort required to adjust and control the many repeat procedures encountered during a workflow, such as: wavefield simulations, seismic data processing, waveform misfit quantification and compute system interactions. However, many of these tools can be difficult to use by others due to a lack of crucial non-code material such as documentation, tutorials and example problems which illustrate how and why a tool should be used. Similarly, loss of active code maintenance and development can make it more difficult for others to leverage these tools without ad-hoc measures taken by each new user. Oftentimes, research codes which grow and develop with a large active community become the most widely adopted.

In this work we present a set of open-source, Python-based tools for adjoint tomography: Pyatoa—a waveform misfit quantification and visualization package and SeisFlows—an automated workflow and optimization tool for full waveform inversion. These packages work together with 2D and 3D numerical solvers to fully automate the adjoint tomography workflow. Extensive non-code material such as documentation and tutorials are meant to facilitate introduction to new users, while unit test suites and automated integration tools help ensure a stable codebase that can be used to run reproducible inversion workflows. These packages have been used for real data inversions of an active subduction zone and numerous synthetic studies. Here we showcase the codebases, their supporting material and ongoing research projects making use of them. Our aim is to promote Pyatoa and SeisFlows as tools that can be widely adopted by the adjoint tomography community.

New Global and Tectonic-type 1D Models of the Upper Mantle

Poster 33, presented Saturday, 29 October

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1D reference Earth models are widely used by the geoscience community and include global, regional and tectonic-type seismic velocity models. The recent growth in the data sampling worldwide presents an opportunity for an improvement in the global and tectonic-type velocity models. Here, we use a very large global dataset of Love and Rayleigh fundamental mode, phase-velocity measurements, performed with multimode waveform inversion using all available broadband data since the 1990s and compute phase-velocity maps in a broad, 17-310 s period range. We then invert the phase-velocity curves averaged over the entire globe and over all locations within 8 different tectonic environments (Archean cratons, stable platforms, Phanerozoic continents, active rift zones, old, intermediate and young oceans and backarcs) for 1D velocity models of the upper mantle. The dispersion curves are very smooth and accurate and are fit by the resulting Vs models with a misfit under 0.1-0.2% of the phase velocity value, at almost all periods. The models display the age dependence of the lithospheric thickness and seismic velocity in continents and oceans. Radial anisotropy is also determined and shows notable variations with depth and with tectonic environments. Interestingly, in the global and most tectonic-type models, we observe a flip of the sign of radial anisotropy from positive to negative values at ~200-300 km depth. In the oceanic tectonic-type models, negative anisotropy in the shallow mantle lithosphere is required by the data. Finally, we also compute models with minimal structural complexity, fitting the data nearly as well as the best-fitting ones but without a sub-lithospheric low-velocity zone. These models are similar in appearance to AK135 but with velocities representing the global average and each tectonic type. They do not correspond to realistic geotherms but provide a useful reference for seismic imaging studies in different settings.

SALSA3D: Updated Tomographic Velocity Models for Improved Travel-time Prediction and Uncertainty

Poster 53, presented Saturday, 29 October

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Monitoring the Earth for nuclear explosions depends on seismic data to detect, locate and characterize suspected nuclear tests. Motivated by the need to locate suspected explosions as accurately and precisely as possible, our team at Sandia National Laboratories and Los Alamos National Laboratory developed a specialized tomographic model of the compressional wave slowness in the Earth's mantle, SALSA3D (SAndia and LoS Alamos 3D; Ballard et al., 2016). While the aim of conventional tomographic modeling is to better understand the structure and dynamic history of the Earth's mantle, the primary focus of SALSA3D is on the accuracy and precision of travel time predictions for P and Pn ray paths through the model with quantifiable uncertainty. We obtain path-dependent uncertainty estimates for travel-time predictions by computing the full 3D model covariance matrix and then integrating slowness variance and covariance along ray paths from source to receiver. While this uncertainty method requires significant additional computational resources to develop and store when compared to simple distance-dependent uncertainty estimates, the result is a more complete prediction capability that can be incorporated into event location estimates using this model. In this contribution, we present updated SALSA3D P and S-wave slowness models. The updated models utilize a more extensive dataset, which provides increased resolution compared to previous iterations of SALSA3D. We capture the increased resolution with finer gridding in the GeoTess (Ballard et al., 2012) parameterization. We observe a significant decrease in the root-mean-square (RMS) residual of the predicted travel times, indicating the new models produce improved travel-time estimates that will result in better location estimates and robustly characterized uncertainties.

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High-resolution Imaging of the Shallow Subsurface and Relationship With Site Responses Using Joint Nodal and DAS Arrays Near Enid, Oklahoma

Poster 10, presented Sunday, 30 October

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During the last decade, Oklahoma observed sharp increase in seismicity due to increased wastewater injection and enhanced oil recovery operations. This phenomenon is also linked to the presence of favorably oriented basement faults and has resulted in major earthquakes (Prague, 2011; Fairview, 2016; Pawnee, 2016; Cushing, 2016).

Horizontal ground motion amplitude and consequently the earthquake intensity can show large variations even within a short spatial extent. To understand the relation between earthquake ground motion and shallow sedimentary shear velocity structure, we deployed a linear array of 39 nodal seismic sensors collocated with a dark optical fiber along a 22 km stretch of state highway (US 412) for a period of 1-month. The study area is located east of Enid town (northern Oklahoma) and cuts across a major fault (Nemaha fault) and several minor faults. The continuously recorded ambient noise is dominated by anthropological sources (traffic, trains, city noise) at high frequencies (> 1.5 Hz) and secondary microseism (~ 60º back azimuth) at low frequencies (< 1.5 Hz).

We reconstruct the surfaces wave propagation along the nodal seismic array using seismic interferometry. Subsequently, we use the dispersive behavior of these surface waves in the high frequency range (1.5 – 4 Hz) to invert for the sedimentary shear velocity structure down to ~ 600 m depth. The low frequency secondary microseism source is limited to a narrow azimuth that lies outside the stationary phase zone of the linear array, which poses a challenge to image the basement structure.

We compare our Vs30 model with the site amplification profile derived from the DAS and nodal data from nearby local earthquakes and observe significant correlation. Further, we also show correlation between the fundamental frequencies of ambient noise H/V ratio and the shallow (<100 m) shear velocity model. Our results highlight the capability of passive seismic methods for high resolution Vs imaging, which can be used for identifying zones of high seismic risk and assist in urban planning.

Structure and Evolution of the Australian Plate and Underlying Upper Mantle From Waveform Tomography With Massive Datasets

Oral Presentation, Sunday, 30 October, 1:50 PM

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We present a new S-wave velocity tomographic model of the upper mantle beneath the Australian Plate and its boundaries that we call Aus22. It includes azimuthal anisotropy and was constrained by waveforms from 0.9 million vertical-component seismograms, with the densest data sampling in the hemisphere centred on the Australian continent, using all available data covering this hemisphere. Waveform inversion extracted structural information from surface waves, S- and multiple S-waves and constrained S- and P-wave speeds and S-wave azimuthal anisotropy of the crust and upper mantle, down to the 660- km discontinuity. The model was validated by resolution tests and by independent inter-station measurements of surface-wave phase velocities.

Aus22 can be used to constrain the structure and evolution of the Australian Plate and its boundaries in fine detail at the regional scale. Thick, high-velocity (and, by inference, cold) cratonic lithosphere occupies nearly all of western and central Australia but shows substantial lateral heterogeneity. It extends up to the northern edge of the plate, where it collides with island arcs, without subducting. The rugged eastern boundary of the cratonic lithosphere resolved by the model provides a lithospheric definition of the Tasman Line. Just east of the Tasman Line, an area of intermediate-thick lithosphere is observed in the southern part of the continent. All the sites of Cenozoic intraplate volcanism in eastern Australia are located on thin lithosphere. A low-velocity anomaly is present in the mantle transition zone beneath the Lord Howe and Tasmanid hotspots, indicative of anomalously high temperature and consistent with a deep mantle upwelling feeding these hotspots and, possibly, also the East Australia hotspot. High seismic velocities are observed in the transition zone below north-east Australia and indicate the presence of subducted lithospheric fragments trapped in the transition zone, possibly parts of the former northern continental margin of Australia.

Anisotropic Seismic Tomography with the Reversible Jump Markov Chain Monte Carlo

Poster 3, presented Saturday, 29 October

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Implementation of stochastic methods in seismic tomography arises as a response to the limitations introduced by traditional non-linear optimization solvers. Since tomographic problems are generally ill-conditioned, additional constraints on the model are set in the misfit function, and the weight given to each minimization term has a level of arbitrariness; different solutions are obtained with different choices for the regularization/smoothing factors. Non-linear optimization solvers are based on a perturbative approach which linearizes locally the forward modeling around a reference model, updated at each iteration until convergence. These methods need the evaluation of the derivatives of the predictions with respect to the parameters of the model, which is not always an easy task and they generally may not provide the uncertainties associated with the solution model.

The reversible jump Markov Chain Monte Carlo method is a stochastic method which performs a random walk in the model space sampling the posterior distribution associated with the model in the light of the observations. This method is a trans-dimensional Metropolis-Hastings where the number of parameters used to represent the continuous fields (as interpolation nodes) is treated as a parameter itself of the inversion, as the positions of the nodes. Using statistical estimators on the sample of models produced by the algorithm it is possible to extract a reference model, typically as an average of the ensemble. With this method no regularization is needed, and uncertainty can be estimated using the ensemble of models sampled. Limitations of non-linear optimization solvers are overcome at the cost of an increase in the computational time required.

Applications of this method involve seismic tomography in subduction zones, where the anisotropic component of the velocity field is relevant, and the inversion of seismological data could provide an interesting insight into the dynamics of these regions.

Whole Earth Oscillations: The Key to Imaging Earth's Deep Interior

Oral Presentation, Saturday, 29 October, 9:30 AM

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Tectonic processes at Earth's surface are driven by convection deep in Earth's mantle. Seismic tomography using earthquakes is the main tool to directly image the Earth's mantle. Such images show regions with slow and fast velocity anomalies, including two large continental size regions just above the core mantle boundary, one located under the Pacific and the other one under Africa (the so called `LLSVPs'). These two regions have low shear wave velocity, but their role in mantle convection as either a thermal plume or a stable compositional pile is still heavily debated.

Here, I will show that the key to unraveling the nature of these two regions are whole Earth oscillations, which are being observed in low frequency seismic spectra. One of the advantages of using whole Earth oscillations is that we can use detailed mathematical perturbation theory, similar to that being used in quantum mechanics to describe, to calculate the effect of 3D mantle structure variations on low frequency seismic spectra. Furthermore, these whole Earth oscillations do not only provide shear wave velocity, but also additional information such as density and attenuation and also discontinuity topography. Density is a key parameter to determine buoyancy and attenuation links to viscosity and grain size, so together they may constrain mantle convection. Recent computer advances have now made it possible to incorporate normal modes with ever increasing complexity into seismic tomography, including cross-coupling (or resonance) between large groups of modes and directly inverting the frequency-domain normal mode data in a `full-spectrum' tomography, analogous to the `full-waveform tomography which is now common practice in time-domain tomography. We will show new models for 3D variations in velocity, density, boundary topography and attenuation for the upper and lower mantle. We find in our models that the two large low shear velocity regions in the lower mantle are partially dense at their base and have weak attenuation, requiring new interpretations in terms of mantle dynamics.

Crustal Structure of Terceira Island (Azores): Sampling a Volcanic Island With a Dense Network

Poster 18, presented Sunday, 30 October

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The Azores islands were built due to a complex geodynamic environment associated with a tectonic Triple Junction, in which differential expansion rates between the branches result in intense seismic and volcanic phenomena. Being of volcanic origin, the seismovolcanic activity observed across the archipelago is highly variable, each island suffering several episodes of strong earthquakes and/or volcanic eruptions since first settled in the XV century. Terceira island, the 2nd most important island in economic and population terms, presents smaller inland seismic and volcanic activity than most of the Azores islands, recent exceptions being the 1980 M6.9 earthquake and the 1998-2000 Serreta eruption, both located offshore. In 2019-2020 a temporary BB-SP seismic network operating in the island, reaching a total of 30 stations and increasing the microseismicity detection level, allowing to derive a 3D model from LET.

The tomographic images show some expected signals like the prominent low Vp and high Vp/Vs anomaly to west of the island, located beneath the Santa Barbara active volcano and the high Vp beneath the Serra do Cume extinct volcano. The fissural volcanic system located roughly between the two volcanic structures of above has a more complex signature, in particular of the Vp/Vs ratio most probably due to the complex effect of fluids and temperature, since this is the area being currently explored for geothermal energy. Two main clusters of seismicity are identified, one beneath Santa Barbara volcano and the other beneath the mid-island fissural system, their distribution clearly being controlled by the Vp and mainly Vp/Vs anomalies distribution. Some sparce seismicity occurs also in eastern Terceira, mainly associated with Lajes Graben.

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CANVAS: An Adjoint Waveform Tomography Model of California and Nevada

Poster 36, presented Sunday, 30 October

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Full waveform inversion (FWI) produces detailed models that can provide key constraints in other seismological fields, from moment tensor inversion to rupture propagation modeling. Though travel time and ambient noise models exist for the entire state of California, an FWI model of the entire state has not been reported. Therefore, we present the CAlifornia-NeVada Adjoint Simulations (CANVAS) model, a multi-scale adjoint waveform tomography model of California and Nevada. CANVAS reaches minimum periods of 15 seconds, resolving structure in the crust and uppermost mantle. CANVAS is created using a dataset of 103 Mw 4.5-6.5 events recorded by over 1300 unique stations during the period of January 2000 to October 2020. CANVAS uses WUS256 (Rodgers et al., 2022) as its starting model. The model is iterated over 5 period bands, starting with a minimum period of 30 seconds, and slowly reducing the minimum period to 15 seconds. We begin our iterations using focal mechanism solutions from the GCMT catalog, but re-invert for the source mechanisms for all 103 events using MTTime (Chiang, 2020), which computes 3D Green's functions using the version of the CANVAS model with 20 seconds minimum period. The recomputed moment tensor solutions show improved waveform fits and double couple (DC) percentages in comparison to the GCMT solutions. The depths of the earthquakes are also recalculated during the source inversion, and the recalculated depths better match the depths reported in the USGS catalog. This work was supported by LLNL Laboratory Directed Research and Development project 20-ERD-008. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-ABS-835847.

Lithospheric Imaging of the Cascadia Subduction Zone Based on Full-waveform Inversion

Poster 56, presented Sunday, 30 October

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The Cascadia subduction zone is one of the relatively young and warm endmember subduction systems, mainly due to the subduction of the Juan De Fuca plate underneath the North American Plate. Studies have shown the complex fluid migration process in this the crust and mantle while the high tremor activity could also be partly attributed to fluid migration in this region. In this study, we aim to obtain high-resolution velocity structures of the crust and upper-mantle of this region based on full-waveform inversion. In particular, high frequency teleseismic P waves are sensitive to sharp discontinuities and velocity variations beneath dense seismic arrays, and ambient noise data can be used to constrain fine-scale crustal structures. By using hybrid spectral element method (FK-SEM), we could combine the teleseismic P wave waveform (both the main P phase and the ensuing scattered waves) and ambient noise cross-correlation data to obtain a detailed shear-wave velocity structure of the Cascadia Subduction Zone (Wang et al., 2021). Our model shows strong variations in the crust and upper mantle in the central Cascadia subduction zone and may further our understanding of the geodynamics in this region.

Resolution and Trade-offs in Anelastic Full-waveform Inversion for Global-scale Models

Poster 19, presented Saturday, 29 October

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Advances in understanding the Earth's attenuation structure are falling behind that of wave speed models due to the complexity of amplitude measurements. Uncertainty in focusing and scattering effects, errors in instrument response and estimation of source complexity, they all complicate the identification of reliable measurements associated with attenuation. The attenuation structure is an essential source of information, which helps to constrain water content, partial melting and temperature variations in the Earth's crust and mantle. Thus, improving the resolution of seismic anelastic models is essential for better understanding the Earth's subsurface structure and its dynamics. To assess the resolution and trade-off between elastic and anelastic parameters in full-waveform inversion (FWI), we perform a series of synthetic anelastic inversions using a realistic configuration of stations and earthquakes. Starting from a 1D Q-model, we fit both amplitude and phase measurements to retrieve a target global 3D Q-model. To that end, we focus on surface waves within periods between 40 and 250 s, from a small data set of 25 earthquakes. Furthermore, we explore recent approaches to approximate the posterior covariance matrix. Within a Gaussian assumption, we test the feasibility of using the adjoint gradients in our iteration history to estimate a low-rank approximation of the Hessian, which is related to the inverse of the posterior covariance. The anelastic/elastic iterations are performed on TACC's Frontera and PRACE's Marconi100 systems, taking advantage of GPU hardware accelerators. We will present our benchmark results to improve strategies for large-scale anelastic inversions.

Submarine Distributed Acoustic Sensing for Crustal Imaging in the Cascadia Forearc

Poster 12, presented Sunday, 30 October

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Subduction zones are active convergent plate boundaries that play a crucial role in Earth's dynamics. However, they are predominantly located in oceans. The sparsity of current seismic instrumentations in those areas significantly diminishes the ability to obtain information on their sedimentary and tectonic history, which in turns limits our understanding of the underlying physical mechanisms. Distributed acoustic sensing (DAS) is providing an

inexpensive solution to closing this gap by converting submarine fibers into dense seismic arrays. In November 2021, a 4-day ocean-bottom DAS experiment was conducted using the Ocean Observatories Initiative Regional Cabled Array in the forearc region of the Cascadia Subduction Zone. DAS interrogators were installed on two subparallel cables, forming a ~60-km array in the north and a ~90-km array in the south. Both of them extend westwards from the shore station in Pacific City, Oregon, to the Cascadia Margin offshore.

Scholte wave signals can be traced clearly in intra-array noise interferometry results, and dispersion curves can be extracted precisely in the frequency band of [0.1, 1] Hz. A level-set tomography method (Muir & Tsai, 2020) is then employed to invert for subsurface shear velocity models. The derived velocity models of the top 4 km reveal two forearc basins in the middle of the north array and the south array, respectively. The bottom of these sedimentary basins are consistent with interfaces from previous active seismic survey nearby. These results demonstrate a cost-effective approach to characterizing submarine geological conditions accurately and efficiently with only a few days' seismic noise record from DAS. Particularly, an ocean-bottom fiber seismic network promises to advance our knowledge of undersea subduction zone environments.

Reference: Muir, J. B., & Tsai, V. C. (2020). Geometric and level set tomography using ensemble Kalman inversion. GJI

Hamiltonian Monte Carlo Sampling for Uncertainty Quantification in Real-world Tomography

Poster 78, presented Sunday, 30 October

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We discuss various variations of the Hamiltonian Monte Carlo sampling algorithm that allow us to solve real-world tomographic inverse problems. By taking the sampling approach, we appraise uncertainty and address nonlinearities in tomographic imaging from a Bayesian perspective, avoiding simplifications of the inverse problem characteristics.

However, utilizing sampling as a means to appraise uncertainty incurs large computational cost. We show how the usage of gradients of the posterior distribution within Hamiltonian Monte Carlo avoids part of this problem, but also what other MCMC techniques are applied when sampling tomographic inverse problems.

Specifically, we look at first arrival tomography based on the Eikonal equation and full-waveform inversion based on spectral element modeling, the latter specifically focusing on retrieving one-dimensional profiles of the Australasian region by fitting surface wave dispersion curves. These two examples show how full uncertainty quantification at scale is becoming possible using modern HPC resources in combination with appropriate algorithms and what these results can actually tell us about the Earth itself.

Fusion of Seismic Tomography Maps Using a Probability Graphical Model

Poster 49, presented Saturday, 29 October

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Probability graphical models (PGMs) have been widely used in image segmentation and super-resolution tasks. We employ the Markov Random Fields (MRFs) to give segmentation results on seismic tomography images with various resolutions. The various resolutions could be due to different tomography approaches or just different data. Image segmentation here corresponds to various velocity intervals. The results describe the structural information and reveal the corresponding relation between the multiple-scale images. By transferring the distribution information from the high-resolution (HR) images, the details in the low-resolution (LR) images can be enhanced by solving a maximum likelihood problem with the prior knowledge from HR models informed. Each pixel in the velocity model is considered as a node, and only the neighboring pixels are connected with edges in an undirected graph. A Gibbs distribution is used to find the optimal segmentation.

Community models provide wide spatial coverage but have limited resolutions. To incorporate the detailed structures in these models with various resolution and spatial scales, a PGM is used for learning the geometric structure inside the velocity models and enhancing the resolution. To evaluate the performance, we compare the PGM with existing physics-driven and machine-learning methods on both synthetic (checkerboard) and real (Ridgecrest) models. The Ridgecrest models consist of shallow-scale (top 1 km) high-resolution Rayleigh wave models developed using ambient noise tomography. Our PGM is evaluated by computing the travel time misfits using the travel time observations from the station pairs. The PGM provides 14 % decrease in travel time misfit for the checkerboard, and the Ridgecrest test shows noticeable improvements in the misfit relative to the original models. Our PGM can merge any type of gridded multiscale and multidimensional datasets, a valuable tool for computational seismology.

Spectral-infinite-element Simulations of Seismic Wave Propagation in Self-gravitating 3D Earth Models

Poster 20, presented Sunday, 30 October

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Simulating seismic wave propagation in a self-gravitating Earth with 3-D heterogeneity is challenging due to the numerical complexities associated with the unbounded Poisson/Laplace equation that governs motion-induced gravity perturbations. Therefore, gravity perturbations are generally omitted using the so-called Cowling approximation. However, gravity perturbations may be significant for large earthquakes (Mw ≥ 6.0) and long-period responses.

To tackle this challenge, we develop a time-domain solver based on the spectral-infinite-element approach, which combines the spectral-element method, inside a domain of interest, with a mapped-infinite-element method in the infinite space outside the domain. Such a combination allows us to solve the complete, coupled momentum-gravitational equations in a fully-discretized domain while accommodating complex 3-D Earth models. We compute displacement and gravity perturbations considering various Earth models, including PREM and S40RTS, and benchmark our results against the spherical harmonics normal-mode approach and the direct radial integration method. Results show that our method is accurate and stable for long simulations. Our method provides new scope for incorporating data from large-magnitude earthquakes into adjoint tomographic inversions.

Lithospheric Thermochemical Heterogeneity in the Continental United States From Seismic Tomography

Oral Presentation, Sunday, 30 October, 9:50 AM

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The lithosphere below the contiguous United States represents >2 Ga of Earth history. Many seismic tomography studies have mapped wave speed variations, but the geologic processes underlying these variations are less well-constrained. Continent-scale studies often assume that thermal variations control seismic anomalies, but phenomena such as melting, melt depletion and metasomatism also influence wave speed and provide insight into past and present tectonic and geodynamic activity. The Vp/Vs ratio is useful for constraining thermal and chemical variations and for evaluating their relative impacts on seismic wave propagation, as it has different sensitivity to composition compared to Vs or Vp alone. We interpret Vs and Vp/Vs from the MITPS_20 tomography model (Golos et al., 2020). This model, derived from a joint inversion of P and S arrival times and Rayleigh wave phase velocities, has good 3D resolution throughout the lithosphere. We utilize the Whole-rock Interpretive Seismic Toolbox For Ultramafic Lithology (WISTFUL), which interprets seismic wave speed in terms of temperature and composition with associated uncertainties. Specifically, WISTFUL allows us to estimate major-element chemistry and temperature at a given location with known Vs and Vp/Vs. We find that while the first-order wave speed contrast between the eastern and western United States can be attributed primarily to a contrast in temperature, regional features require geochemical heterogeneity. Further, within the central US, compositional enrichment (Mg number 89-90) and thermal anomalies (~900˚C) may be related to rift structures; in the Appalachians, elevated temperatures (~850˚C) are consistent with proposed asthenospheric upwellings. This workflow holds promise

for identifying signatures of tectonic processes based on seismic observations and for understanding lithospheric evolution.

Double-difference Seismic Attenuation Tomography

Poster 17, presented Saturday, 29 October

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Determining seismic attenuation (Q) structure is an effective way of characterizing rock physical properties in the crust and mantle. A common way to determine Q structure is to invert observed earthquake spectra for the path attenuation term, t*, from a set of earthquakes at a set of stations, and then perform 3D Q tomography, analogous to seismic velocity tomography. However, Q tomography is generally more difficult than velocity tomography as a result of the larger errors in t* measurements due to the trade-off between source, path and site parameters when fitting earthquake spectra. Here we present our recently developed double-difference attenuation (DDQ) tomography method (Guo and Thurber, 2021, 2022) that can mitigate this trade-off to measure more accurate attenuation data for Q tomography. The workflow for DDQ tomography consists of three main elements: (1) multiple event-multiple station inversion of spectra for attenuation parameter t*, low-frequency spectral level, corner frequency f_c and frequency-dependent site response; (2) multiple event pair-multiple station inversion of spectral ratios for differential t* (dt*) values, f_c and the ratio of low-frequency spectral level; (3) tomographic inversion of t* and dt* data for 3-D Q structure. Note that site response and instrument response divide out for each spectral ratio. We have applied the method to The Geysers geothermal field in California using P-wave data from thousands of earthquakes in years 2005 and 2011. Our results show that more accurate dt* values can be obtained using our spectral ratio approach and the resulting Q model is better resolved than the Q model determined using t* data alone. Vp and Qp model changes between 2005 and 2011, determined by differencing the models, reveal temporal changes inferred to reflect changes in fracturing and saturation state due to fluid injection. Presently, we are applying our method to the subducting Pacific slab beneath northern Honshu, Japan, which we expect will better constrain the physical properties of the Double Seismic Zone in the slab.

Model Parameterization and Sensitivity Kernels in 3D Anisotropic Media

Poster 13, presented Saturday, 29 October

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The presence of anisotropy in the uppermost mantle is well established. In subduction settings, anisotropy is complex, with different elements—the subducting plate, the mantle wedge and the crust—potentially having different forms of anisotropy. Seismic imaging studies of anisotropy require some form of parameterization for the elastic anisotropic medium, both in terms of the elastic symmetry (e.g., general/trivial, transverse isotropic, orthorhombic) and how the elastic symmetry is represented (e.g., Voigt matrix, Thomsen, Chen–Tromp). A key question is: What kind of parameters should be used to characterize the elasticity tensor for efficient recovery of the true Earth anisotropy? With this goal in mind, we study a new parametrization of the elastic tensor that is defined with respect to an orthonormal basis, and we construct sensitivity kernels for these parameters. The sensitivity kernels relate a change in a particular waveform measurement to a change in a particular model parameter, and therefore they help inform what kinds of measurements and source–station geometries will be optimal for recovering anisotropic structures. We explore the influence of choices in measurements and choices in anisotropic parameters on the sensitivity kernels, and we compare the kernels with ones generated using previously proposed parameterizations. Our study prepares us for realistic synthetic inversions for complex anisotropic structures, which, in turn, will guide efforts for performing adjoint tomography in the Alaska subduction zone.

Improving Results and Interpretation in Time-dependent Tomography and Between Temporal Campaigns

Oral Presentation, Sunday, 30 October, 10:45 AM

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Imaging time-varying processes helps reduce the non-uniqueness in interpretation. However, artificial differences between estimated models need to be identified and investigated to show the significance of changes between models (Hobé et al. 2021). This presentation describes novel and possible avenues to improve understanding and results of Time-Dependent Tomography, including comparisons between temporal campaigns.

An increase in laboratory data allows and will continue to allow improved understanding of how large expected model changes can be for time-varying processes. Increased focus on identifying such maximum differences in laboratory studies may accelerate this understanding. Improvements in reconstruction, hypothesis tests and other synthetic tests will help identify expected model changes for time-varying processes and artificial model changes for a constant subsurface. Improving inversion methods to produce improved time-dependent results (Hobé & Tryggvason, 2022). These include inter-model minimization, and joint, or constrained inversion with other geophysical methods. To improve these methods, we can create strategies to prevent unwanted model components from transferring between epochs, or inversion sub-problems. Improved understanding of errors and their influence will further improve results. Additionally, new frameworks already exist that produce geologically consistent results, or new methods may make it impossible for the results to include geologically impossible features.

References: Hobé et al. (2021): Imaging the 2010-2011 Inflationary Source at Krysuvik, SW Iceland, Using Time-Dependent Vp/Vs Tomography, In Proc. World Geoth. Cong. 2020+1; Hobé & Tryggvason (2022): Visualizing Best and Worst Case Scenarios in Joint, Constrained, and Time-Dependent Inversions I: Null-Space Transfer and Image-Space Contradictions, submitted to Geoph. J. Int.

Fiberoptic Versus Geophone / Accelerometer Data in Elastic Full Waveform Inversion of Borehole Seismic Data

Poster 16, presented Sunday, 30 October

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In long-term monitoring problems, such as those associated with CO_2 storage, elastic full waveform inversion of fiberoptic vertical seismic profile data (as opposed to a full 4D seismic program) may represent a practical compromise between reliability and cost. However, there is little real evidence available concerning the ability of DAS borehole data to meaningfully constrain subsurface elastic properties, especially in the presence of a complex onshore near surface. And, as far as we are aware, there are no apples-to-apples comparisons of inversions from standard multicomponent phones versus those generated with DAS data. Feasibility studies have in fact been suggestive that optimal models are produced not by DAS or geophone/accelerometer data in isolation, but in combination. In part to shed light on these questions and observations, in 2018, our group, in collaboration with the Containment and Monitoring Institute (CaMI), carried out a baseline multi-offset, multi-azimuth VSP experiment at the CaMI Field Research Station, in which a 1Hz Vibroseis source occupied approximately 400 points around a borehole, which was instrumented with DAS and broadband accelerometers from surface to the injection zone. A frequency-domain elastic FWI approach was formulated to (1) accommodate all of these seismic data types simultaneously, (2) avoid the problematic near-surface and (3) parameterize using available well-log trends. Elastic models were generated, with the relative weighting of DAS data varied from low to high. We observe meaningful, interpretable models and excellent data matches across the board, but we also observe several problematic trends in model structure associated with too high a reliance on DAS data from straight fiber alone. We conclude that the introduction of shaped DAS fibers, or at least small numbers of broadband sensors, could be important in making the DAS-VSP-FWI monitoring mode reliable.

Normal Mode Constraints on Vs, Vp and Their Ratio in the Earth's Mantle

Poster 27, presented Saturday, 29 October

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Normal mode observations of variations in shear-wave (Vs) and compressional-wave (Vp) velocities provide constraints on the origin and nature of the two lower mantle Large Low Shear wave Velocity Provinces (LLSVPs). In contrast to body waves, normal modes do not suffer from differences in data coverage throughout the globe, making them well suited for global mantle studies. Modes are ideal for constraining the ratio R(S/P) = dln(Vs)/dln(Vp), which is generally found to be greater than 3 in the lower mantle (e.g. Romanowicz, 2001; Koelemeijer et al., 2016), larger than expected for an isochemical mantle without phase transitions (Karato & Karki, 2001).

Here, we use an extensive normal mode data set to develop new tomographic models of 3D variations in Vs and Vp. Normal mode spectra can be inverted in two ways: 1) a one-step direct spectrum inversion or 2) a two-step inversion with splitting function measurements as intermediate step. We investigate the effects of the new one-step inversion approach compared to the more commonly used two-step inversion and find that one-step R(S/P) values are generally lower than for the two-step models. We also explore different ways in which to express R(S/P) and the thermochemical interpretations drawn from them. Combining distributions of dln(Vs), dln(Vp) and R(S/P) with the 1D R(S/P) average or median, provides more information than looking at 1D R(S/P) alone. These distributions are suitable for applying a Metropolis-Hastings algorithm to determine the ranges of temperature and composition that fit the observed distributions. In addition to large-scale variations in Vs and Vp, imaging small-scale variations in Ultra-Low Velocity Zones (ULVZs) using body waves may shed some light on their thermochemical nature and a potential link with the much larger LLSVPs.

Adjoint Tomography of an Accretionary Wedge and Shallow Slow-slip Regions in the North Island of New Zealand

Poster 70, presented Sunday, 30 October

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The Hikurangi subduction zone in the North Island of New Zealand hosts repeating slow-slip events, a thick accretionary wedge, subducted seamounts and a fully-locked plate interface that is capable of generating megathrust earthquakes. Recently, Chow et al. (2022a,b) undertook the first application of earthquake-based adjoint tomography of the Hikurangi subduction zone and imaged two high-velocity anomalies below the East Coast of the North Island, which have been interpreted as previously unidentified, deeply subducted seamounts. The presence of these seamounts is supported by independent evidence including seafloor bathymetry data and the presence of nearby geophysical anomalies. They are also linked with spatial variations in slip behavior observed along the Hikurangi subduction margin. In this tomographic study, we extend the domain of Chow et al. (2022a,b) 400 km to the northeast to include the 2017-2018 IODP (International Ocean Discovery Program) drill sites (Barnes et al., 2020), the 2021 M7.3 East Cape earthquake (Okuwaki et al., 2021), offshore seamounts identified by active source seismics (Bell et al., 2010) and a thick low-velocity wedge in the northern margin (Kaneko et al., 2019). Using 60 geographically well-distributed events recorded by 88 permanent and temporary broadband stations, we perform iterative model updates using spectral element and adjoint simulations to fit waveforms with periods ranging from 6 – 30 s. We present ongoing efforts towards imaging and understanding the accretionary wedge of the Hikurangi subduction zone and its link to spatial variations in megathrust slip behavior.

Implementation of "Spherical Earth" for Box-tomography in Regional Scale

Poster 5, presented Saturday, 29 October

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We present the development of a computational framework for the full-waveform inversion of the 3D anisotropic structure of the subduction zone of the Ionian slab at the Tyrrhenian Sea (Italy), to a depth of approximately 500 km. Numerical simulations at the desired resolution in a global setting are computationally extremely costly. Therefore, we jointly use spectral-element SPECFEM3D and AxiSEM software in order to implement the so-called "box tomography" [1]. The global simulation is performed with AxiSEM for a 1-D Earth, whereby the wavefield is constructed at the sides of the "box" (studied region), which covers an area of 11° in latitude and 18° in longitude, where it is propagated in 3D with higher detail using SPECFEM3D-Cartesian. We need to apply an orthographic projection prior to implementing the Earth's curvature in the computational mesh. We test our framework against data of regional quakes and teleseisms, to validate the "spherical" SPECFEM3D implementation and the hybrid AxiSEM-SPECFEM3D, respectively. We use isotropic and anisotropic regional models[2]. The results of the forward simulation are then used for the inversion.

[1] Masson, Y. and Romanowicz, B., 2017. Box tomography: localized imaging of remote targets buried in an unknown medium, a step forward for understanding key structures in the deep Earth. Geophysical Journal International, 211(1), pp.141-163.

[2] Rappisi, F., VanderBeek, B.P., Faccenda, M., Morelli, A. and Molinari, I., 2022. Slab geometry and upper mantle flow patterns in the Central Mediterranean from 3D anisotropic P-wave tomography. Journal of Geophysical Research: Solid Earth, p.e2021JB023488.

Finite-frequency Tomography in the Chile Triple Junction Region

Poster 67, presented Saturday, 29 October

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The Chile Triple Junction (CTJ) is the point where the Antarctic, the Nazca and the South American plates meet and is presently a ridge-trench-trench triple junction. As a consequence of the Chile ridge subduction, a slab window, which is a gap within the subducting oceanic lithospheres, is considered to be developed beneath southern Patagonia. We analyzed broadband seismograms to constrain the seismic velocity structure beneath the forearc region in the vicinity of the CTJ.

The seismic array of 13 Ocean Bottom Seismometers (OBS) had been deployed just south of CTJ for approximately two years, from 2019 January to 2021 January (Ito et al. 2022). We also collected broadband seismograms of the IRIS stations within the distance of 30˚of the OBS array. We measured absolute P-wave travel times by the Adaptive Stacking method (Rawlinson and Kennett, 2004) and differential travel times of all possible station pairs by cross-correlating two seismograms.

Combining the measured regional travel times with global arrival times from the ISC Bulletin, we conducted tomographic inversion to estimate the three-dimensional seismic structure. In our method, we employed ray-theoretical kernels for the onset times and ray-theoretical finite frequency kernels for differential travel times measured by cross-correlation. For tomographic inversion, we employed a conjugate-gradient method with a first-order smoothness constraint to obtain the 3D P velocity perturbation with respect to an average one-dimensional structure. We repeated the processes of event relocation, tomographic inversion and one-dimensional structure determination by spherically averaging the 3D velocity structure until convergence was achieved.

Imaging of the Yellowstone Plume Using Box Tomography

Poster 76, presented Sunday, 30 October

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The origin and magmatic nature of the Yellowstone hotspot, one of the largest intraplate continental volcanoes in the world, is still unclear. Recent tomographic studies (e.g. Nelson and Grand, 2018) indicate a narrow vertically oriented plume-like low shear velocity conduit originating at the base of the mantle, somewhat offset to the southwest from the location of the Yellowstone hotspot and strongly deflected horizontally around 1200 km depth. However, the resolution at mid-mantle depths is particularly poor. Here, we aim to develop a high-resolution 3D elastic model of the deep structure beneath the Yellowstone hotspot using the "box tomography" approach. We couple a global 3D solver, SPECFEM3D GLOBE, for the computation of the wavefield and Green's functions outside of the box in a reference 3D model, with a regional 3D solver, RegSEM, for the computation of the wavefield within the box. The wavefield outside of the box needs to be computed only once. The contribution of body waveforms at teleseismic distances is necessary to properly illuminate mid and lower mantle structure. The starting, reference 3D model is the global radially anisotropic SEMUCB_WM1 model (French and Romanowicz, 2014), which shows a faintly resolved low velocity plume beneath Yellowstone (French and Romanowicz, 2015). We constrain the starting crustal model from surface wave dispersion data extending down to 10s period, using a combination of earthquake-based and ambient noise measurements. We first compute the required global wavefields in the reference 3D model down to 20 s period and record these fields on the box boundaries. Inversion iterations are then performed within the box, progressively decreasing the cut-off period from 40s to 20s. While we will mostly be using a Gauss-Newton optimization approach for the inversion, using a physics-based Hessian computed by asymptotic normal mode theory (NACT, Li and Romanowicz, 1995), the last iterations of the model will be performed using an adjoint approach (Tromp et al., 2008). We will present preliminary results and next steps.

Modeling and Observation of Train Signals in the Urban Environment

Poster 28, presented Sunday, 30 October

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Trains are massive objects whose limited maneuverability and relatively consistent speed deliver robust and continuous seismic signals that allow subsurface imaging in the urban environment. However, the ground vibrations felt in urban areas are increasingly a cause of concern as spatial limitations have resulted in infrastructure projects with high-density tracks that provide transport for rising populations and their demands for goods. In this study, we perform comprehensive simulations of elastic waves induced by moving trains in a three-dimensional urban environment based on the spectral element method (SEM) using the open-source software package SPECFEM3D Cartesian. The model incorporates multiple moving sources corresponding to the train speed, wheel spacing and average weight of the train compartments. The simulated train signals are compared with real data for VIA rail passenger trains collected in the township of Pittsburgh, Ontario, using two three-component geophones. The results demonstrate that the simulated data matches the predominant signal from the real data. Such simulations may be critical for improved subsurface imaging using noise tomography of the urban environment and the predictive tool for environmental and sociological impacts of ground vibrations caused by urban traffic.

Increasing the Resolution of Global and Regional Tomography: Progress and Challenges

Oral Presentation, Saturday, 29 October, 1 PM

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The problem of seismic tomography can be formulated, following Backus and Gilbert, as finding localized Earth-structure averages over the smallest resolving lengths possible, given the data sampling and data errors. The resolving length at a point is the width of the local averaging kernel, and the optimal kernel is the narrowest one such that the model error is below a specified level. The model error is smaller for broader averaging kernels, and "low-resolution" solutions can offer valuable, accurate models, including reference ones. "High-resolution" models reveal heterogeneity within the Earth at the fine scales of tectonic and geodynamic processes and can illuminate these processes' mechanisms. As it is difficult to estimate the model error, it is also difficult to determine the optimal resolution, such that the error is under a threshold. In surface-wave imaging, empirical model errors can be estimated based on the mutual consistency of phase-velocity maps at different periods and optimal-resolution tomography has recently been developed based on this.

Another important problem is how to get around the non-uniqueness of tomographic models. Multi-disciplinary inferences from the models often rely on their features that are important in terms of the Earth's thermo-chemical structure and dynamics but highly non-unique in terms of inverse problem solutions. Thermo-chemical imaging using computational petrology can be effective in narrowing the bundles of acceptable models by excluding the physically implausible ones. Although thermodynamic constraints can also bring extra uncertainties, the petrological inversion of seismic data can be tuned so as to reliably increase the resolution of the thermal structure—in particular, of the lithosphere and asthenosphere.

The Remnants of Continental Collision in Southern Appalachians: Constraints From Joint Full-waveform Inversion

Poster 64, presented Sunday, 30 October

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The Appalachians is a passive continental margin which has gone through several stages of collision and splitting in geological history, first through formation and breakup of the Rodinia and then the formation and breakup of the Pangea. Therefore, the Appalachians provide a good example to study the continental collision process. In Southern Appalachians, Laurentia and Gondwana collided at about 300 Ma and formed Pangea. The shallow structure of the suture zone is well studied (Hoppers er al., 2017), while how the collision affected the upper mantle is not clear. Therefore, high-resolution imaging of the structures of crust and lithospheric mantle beneath southern Appalachians is crucial to understand the links between the crust and mantle structure.

Full-waveform inversion (FWI), with more accurate 3D numerical modeling of seismic wavefield, 3D sensitivity kernels as well as iterative inversion procedures aimed at reducing the misfit between data and 3D synthetics, is a powerful tool to investigate the subsurface structures. For regions with dense and well-distributed seismic networks, FWI based on ambient-noise data may help resolve the fine-scale crust structures. On the other hand, if dense linear arrays exist in the region, FWI based on high-frequency P waves and their coda/scattered waves can be applied to reveal small-scale heterogeneities and sharp interfaces in the lithosphere based on hybrid modeling techniques such as SEM-FK (Tong et al, 2014). The joint inversion of ambient noise data and teleseismic P waves may utilize the complementary sensitivity of these two datasets and provide complementary sensitivity and hence help improve the lithospheric resolution (Wang et al., 2021). In our study, we applied the joint FWI of ambient noise data and teleseismic data to map the Vs structures beneath the Appalachians. Our model identifies strong lateral heterogeneity in the crust and lithospheric mantle and may provide new constraints on the collision history of Laurentia and Gondwana.

Seismotectonic Characteristics of the Taltal Segment in Northern Chile, Inferred Using Local Earthquake Tomography

Poster 59, presented Saturday, 29 October

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The seismotectonic characteristics of northern Chile offer a great opportunity to perform seismic experiments to better understand the subduction process in highly erosive margins. Here, the tectonic setting where the oceanic Nazca plate subducts beneath the continental South American plate, together with the heterogeneities on the seafloor and the prominent peninsulas in the coastline, contribute to diversify the modes in which the stress is release in the region.

In particular, the Antofagasta region between ~22°S and ~26°S has been the subject of a notable scientific attention; however, the seismotectonical studies have put their focus mainly in the coastal areas affected by large earthquakes during the past 30 years, leaving unattended the processes in the overriding plate from the coastline to the volcanic arc.

By benefiting from a large temporary deployment with 88 short period geophones and the high rate of seismicity in the region, we derive regional 3D *Vp* and *Vp/Vs* velocity models to tectonically characterize the Taltal segment. We use the *Regressive ESTimator* (*REST)* package for automatic onset detection and create an earthquake catalog with 52168 hypocenters and their P- and S-wave arrival times. Following acceptability criteria, we create a high-quality dataset and invert for 3D *Vp* and *Vp/Vs* models using local earthquake tomography.

Vp model shows the Nazca plate with a Vp~ 8 km/s dipping eastward. In contrast, *Vp/Vs* highlight prominent features with values < 1.76 in the overriding plate that collocate with large scale structures such as the Atacama fault in the coastline and the West Fault System towards the Andes. Finally, distribution of seismicity is mainly located in the plate interface between 20-150 km depth following the current slab models; however, we observe a dip change at intermediate depths (150 - 200 km) that could be related to a consistent slab-pull activity.

WINTERC-G in Eastern North America: Local Control for a Global Multiparameter Model of the Mantle

Poster 43, presented Saturday, 29 October

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Since the early efforts of tomography, continents were understood as broadly different from the oceans as well as internally heterogeneous on any lateral scale that could be resolved. One option for mitigating the influence of local complexity within continents on the large-scale tomographic images is the development of local "control" on the basis of independent data.

An example of this approach is illustrated using Eastern North America as the test bed. We combine WINTERC-G, a global thermochemical 3D model of the upper mantle with high lateral resolution, constrained by surface-wave, gravity and other data and high-quality data sets of receiver functions sensitive to impedance and anisotropy changes with depth.

These high-quality data sets are available for three regions with vastly different tectonic history and present-day structure of the lithosphere: the eastern part of the Archean Superior craton, the Adirondacks region of the Proterozoic Grenville Province and the New England region of the Paleozoic Appalachian Orogen.

There is a broad agreement in estimates of the vertical extent of the lithosphere and lateral changes in it on the scale of 100-200 km. Receiver function constraints may thus be viewed as a useful verification tool. There are, however, intriguing examples of clear mismatch that offer opportunities to resolve structural complexities in the lithosphere, asthenosphere and the transition between the two. We discuss a case of a cold fast feature that appears to reside beneath the lithosphere of the Adirondack region.

Finally, we re-confirm a fundamental difference in the nature of the lithosphere-asthenosphere boundary between cratons (like the Superior) and younger regions. While Proterozoic and younger areas show evidence of layering throughout the vertical extent of the lithosphere, under the craton the lower ~50 km of the lithosphere has no abrupt vertical gradients in properties that can be detected with receiver functions.

Ambient Noise Tomography Across Dense Nodal Arrays

Oral Presentation, Saturday, 29 October, 1:50 PM

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High-resolution tomography is desirable to fully understand detailed subsurface structure. This can generally be achieved either by modeling existing data more accurately or significantly improving the data coverage. We focus on the latter in our recent studies, where we investigate high-resolution crustal imaging across various large N nodal geophone arrays. The approach is particularly powerful when combined with the methodology of ambient noise cross-correlation where ray path density increases as a function of the square of N. In this presentation, we will summarize the results of recent studies in various regions including Yellowstone, central Alaska and central Taiwan. In Yellowstone, a ~600 nodal array was deployed along all available roads in the national park. We apply ambient noise tomography which reveals detailed 3D Vs structure associated with the magmatic and hydrothermal system. In central Alaska, a ~300 nodal linear array was deployed along the Parks Highway across the Alaska Range. Using beamforming/slant stacking, we resolve both location-dependent Rayleigh wave ellipticity and phase velocities. By inverting surface wave data, we resolve the 2D crustal Vs profile that reveals detailed crustal structure of the region. In central Taiwan, as part of the TAIGER project, a ~60 geophone linear array was deployed from the west coast to east coast cutting through the Central Mountain Range and both fundamental and first higher model Rayleigh waves can be clearly observed in noise cross-correlations. We use double beamforming tomography to image the 2D Vs profile where major structural boundaries and faults are identified.

Complex Seismic Anisotropy Beneath the Central Appalachian Mountains from SKS-splitting Intensity Tomography

Oral Presentation, Saturday, 29 October, 2:10 PM

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The tomographic inversion of shear wave splitting data for upper mantle anisotropy has been a longstanding challenge for classical analysis techniques. This roots in the ray-based approximation of classical approaches and the near vertical incidence of core-mantle converted phases that serve as source. Recent developments involve the calculation of finite frequency sensitivity kernels for SKS-splitting intensity observations which allows to take into account the laterally broadened sensitivity for the anisotropic structure with depth. This technique requires a dense station spacing to allow for overlapping sensitivity kernels which is satisfied by the MAGIC-seismic profile crossing the Central Appalachian Anomaly (CAA). This region is of particular interest, as it is accompanied by an abrupt change of fast axis orientation and a thinned lithospheric structure. The nature of this anisotropic feature might shed light into the underlying mechanism of the CAA as well as the relatively young volcanism present in this area. We implement a two-step Wiener-filter approach to suppress the influence of noise and equalize the period of the waveform for better data coverage and more consistent shear wave splitting intensity measurements. We test the applicability of the splitting intensity tomography in the described setting by comparison of its results with classically derived multi-layer splitting analysis. We review the results given by the statistical analysis of the splitting intensity tomography by comparing the observed splitting parameters and waveform data with 2.5D-forward modeled shear wave splitting using finite differences. Our ongoing work is aimed at implementing joint inversions for anisotropy parameters that include receiver function constraints to overcome the limited sensitivity for shallow anisotropic structures due to the lack of overlapping sensitivity kernels.

Influence of Shear-wave Velocity Heterogeneity on SH Wave Reverberation Imaging of the Mantle Transition Zone

Poster 29, presented Saturday, 29 October

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Waveform stacks of long-period (T > 10 s) shear-wave reverberations between the surface and reflecting boundaries below seismic stations have been used for studying the mantle transition zone (MTZ), but finite-frequency effects and inaccurate input velocity models may complicate interpretation of the stack results. In this research we explore the uncertainty of a common-reflection point (CRP) based method modeling layering in the mantle using transverse component from both recorded and synthetic waveforms. Firstly, our CRP mapping of recorded waveforms from USArray places the 410-km and 660-km phase boundaries about 15 km deeper beneath the western US than beneath the central-eastern US if it is based on the 1-D PREM model. This apparent east-to-west deepening of the MTZ disappears in the CRP image if we account for shear-wave velocity variations in the mantle, illustrating the necessity of using 3D velocity structures to obtain accurate reverberation travel times. Secondly, we attest the east-to-west deepening in CRP mapping using synthetic waveforms from the 3D velocity model S40RTS and test the performance of the ray-theoretical travel time correction. The ray theory turns out to overpredicts the travel time delays of the reverberations if 3-D velocity variations in the mantle are prescribed by global models S40RTS, SEMUCB-WM1 and TX2015, suggesting that the finite frequency effect is not negligible. Thirdly, we add different sizes of topography to the MTZ and find that undulations of the 410-km and 660-km are underestimated in size and amplitude when their wavelengths are smaller than the Fresnel zones of the wave reverberations in the MTZ.

Lithospheric Structures of Western Mid-continent Rift Revealed by Full-waveform Joint Inversion of Ambient-noise Data and Teleseismic P Waves

Oral Presentation, Sunday, 30 October, 2:10 PM

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The Midcontinent Rift (MCR) is the fossil remanent of a massive meso-proterozoic rifting event that failed to split the North American continent during the Grenville orogeny. With a total span of ~3,000 km distance, it is filled with thick, dense and highly magnetized volcanic rocks and forms one of the most striking features on the gravity and magnetic anomaly maps of North America. It presents an excellent case study of how and where such rift forms and why it fails to develop into oceanic spreading centers as it evolves into the late stages of continental rifting.

To better understand the lithospheric processes related to the active rifting and its subsequent failure, we apply a novel full-waveform joint inversion method of ambient noise data and teleseismic P waves for this seismically inactive region, utilizing three years (2011-2013) of seismic recordings by the Superior Province Rifting Earthscope Experiment (SPREE) (with ~13 km average station spacing) and the USArray Transportable Array (~70 km average station spacing). Ambient-noise data are downloaded and processed using the NoisePy package (Jiang et al., 2020) following standard procedures of Bensen et al. (2007). Seven teleseismic events with high signal-to-noise ratio (SNR>5.0) and good coherence in both R and Z components across the SPREE arrays are manually selected and analyzed.

Through 8 iterations of joint inversions, we obtain new 3D high-resolution Vs, Vp and density models from the surface down to 200 km which not only show major velocity anomalies and discontinuities in agreement with previous seismic studies, but also reveal high density structures in the upper crust consistent with the Bouguer gravity data. We also observe strong low Vs anomalies around Moho depth along the MCR that indicate significant underplating associated with the rifting event. Checkerboard tests confirms the image resolution beneath the dense arrays. The further interpretation of these images may help us better understand the tectonic evolution of MCR.

Imaging the Alaskan Lithosphere Using Full-waveform Seismic Inversion

Poster 48, presented Sunday, 30 October

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Alaska is one of the most tectonically active regions in North America, with unique and complex geologic structures shaped by multiple episodes of tectonic processes in the geologic history. Mapping the shear velocity and anisotropy within the Alaskan lithosphere can provide important constraints on the subsurface structures and improve our understandings on the tectonic evolution of this region.

In this study, we use the high-quality broadband seismic data provided by the USArray deployment in Alaska to image the shear velocity as well as the radial and azimuthal anisotropy of the crust and uppermost mantle. We jointly use the ambient noise data and the local earthquake data for inversion. For ambient noise data, broadband continuous seismic data are collected and processed to extract the three-component empirical Green's functions (EGFs) between station pairs. Frequency-dependent travel-time shifts are measured between the EGFs and the simulated Green's functions. For local earthquake data, to mitigate the effect of uneven source distribution, we measure the difference of the frequency-dependent travel-time shifts between station pairs (double difference, Yuan et al. 2016). The measurements are inverted to obtain the model of shear velocity and anisotropy using the adjoint tomography method. The dynamic mini-batch technique (van Herwaarden et al. 2020) is used to accelerate the inversion process.

We present our shear-velocity and anisotropic model from the surface down to ~70km depth, revealing the subduction-zone structures in the southern region, several high-radial-anisotropy anomalies related to extensional deformation history and a fast-axis pattern consistent with the current tectonic movement. Tectonic implication of the model is discussed taking into account shear velocity, radial and azimuthal anisotropy, along with other geophysical observations.

Understanding Subsurface Fracture Evolution Dynamics Using Time-lapse Full Waveform Inversion of Continuous Active-source Seismic Monitoring Data

Poster 30, presented Sunday, 30 October

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An advanced cross-well survey system of continuous active source seismic monitoring (CASSM) was designed for autonomously acquiring datasets with temporal interval of minutes to monitor the hydrofracturing procedure at the F.E. Warren Air Force Base in Wyoming, US. Ray-based seismic tomography by fitting picked time-lapse travel-time differences has been applied to search for time-lapse velocity reductions of the fracture initiation and propagation. However, the tomographic methods suffer from the insensitivity to the low velocity zones and small velocity reductions (due to random picking errors) and low spatial resolution, limiting the understanding of studying seismic velocity response of the fracture evolution.

In this work, we apply double-difference time-lapse full waveform inversion (DD-TLFWI) with a correlative misfit to the CASSM data to capture velocity variations introduced by meter-size fracture evolution. For preprocessing, we apply time-lapse cross-equalization processing to reduce non-repeatable data noise and suppress the interference of waveform changes outside of facture zones. Finally we estimate 14 time-lapse P-wave velocity (Vp) models over 75-minute seismic monitoring. We then use rock physics modeling to interpret inverted time-lapse velocity changes. We find (1) a velocity reduction ~45 m/s due to increasing pore pressure to ~120 psi, which likely causes an increase of the porosity ~0.01 in the water saturated clay; (2) a velocity reduction ~180 m/s immediately after injection of fracking fluid (HRC) with ~0.05 porosity increase; (3) a further velocity reduction ~200 m/s after fracture emplacement caused by gas-bubble generation (~2% gas saturation) from HRC induced biogeochemical transformations and (4) that the induced zone of velocity reductions can delineate the fracture zone that shows the agreement with the fracture driller's estimation.

Towards Box Tomography of the Root of the Iceland Plume at the Base of the Earth's Mantle

Poster 72, presented Sunday, 30 October

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The introduction of accurate numerical simulations of the teleseismic wavefield has led to improved resolution in full waveform tomography, shedding light on the morphology of geodynamically important features such as mantle plumes and subducted slabs. However, reaching the high frequencies that are necessary to resolve finer scale structures is challenging because of the dependence of computational time on the 4th power of frequency. Moreover, the available distribution of sources and stations is highly uneven, so that only specific targets in the deep earth are sufficiently well illuminated by seismic waves to warrant their imaging at higher resolution.

The concept of "Box Tomography" provides a framework that holds promise for improved image resolution of target small-scale objects located in the deep mantle, such as ultra-low velocity zones (ULVZs). In this approach, a global solver is used to compute the teleseismic wavefield outside of a remote target region (or "box"). The recorded wavefields at the box boundaries are coupled with the computation of the wavefield inside the box, performed using a regional solver. At each iteration of the tomographic inversion, the wavefield and the model are updated only within the box, significantly increasing the efficiency of the imaging process. We have designed a flexible way to couple two distinct solvers with different mesh discretization, including solid-fluid across the core-mantle boundary and perfectly matched layer absorbing conditions in the regional solver. We present details of our approach and first steps towards its application to the imaging of the ULVZ at the root of the Iceland Plume. We begin by developing an improved reference global 3D model, starting from the radially anisotropic shear velocity model SEMUCB_WM1 (French and Romanowicz, 2014). To do so, we extend our global body waveform dataset to shorter periods (18s versus 32s) and relax the fixed scaling between P and S velocity across the mantle.

Seismic Imaging Reveals a Melt-rich Storage Zone Below Yellowstone Caldera

Poster 44, presented Sunday, 30 October

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Seismic tomography has provided key insight into Yellowstone's crustal magmatic system, but important questions remain, including the melt distribution in the subsurface and the current stage of Yellowstone's volcanic life cycle. Here, we present new tomographic images of the shear wave speed below the Yellowstone supervolcano based on full waveform inversion of ambient noise correlations, which reveal that Yellowstone's mid-to-upper crustal magmatic system may contain more melt than previously recognized. Our tomographic inversion approach utilizes vertical component noise correlation functions from 4,991 inter-station pairs and minimizes frequency dependent travel-time differences between data and 3D synthetic waveforms in 5 overlapping period bands between 5 – 30 s. The final model, which is achieved after 10 adjoint iterations, illuminates a strong Vs anomaly centered below Yellowstone caldera in the mid-to-upper crust, with Vs reductions of > 30%. The slowest seismic wave speed (V_S < 2.3 km/s) is present at depths between 4 – 8 km, overlapping with petrological estimates of the assembly depth of erupted rhyolite bodies. Assuming Yellowstone's magmatic system is a crystal mush with broadly distributed melt, we estimate a partial melt fraction of ~ 18%.

Bayesian Imaging of the Hawaiian ULVZ From Sdiff Postcursors

Poster 23, presented Saturday, 29 October

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The Hawaiian ultra low velocity zone (ULVZ) on the core-mantle boundary (CMB) has been the subject of significant debate over recent years. Attempts to uniquely constrain the shear velocity reduction, as well as ULVZ morphology, are met with difficulty owing to significant computation associated with full waveform modeling and lack of good source-receiver coverage, leading to studies assuming a simplified cylindrical anomaly.

Postcursors of S core-diffracted waves (Sdiff) are sensitive to strong anomalies in the S-wave velocity structure near the CMB, with resulting delayed arrival times of greater than 30 seconds observed for data sampling beneath Hawaii.

Using 2D multi-arrival wavefront tracking simulations (Hauser et al, 2008), we can model the full multi-pathing behavior of Sdiff postcursors, caused by ULVZs, and compute arrival times for a given input velocity structure. These are then compared to arrival time data, picked from full waveform synthetics or event data by deconvolving Instaseis synthetics (van Driel et al, 2015) of Sdiff arrivals with the waveforms. Capitalizing on short computation times on the order of seconds as opposed to hours required for full waveform calculations, we use a Bayesian inversion algorithm to generate a probabilistic tomographic model of the ULVZ using a level-set parameterisation.

We test our inversion set up by calculating reference arrival times using full waveform synthetics for the true event and station distribution possible for Hawaiian imaging for a number of known ULVZ velocity input models. This allows us to characterise the trade-offs between between size and shear velocity reduction and the resolvability of the ULVZ morphology. We then perform the Bayesian inversion on a real data set of Sdiff measurements sampling CMB structure beneath Hawaii.

Using this novel approach, we seek fundamental new constraints on the physical parameters, and their associated errors, of the Hawaiian ULVZ. Our results suggest that the Hawaiian ULVZ is smaller than previously imaged, elliptical in geometry and aligned with the LLSVP boundary.

Optimal Transport for Elastic Source Full Waveform Inversion

Poster 58, presented Sunday, 30 October

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Full waveform inversion (FWI) is a state-of-the-art method for imaging the earth's subsurface. However, FWI is notorious for local-minimum trapping, or "cycle skipping," and thus requires an accurate initial model. Cycle skipping is caused by the nonconvex nature of the misfit optimization landscape in its typical least-squares formulation. The Wasserstein-2 distance, denoted W_2, is convex with respect to shifts and dilations, both of which occur naturally in seismic data. Therefore, we propose using this optimal transport metric as our misfit for FWI. Previous work using optimal transport for source inversion, whose applications include microseismic event detection and deformation mechanics in subduction zones, has shown promise. However, this work uses the acoustic wave equation, which is less accurate than the elastic wave equation. We extend these results to elastic source inversion in two spatial dimensions and show that they translate well to the elastic model.

In this talk, we will show an explicit comparison of the optimization landscapes with respect to source location for the L^2 misfit and W_2 distance for the IASP-91 model. We assume that we have known Lamé parameters using the open-source global tomography model TX2019. We will then show inversion results using USArray data from the western United States for earthquake sources in the Pacific Ocean. We use the adjoint-state method with a renormalized W_2 misfit to efficiently implement FWI. We validate our optimal-transport method by comparing computational cost and inversion results for travel-time tomography, reverse-time migration and least-squares FWI. Finally, we compare our inversion results with an elastic forward model to those with an acoustic forward model to exhibit gained resolution from the elastic model.

Validating Tomographic Models of Alaska Using Seismic Wavefield Simulations

Poster 22, presented Sunday, 30 October

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The 2017 deployment of the EarthScope Transportable Array of seismic stations in Alaska and western Canada has led to new data coverage, new results and new interest in the subsurface structure of the crust and upper mantle. Seismologists have used body waves from regional and teleseismic earthquakes, surface waves from teleseismic earthquakes and ambient noise and arrival times from local earthquakes to produce a large number of tomographic models that characterize the elastic structure (Vp, Vs) of the region. Motivated by a future earthquake-based adjoint tomographic study of Alaska, we establish a benchmark data set of waveforms from 100–200 crustal and intraslab earthquakes that are selected to provide the best volumetric coverage of the crust and uppermost mantle. We use the software package SPECFEM3D to perform seismic wavefield simulations within a chosen set of 3D tomographic models available from the IRIS Earth Model Collaboration. For each tomographic model, we quantify the misfit between the three-component synthetic seismic waveforms and the corresponding recorded waveforms. Considering several different misfit metrics, we evaluate the performance of each tomographic model according to the regional earthquake data set. Our goal is to identify the best-performing initial 3D velocity model for proceeding with an adjoint tomographic inversion of Alaska using the Pyatoa software package.

Off-great-circle Propagation of Earthquake Surface Waves in the NW Himalaya and Adjacent Areas

Poster 45, presented Saturday, 29 October

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The steering of surface waves away from the great-circle path containing source and receiver is primarily caused by the heterogeneity of the medium through which they traverse. Off-great-circle propagation has been observed in various regions around the globe. It was previously assumed that using shallow, regional crustal earthquake sources would eliminate such issues in the Himalayas. We will show that regional events recorded by the Kashmir-Zanskar experiment in NW Himalaya deviate from the great-circle path by up to 20°. These observations from ~8 years of data recorded by the network led to a detailed ordination of regions' heterogeneities. We further developed a simple clustering algorithm to spatially stack source-receiver paths that are closer by ~2% of their respective path lengths. After visualization, we removed the outliers and computed error statistics for each of the 450 clusters. We observe that clusters from the Pamirs, Hindu-Kush and Tien-Shan have highest variance compared to those from Himalaya, Tibet, mid-ocean ridges traversing the Indian peninsula. As a result, clusters originating or recorded in such heterogeneous regions were assigned an error twice the standard deviation (i.e., $\pm 2\sigma$) rather than $\pm 1\sigma$ for the remaining paths. This resulted in the creation of a redundant database of fundamental-mode dispersion measurements for the region, with close-to-realistic error bounds obtained on over 7000 source-receiver paths. These individual paths are currently being used, in a Bayesian framework, to obtain a detailed 3-dimensional shear-wave velocity structure of the region. For example, the major highlights from 20 sec period dispersion map at resolution of 0.25x0.25 degrees are a) high velocity coincident with surface location of batholiths in Kohistan and Ladakh Himalaya and b) low velocity signature of adjacent sedimentary basins of Tarim, Katawaz and foreland Himalaya. Uncertainty estimation of the corresponding solution-model points towards $\pm 1\sigma$ of <0.3 km/s for the above mentioned regions.

Seismoelectric Effects for Subsurface Characterization

Oral Presentation, Sunday, 30 October, 11:25 AM

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Classical approaches for Earth subsurface imaging rely predominantly on seismic techniques, which alone do not directly capture fluid-specific properties. On the other hand, electromagnetic (EM) measurements add constraints on the fluid phase through, for example, electrical conductivity. However, EM signals alone do not offer direct information of solid properties. In the recent years, there have been efforts to combine seismic and EM data for exploration geophysics. The most popular approach relies on joint inversion of decoupled seismic and EM data. However, by analyzing fully coupled poroelastic seismic and EM wave equations, one can capture a pore scale behavior known as seismoelectric effects and more accurately resolve both solid and fluid properties.

We will present the equations used to model the seismoelectric response, which corresponds to electrokinetically couple Biot's poroelastic seismic and Maxwell's electromagnetic wave equations. To solve these equations, we use a spectral-element method (SEM). The SEM, in contrast to finite-element methods (FEM) uses high degree Lagrange polynomials. Not only does this allow the technique to handle complex geometries similarly to FEM, but it also retains exponential convergence and accuracy due to the use of high degree polynomials. Finally, we will discuss applications such as carbon storage sequestration and geothermal resources monitoring.

Finite-frequency Kernels for Pg/Lg Phases

Poster 51, presented Saturday, 29 October

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A major seismological challenge is to determine the short wavelength structure of the crust and uppermost mantle on a regional scale. The difficulty arises from trying to decipher the complex wave train known as Pg/Lg which consists of waves that reverberate in the crust. Pg/Lg is affected by the presence of large velocity gradients and discontinuities in the crust as well as layer interfaces and the free surface. Past tomographic studies of the crust and upper mantle have infrequently used Pg/Lg because of its observed variability, complexity and waveguide character. In this study, we improve our understanding of regional wave propagation by calculating travel-time sensitivity kernels within different crustal models at 2s dominant period using the adjoint method. Our results show that Pg/Lg sensitivity kernels have complicated structure even with simple models and show notable variability with respect to layer velocities, interface smoothness and frequency passband. The sensitivity kernels confirm that Pg/Lg is made up of reverberating wave-guided body waves. The complex sensitivity patterns are explained by post critical reflectivity and transmission coefficients at the surface and the MOHO and also converted phases near the source/receiver. Since P reflection coefficients are influenced by S velocity, Pg travel times do have sensitivity to S-wave velocity near the surface. This effect on the travel time could be significant if large S-wave velocities anomalies are present such as a sedimentary basin. We conclude that full-waveform approaches would be helpful to accurately model Pg/Lg phases along with joint inversion for P and S wave velocity. LA-UR-22-25200

The Collaborative Seismic Earth Model: Generation 2

Poster 74, presented Sunday, 30 October

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We present the second generation of the Collaborative Seismic Earth Model (CSEM), a multi-scale global tomographic Earth model that continuously evolves via successive regional and global-scale refinements. Given finite computational resources, a systematic community effort enables the Earth model construction within the CSEM-architecture. It thereby takes advantage of the distributed human and computing power within the seismological community. The update methodology utilizes the latest version of the CSEM as the initial model for regional tomographies. This setup allows to

consistently incorporate previously accumulated knowledge into each new iteration of the CSEM.

The current version of the CSEM includes 21 regional refinements from full seismic waveform inversion, ranging in size from several tens of kilometers to the entire globe. Some noticeable changes since the first generation include tomographies for the Central Andes, Iran, Western US, Southeast Asia, Africa, China and a global long-period model that improves resolution in areas that are not specifically included in any of the submodels. Across all regional refinements in the current CSEM, three-component waveform data from 1,800 events and over 750,000 unique source-receiver pairs are utilized to resolve subsurface structure. Minimum periods of models range between 8 and 55 seconds.

A global full-waveform inversion concludes the development of the second generation of the model, ensuring that regional updates do not conflict with whole-Earth structure. In this contribution, we will present the state of the model and results of the global inversion. Active participation in the project is encouraged and the model is available upon request.

Adjoint Tomography of the Middle East

Poster 66, presented Sunday, 30 October

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High-resolution seismic images of the lithosphere are essential for understanding tectonic and geodynamical processes and assessing seismic hazards in earthquake-prone regions. One such example embodying various plate boundary motions and intraplate deformations is the Middle East and its surrounding area, including Anatolia, Caucasus, Iran, etc. Imaging the subsurface beneath the Middle East is challenging because of the unevenly distributed source and stations and sparse data coverage, mainly in the Arabian Peninsula. In this study, our goal is to build a transversely isotropic adjoint tomography model of the region using all available waveform data we can have access: publicly available waveform data from IRIS and the regional Kandilli Observatory network in Anatolia combined with those from the Saudi Geological Survey, Iraq, Iran, etc. through our collaborations. Starting from the global adjoint tomography model GLAD-M25, we have so far performed 12 conjugate-gradient iterations combining multitaper travel-time measurements of 15-50 s body waves with 50-100 s surface waves from 210 regional earthquakes and 1400 stations using Texas Advanced Computing Center's Frontera system. Our preliminary results are consistent with the tectonics and geology of the region, highlighting volcanic and slab features, the boundary between the Arabian shield and the Arabian platform in the upper mantle, remnant of the subduction along the Zagros suture zone, etc. After the 12th iteration, we interpolated the crustal mesh using three spectral elements and started gradually decreasing the minimum surface-wave period in measurements. We also explore combining double-difference surface-wave measurements with those of multitaper body waves to achieve higher resolution in densely covered regions. We will present our model and FWI strategies with a future outlook.

Symplectic Geometry and Hamiltonian Monte Carlo Method

Poster 55, presented Saturday, 29 October

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"Symplectic geometry and Hamiltonian Monte Carlo (HMC) Method," which is the title of my master thesis, is an application of a non-Euclidean geometry to an inverse problem. HMC is a probabilistic sampling method with the basis of Hamiltonian dynamics. One of the main advantages of HMC algorithm is to draw independent samples from the state space with a higher acceptance rate than other MCMC methods. In order to understand how higher acceptance rate is achieved, I have studied HMC in the light of symplectic geometry. Hamiltonian dynamics is defined on the phase space (cotangent bundle), which has a natural symplectic structure, i.e. a differential two-form which is non-degenerate and closed.

First, Hamiltonian function is defined on the phase space, which corresponds to the total energy of the system, and then by using the non-degeneracy property, a vector field can be found in which Hamiltonian function is invariant along the integral curves of the field. The invariance of the Hamiltonian function results in high acceptance rate, where we apply accept-reject test to satisfy detailed-balance property.

In my presentation, first, I am going to describe the relation between symplectic geometry and HMC; then show an application of HMC to a 2D-tomography problem. As an application, we created a synthetic travel time data using a velocity model similar to Marmara Sea, Turkey. Then we inverted the travel time data for a velocity model by using HMC. We tried to obtain several different models which are compatible with the synthetic data.

Crustal Structure of the East European Craton and Surrounding Orogens From Ambient Noise Tomography: Key Aspects of Craton Erosion and Mantle Plume Impact

Poster 4, presented Sunday, 30 October

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The East European Craton comprises multiple Archean nuclei surrounded by Proterozoic terrains surviving multiple supercontinent cycles and mantle plume impacts. We investigate the crustal structure of the EEC and its transition to younger continental Europe across the Trans-European Suture Zone using seismic ambient noise analysis at permanent and temporary broadband seismic networks that operated in Northern and Eastern Europe from 1999 to 2020. We obtain empirical Green's functions between simultaneously recording pairs of stations, using a novel designaling method based on the Continuous Wavelet Transform. We then investigate the phase velocity dispersion of fundamental mode Rayleigh waves assuming that vertical cross-correlograms take the form of Bessel functions. We also extract the attenuation factors of surface waves from their coda decays. Phase velocities and quality factors are combined into a frequency-dependent anisotropic tomography, illuminating the EEC crustal structure and accreted terrains at an unprecedented resolution. We further use a Markov chain Monte Carlo method to invert isotropic phase velocities into depth variations of shear wave velocities. High velocity anomalies dominate the Precambrian Shields and an Ediacran-age large volcanic province. Several paleorifts thought to be associated with mantle plume impacts scar the crust of the EEC and show specific velocity and anisotorpy patterns. Collisional fronts that halted at the edge of the craton are marked by Moho steps and velocity changes, marking the long-lived and dynamic tectonic evolution of the European continent.

Radial Anisotropic Structure of the Upper Mantle

Oral Presentation, Saturday, 29 October, 11:05 AM

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We investigate the radial anisotropic ($\xi=[\beta_h(z)/\beta_v(z)]^2$) structure of the Earth's upper mantle. Our findings come from building a new ξ model from ~$0.4\text{x}10^6$ vertical and transverse waveforms propagating along common great-circle paths assuring uniform spatial sampling. Waveforms are jointly inverted for isotropic shear wave speed ($V_s^2=[2\beta_v(z)^2+\beta_h(z)^2/3)$ and ξ. CRUST1.0 is used for crustal corrections but we the test effect of crustal errors on ξ mantle structure. A model similar to anisotropic PREM is used as a starting mantle model. The path-average V_s and ξ measurements are tomographically inverted for a 3D V_s and ξ model. Azimuthal anisotropy effects are accounted for during the tomography. Beneath the ocean basins, the average ξ increases from ~1.03 below the Moho, peaks at ~1.06 at ~150 km depth, decreasing to ~1 at ~250 km depth. The thickness of the ξ>1 layer increases slightly with the increasing age of the oceanic lithosphere. At >200 km and deeper below the East Pacific Rise, and starting at somewhat greater depths beneath the slower spreading ridges, ξ<1. The V_s signature of mid-ocean ridges vanishes at about 150 km depth while the ξ signature extends significantly deeper. At ~200 km and greater depths below most of the backarc basins of the western Pacific, ξ<1. Beneath the continents, the average ξ decreases from ~1.07 below the Moho to ~1 at ~200 km depth. However, there is a distinct difference between the active and stable parts of the continents. ξ beneath the active portions of the continents decreases

from ~1.07 below the Moho to ~1 at ~200 km depth. However, ξ beneath the stable parts of the continents decreases from 1.06 below the Moho to ~0.98 at ~175 km depth before increasing to ~1.01 at ~275 km depth, then back to 1 at ~350 km depth.

From Travel-time to Adjoint Waveform Tomography in SE Asia

Oral Presentation, Sunday, 30 October, 1 PM

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Southeast Asia lies at the confluence of three major tectonic plates: the (Indo-) Australian, Eurasian and Philippine Sea plates. This actively convergent setting has given rise to extensive subduction, with slab descent rates of up to 5-10 cm/yr. The associated earthquake activity provides a potentially valuable resource for detailed seismic imaging of the lithosphere and underlying mantle. However, the sparse coverage of stations that produce open source waveform data has strongly influenced the outcome of such studies. Regional and global travel-time tomography has generally provided the most detailed images; this is because travel-time picks from restricted access stations are usually provided to the ISC by national agencies such as BMKG, thus increasing the data coverage by an order of magnitude.

Here, we carry out both regional travel-time tomography using ISC arrival times and adjoint waveform tomography, using data from both open and restricted access stations and compare the results. Extensive grooming of the ISC dataset is required to minimise the influence of picking and other errors, which results in a dataset of nearly 500,000 P-wave picks and 100,000 S-wave picks. This significant difference in the number of arrivals results in a more detailed P-wave model in comparison to the S-wave model, although the latter is still able to resolve the more extensive subducting slabs. For the adjoint waveform tomography, we exploit waveforms generated by 143 earthquakes recorded at 440 terrestrial stations in Southeast Asia within the period range 20-150s. This produces a detailed S-wave velocity model of the region, with resolution comparable to the P-wave travel-time tomography model. However, the P-wave model from adjoint waveform tomography is less detailed and does not facilitate direct comparison with the P-wave travel-time tomography model. These similarities and differences, and their underlying causes, will be further examined in this presentation.

An Overview of Full-waveform Inversion Workflows to Image the Deep Earth

Poster 52, presented Sunday, 30 October

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Seismic tomography implies the solution of an inverse problem that allows for imaging Earth's interior at different scales. The methodology entails comparing seismic data to initial model predictions, also known as synthetic data. The increasing computational resources, progressing knowledge in seismic wave propagation and numerical methods have made full-waveform inversion (FWI) a popular method in passive-source seismology, where 3D earthquake or ambient noise simulations are combined with 3D data sensitivity kernels to fit 3-component seismograms. FWI has well-defined workflows involving numerical wave simulations to compute synthetic seismograms and data sensitivities to model parameters, pre-processing and post-processing stages. However, different scales may need different treatment of data, parameterization of the inverse problem and model updates which potentially complicate workflows. Depending on the computational domain and the target resolution, the cost of simulations and the size of data assimilated in inversions may increase drastically. Hence, an ideal workflow requires integrating multiple software components that deal with different workflow stages from data processing to optimization of inversion while capturing the physics and complexity of the problem. In this study, we analyze the effect of different choices for waveform (e.g., multiple period bands, measurements, etc.) and kernel processing (e.g., pre-conditioning, smoothing, masking source and receivers, etc.) for different scale problems: 1) 2D axisymmetric global, 2) 3D continental scale (Middle East) and 3D global anisotropic and anelastic FWI. We will discuss our observations and future directions. Ultimately we will provide containerized multi-scale FWI workflows as readily available training tools as part of the NSF-funded Seismic Computational Platform for Empowering Discovery (SCOPED) project.

Large Low-velocity Provinces (LLVPs) in the Lowermost Mantle

Oral Presentation, Saturday, 29 October, 9 AM

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The two large low-velocity provinces (LLVPs) in the lowermost mantle have been known since Adam Dziewonski's "Mapping the lower mantle" article in 1984. LLVPs are the biggest 3D structures below the 660-km discontinuity. They take center stage in geodynamic modeling of the mantle and have been associated with early-earth differentiation, the steady accumulation of crustal fragments at the core-mantle boundary, and the formation of mantle plumes and hotspot volcanism.

In my talk I will describe the constraints on the dimensions of LLVPs in tomographic models and review forward-modeling studies of body waves that have illuminated the intricacies of LLVPs. I will highlight opportunities for new investigations of the correlation of Vp and Vs structure, the ratio of the magnitude of Vp and Vs anomalies, and the density structure in D" to further scrutinize the roles of temperature, compositional heterogeneity, and phase transitions on mantle convection.

Adjoint Waveform Tomography of the Western US for Improved Waveform Simulations and Source Characterization

Oral Presentation, Sunday, 30 October, 1:30 PM

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We report a new model of the three-dimensional seismic structure of the crust and upper mantle structure of the Western United States (WUS) obtained by adjoint waveform tomography. Model WUS256 resolves radially anisotropic shear and compressional wavespeeds and density and is based on inversion of over 94,000 waveforms from 72 earthquakes recorded by nearly 3,400 stations. We started with the SPiRaL global model (Simmons et al., 2021) and waveforms in the period band of 50-120 seconds. We followed a conservative multiscale inversion approach with 8 stages and 256 total inversion iterations which enabled monotonic misfit reduction to 20-second minimum-period waves. The WUS256 model reproduces major features seen in recent tomographic studies, but often with stronger and more concentrated shear wavespeed (VS) anomalies. It also shows significant improvement in the waveform fits over the starting and other models. In particular, the resulting model improves the fit to dispersed and scattered shorter period surface waves. We quantify the improvement in waveform fit by showing the relative reduction in both time-frequency phase (TF) and pointwise root-mean square (L2) misfits between the starting and inversion models. The WUS256 model reduces the mean TF and L2 misfits for both the inversion and an independent validation data set by a comparable amount (>64%). The improvement in waveform fit indicates that the model can be used to reproduce path effects on regional complete waveforms and moment tensor inversions. We are running updates of source models (depth and moment tensor) using 3D Greens functions. Further improvements of 3D structure are under way to resolve upper crustal structure (e.g. sedimentary basins) with shorter period data and denser path coverage.

Forty Years of Global Mantle Tomography: Achievements and Challenges Ahead

Oral Presentation, Friday, 28 October, 6 PM

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Forty years ago, the first global seismic images of the earth's mantle spectacularly demonstrated the power of seismic tomography, by confirming the presence of long wavelength structure associated with plate tectonics. They also revealed the presence of two large low shear velocity provinces at the base of the mantle, surrounded by a ring of fast velocities, that to this day are referred to as LLSVPs and the "graveyard of slabs", respectively. Soon, subducted slabs were mapped across the transition zone and beyond, confirming material transfer between upper and lower mantle. With the explosion of high quality, digital, three-component broadband data and the improvement in theory, progressively sharper images of mantle structure were obtained. The agreement between models obtained by different groups is now strong down to wavelengths of about 2000 km. Most of these models were obtained by first extracting secondary observables, such as, most commonly, travel times of the most prominent energy arrivals (seismic phases), that can be easily identified and isolated in the records. While full waveform tomography already showed its potential decades ago, in the last fifteen years, the introduction to global seismology of efficient numerical integration of the wave equation, and specifically the spectral element method, opened up new horizons, making it possible to more accurately exploit the scattered wavefield and sharpening up images of slabs, mantle plumes and LLSVPs, among others.

I will discuss how our understanding of mantle dynamics has evolved owing to progress in global mantle tomography and current efforts at further sharpening images. Many challenges remain, among them, how to speed up numerical wavefield computations so as to reach higher frequencies, how to overcome uneven sampling of the mantle, how to evaluate model uncertainty and dependence on the starting model or how to better constrain dynamically important lateral variations in seismic anisotropy.

Comparing Lithospheric Thickness From Sp Receiver Functions and Tomography in the Southwestern US

Poster 37, presented Saturday, 29 October

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The thickness of the lithosphere in the western United States has been found to be thinner than that of the stable continental interior of North America. Explanations for this thin lithosphere range from active tectonics to the presence of partial melt. Past studies of Sp receiver functions (RFs) and tomography models in the western U.S., which to first order agree, have led to significant improvements in our understanding of mantle structure and related dynamic and tectonic processes. However, significant uncertainty remains as the results from such studies have yet to be consistently integrated. In our analysis we calculated Sp RFs using data from over 1000 broadband stations from more than 50 temporary and permanent networks, ranging from 31°N to 43°N and 112°W to 126°W. The observed average depth of the lithosphere-asthenosphere boundary (LAB) phase across the region in our RF study is 65.3 km, with a total range from roughly 30 to 100 km.

Preliminary comparisons between the results from our Sp RF analysis and the absolute shear velocity tomography model of Shen and Ritzwoller (2016) reveal that in roughly 80% of our study area, there is agreement between the inferred LAB depth from RFs and the depth range of the corresponding negative velocity gradient from tomography. However, no correlation exists between RF LAB depth and other constraints from tomography, including depth of the maximum negative velocity gradient, maximum velocity or minimum velocity, for a given location. A potential weak correlation is seen between RF LAB amplitude and the absolute difference between minimum and maximum velocities from tomography, at a given location. This correlation itself appears to be driven by the minimum velocity. Ongoing analysis is being done to better determine how Sp RFs and tomography models can be used together to further our understanding of the lithosphere-asthenosphere boundary.

Imaging the Lithospheric Structure Beneath Portugal With Seismic Ambient Noise

Poster 6, presented Sunday, 30 October

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We used ambient seismic noise tomography to obtain a new high-resolution three-dimensional S-wave velocity model of the lithosphere beneath Portugal. The broadband seismic data for this study was recorded on a temporary deployment covering the entire Portuguese mainland in operation between 2010 and 2012, in the scope of the WILAS project. We process the vertical component data with phase correlation and time-frequency phase weighted stack to obtain Empirical Green functions for 3900 station pairs. We use a random sampling and subset stacking strategy to compute robust Rayleigh wave group velocities in the period range of 7-30 s and the associated uncertainties. The tomographic inversion is performed in 2 steps: First, we determine group velocity lateral variations for each period using a regionalization method based on a continuous formulation of the inverse problem that uses smooth local basis functions. Next, we invert them at each grid point using a new trans-dimensional inversion scheme to obtain the 3D shear-wave velocity model. The final 3D model extends from the upper crust (5 km) down to the uppermost mantle (60 km) and has a lateral resolution of approximately 50 km. Our 3D model correlates well with surface geology, particularly at upper and middle crust levels. The transition between the Lusitanian Basin and the Ossa Morena Zone is marked by a contrast between moderate and high-velocity anomalies. Two significant faults, the Manteigas-Vilariça-Bragança fault and the Porto-Tomar-Ferreira-do-Alentejo fault have a clear signature from the upper crust down to the uppermost mantle (60 km). In contrast, others seem to be limited to the upper crust. We provide the missing link between previous crustal- and mantle-scale studies, presenting Portugal's new upper lithospheric-scale high-resolution 3D seismic model.

This work was funded by Fundação para a Ciência e a Tecnologia (FCT) I.P./MCTES through national funds (PIDDAC) – UIDB/50019/2020 and supported by projects SIGHT (PTDC/CTA-GEF/30264/2017) and RESTLESS (PTDC/CTA-GEF/6674/2020).

The Spiral Global Travel-time-based Model to Serve as a Starting Model for Global Adjoint Tomography

Poster 73, presented Saturday, 29 October

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The SPiRaL tomography model is based upon millions of body wave travel times and surface wave dispersion estimates for the entire globe. The SPiRaL model properties include P- and S-wave velocities, 3D radial anisotropy variations, modeled variations in the crust and multiple resolutions with a minimum node spacing reaching ~25 km. The immediate purpose for the development of SPiRaL is accurate regional and teleseismic travel time prediction for event location estimation. An additional purpose for developing SPiRaL was to provide a valuable starting model for global full-waveform inversion. Recently, it has been shown that SPiRaL is on par with several independently developed full waveform-based models at predicting waveforms for a limited set of events in multiple regions (Simmons et al. 2021) as well as a much larger set of events in the western United States (Rodgers et al. 2022). The waveform fit analysis is currently being expanded to a global set of events and comparison between SPiRaL and other global models. This analysis will provide a benchmark for SPiRaL on the global scale in terms of waveform fit metrics and a more complete picture regarding the value of SPiRaL as a global full-waveform inversion model and the target starting minimum wave period to consider for the initial model updates. In parallel, we are building upon open-source software including SPECFEM_GLOBE (Komatitsch and Vilotte, 1998; Komatitsch and Tromp, 1999) and SeisFlows (Modrak et al., 2018) in an attempt to automate (or at least streamline) global

adjoint tomography on LLNL supercomputing platforms using SPiRaL as a starting model. This streamlining will allow us to take advantage of our computational resources to develop our initial global waveform-based model and provide a way to efficiently perform the necessary nonlinear optimization iterations.

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Shear Velocity Structure of Northeastern India From Ambient Seismic Noise Tomography

Poster 2, presented Sunday, 30 October

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The northeastern Indian region is tectonically complex that developed mainly due to north-south continental collision along Himalaya and east-west subduction within the Indo-Burma ranges. We carry out seismological investigation of this region for the geodynamic and tectonic concepts as well as to support and append the complementary results to previous studies. Our study region encloses (22.50° N, 86.61° E) to (28.10°N, 96.40°E) where continuous data from twenty three broadband stations, deployed by the National Centre for Seismology (New Delhi) and our research group, are utilized for the years between 2016 and 2020 (1827 days). The work comprises calculation of Green's function using cross-correlation of ambient noise for 253 receiver pairs. We have used data with sampling rate of 40 samples per second and traces having spectral frequency band of 0.01 Hz to 20.00 Hz. These are used to extract the dispersion data, using multiple filter analysis, for the periods between 5s and 55s. The inversion of cleaned dispersion data reveals the tomographic images of the region in depth that support the controversial idea of pop up mechanism of the Shillong plateau and its origin. Our results identify three tectonic domains: Shillong plateau, Brahmaputra valley and Indo-Burma convergence zone characterized by distinct shear wave velocities. We observe a high shear wave velocity anomaly, possibly associated with a N-NE to S-SW trending slab comprising Indian lithosphere in the Indo-Burma Convergence Zone.

Seismic Evidence of Slab Segmentation and Melt Focusing Atop the 410-Km Discontinuity in NE Asia

Poster 21, presented Saturday, 29 October

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The geometry of subducting slabs is controlled by mantle rheology and time evolving processes of surface plate boundaries. Imaging of a detailed slab distribution can provide information to understand physical and chemical properties of the upper mantle. Based on new high-resolution 3D tomography of stagnant Pacific slab in northeast Asia, we revealed a prominent gap within the stagnant Pacific slab showing an abrupt change in its lateral trends that follow the trace of plate junctions associated with plate reorganization at the western Pacific margin during the Cenozoic. Focused partial melt above the slab gap was inferred based on the spatial coincidence between the high Vp/Vs anomaly and the negative reflectivities above the 410-km discontinuity by local receiver function studies. The slab gap is possibly filled with low-velocity anomalies within the MTZ as evidenced by wavefield focusing of teleseismic body waves and absolute velocity imaging from previous studies. We explain the spatial coincidence between the low-velocity anomaly within the MTZ and the focused melt layer above the MTZ by the process of mantle dynamics related with secular variation of slab geometries by tearing. Isolated low-velocity anomalies within the MTZ imaged by seismic tomography without previous thermal disturbances (e.g., hot plume) are suggested to be the products of distinct MTZ compositions disturbed by former nearby slab subductions. Our results suggest a close dynamical relationship between the subducting slab and the MTZ, which promotes the formation of multi-scale chemically distinct domains in the deeper upper mantle.

Central Italy High-resolution Model for Accurate Ground Motion Simulation

Poster 24, presented Sunday, 30 October

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A challenge in earthquake seismology is the provision of realistic and accurate ground-shaking scenarios for seismic hazard and risk assessment. Owing to the exponential growth of HPC resources, the application of physics-based methods to ground motion characterization has become increasingly popular. However, physics-based techniques could break down in the simulation of high-frequency ground motion, particularly at frequencies higher than 1 Hz, which are the most relevant for earthquake engineers. A main issue is represented by the limited resolution of seismic wave speed models. Currently, one of the best approaches to retrieve high-resolution wave speed models relies on the combination of the Spectral Element Method (SEM) with adjoint-state methods within the framework of (3D) Full Waveform Inversion (FWI).

Here we use the Salvus software to resolve the velocity structure of central Italy, which is exposed to high seismic hazard. We invert a dataset including 248 events (occurred between 2005 and 2019, with a magnitude ranging between 2.8 and 5.5) recorded by the Italian seismic network and provided by INGV. We implement a multi-scale approach to 3D-FWI by progressively incorporating the high-frequency content of waveform recording. In the first cycle of iterations, we retrieve the long-wavelength structure of the model. At this stage, we also perform several tests, e.g. different source/receiver cutouts, to properly tune the FWI configuration parameters to our problem. Then we use the best fitting model as the initial model of a second cycle of iterations, combining it with Vs30 and topographic data. By accounting for site effects, we maximize the level of detail in the starting model, thus preventing the FWI algorithm from being trapped in local minima. The retrieved high-resolution wave speed model will shed light on the velocity structure of central Italy, thus improving the seismic hazard assessment of this region.

Global 3D Model of Mantle Attenuation Using Seismic Normal Modes

Poster 15, presented Saturday, 29 October

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Seismic tomographic mantle models of wave velocities have a limited ability to distinguish between a thermal or compositional origin for 3D structure variations. Complementing 3D velocity variations with 3D variations in seismic attenuation (loss of energy due to conversion into heat) can help us to make that distinction, contributing to understanding mantle convection evolution and the origin of lower mantle large low-seismic-velocity provinces (LLSVPs). Efforts in imaging 3D attenuation have mainly focused on the upper mantle. Here, we present a global 3D attenuation mantle model using whole Earth oscillations, or normal modes, together with surface waves. We compare two methods of inversion: i) a two-step inversion using normal modes and surface waves and ii) a one-step direct spectrum inversion, using normal modes.

Using both inversion methods, we find high attenuation in the low velocity spreading ridges, suggesting the upper mantle is dominated by a thermal origin and agreeing with previous studies. In the lower mantle, we find low attenuation in the center of the slow LLSVPs and the highest attenuation in the fast 'slab graveyard' surrounding the LLSVPs. To explain these results, we compare our 3D attenuation model to wave speeds and attenuation predicted by a laboratory-based viscoelastic model. This analysis indicates that high attenuation in the slab regions can be explained by a small grain size in combination with cold temperatures, while low attenuation in LLSVPs can be explained by a large grain size combined with high temperatures. Since grain size is related to viscosity in diffusion creep, LLSVPs may have high viscosity, making them long-lived stable features.

Seismic Imaging of Sedimentary Basins with Complex Seismic Wave Propagation

Oral Presentation, Sunday, 30 October, 9 AM

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Sedimentary basins are geologically, tectonically, seismically and societally relevant features of Earth. Large sedimentary basins (e.g., Los Angeles, Tokyo, Seattle, Cook Inlet) are characterized by having several km of sedimentary strata, including unconsolidated (low Vs) sediments at the surface and sedimentary rock layers at the greatest depths. They are often underlain by and are adjacent to bedrock (high Vs). This material contrast leads to profound influences on seismic wave propagation, with seismic waves slowing down and reflecting at the basin boundaries, leading to increased amplitudes and shaking duration. These basin waves carry a history of both transmission and repeated reflection, making them challenging to model and use within tomographic inversions. In principle, recorded seismic waves from inside and outside sedimentary basins contain sensitivity to detailed basin structures, namely, their subsurface topography and their internal velocity heterogeneity. Here we explore both realistic and idealized 3D models of a sedimentary basin in central Alaska (Nenana basin), and we perform 3D seismic wavefield simulations to examine how these models influence local and teleseismic waves. We have two primary goals: 1) to explore basin wave propagation effects in numerical simulations and from recorded wavefields and 2) to prepare for an adjoint tomographic inversion for velocity structure inside and outside the basin, using the relatively sparse data coverage of central Alaska.

A Neural Network Travel Time Function for Direct Travel Time Tomography

Poster 63, presented Saturday, 29 October

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Travel time inversion and modeling play an important role across geophysics (from exploration to global seismology). Moreover, emerging acquisition technologies like distributed acoustic sensing (DAS) promise a new era of seismological discovery by allowing a high-density of seismic observations. Conventional travel time computation algorithms could not handle millions of receivers made available by DAS arrays. Using the eikonal equation, physics-informed neural network (PINN) have shown promising advantages when applied to these applications. Some of these include, a mesh-free computation, fast and more accurate travel time calculation without the need of storing travel time lookup tables and has a capability as a storing mechanism for a 3D global velocity model (e.g., GLAD-M25 model). With all of these nice properties, however, incorporating boundary conditions, like our recorded travel times, has proven to be a significant challenge to PINN training as a result of the dual-term (partial differential equation and data) loss function.

Here, we propose a new formulation for the eikonal equation that reduces the loss function used to train the neural network to one term. A change of variables allows us to include the data in the partial differential equation loss as a hard constraint. We theoretically and empirically demonstrate that our new formulation for the eikonal equation makes the training more robust and accurate compared to the soft constraint (factored eikonal) approach. Our approach demonstrates capability to handle sparse data and ill-posed problems via cross-well and surface travel time tomography applications. The robustness of the method comes from the fact that we can simultaneously invert for both of the travel time and velocity during the PINN training. More interestingly, by incorporating a data neural network, we can implement the inversion using sparse recording; a feature welcomed in applications related to near surface and global tomography.

Fast and Automated Global-scale Waveform Inversion

Oral Presentation, Saturday, 29 October, 9:50 AM

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Seismic waveform inversion are becoming more feasible with growing computational resources. This, combined with the increasing quantity and quality of available seismic waveform data, provides an opportunity to vastly improve the current state-of-the-art Earth models.

We present a global-scale study where we created a 3D mantle model of the Earth using data from 2100 earthquakes. We started from an isotropic one-dimensional model and made 300 model updates by inverting millions of waveforms, including both body- and surface-waves, down to a period of 33 s. The process was fully automated using Inversionson and Salvus. Inversionson is an FWI workflow manager which fully automates the process and is designed for using Salvus as the wave propagation solver. The workflow is optimized for both (1) computational time and (2) human time. (1) By using wavefield-adapted meshes which effectively transform 3D wave propagation to a quasi 2D problem, exploiting the lateral smoothness of seismic wavefields and by using stochastic optimization schemes which allow for rapid (reasonable) model updates while exploring the dataset. (2) By limiting data-transfer between HPC and local machines, moving all processes to the HPC side, allowing for easy parallelism over seismic events.

We demonstrate how our methodology can make waveform inversion workflows much more efficient without sacrificing quality of results. We will also show the model we created in the process.

Modernized Adjoint Tomography Workflow Applied to the South California Earthquake Center Community Velocity Models

Poster 54, presented Sunday, 30 October

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The South California Earthquake Center (SCEC) Community Velocity Models (CVMs) are an essential product of SCEC. They represent an aggregation of geophysical and geological data sets, packaged in the form of three-dimensional models in terms of Vp, Vs and density. The CVMs are actively used in research for numerical wavefield propagation simulations at regional and local scales, including for seismic hazard assessment, such as within CyberShake. The most recent updates to the CVMs occurred in 2014 (CVM-S4.26) and 2015 (CVM-H15.1), both of which incorporated multi-year efforts of performing wavefield-simulation-based adjoint tomography to improve portions of the previous CVMs. Here we demonstrate it is possible to leverage recent developments in open-source software to update the SCEC CVMs. We rely on a self-contained, interconnected suite of python utilities (Pyatoa, SeisFlows, Specfem3D) which streamlines the whole adjoint tomography process and, in turn, should enable easier assimilation of recent earthquake data into community-driven models. To mitigate the computational cost associated with the tomographic process, we also estimate the minimum resolvable period at each station to determine the optimal range of frequencies to consider. Finally, all events used in our inversion are obtained with the mtuq moment tensor inversion code based on full waveform misfit to ensure that we use the best sources possible. We demonstrate the workflow with a test set of 20 earthquakes.

Source Encoding and Uncertainty Quantification for Global Waveform Inversion

Oral Presentation, Saturday, 29 October, 5 PM

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In this talk, we discuss two current challenges in global waveform inversion, namely, 'source encoding' and 'uncertainty quantification'.

First, we present a crosstalk-free 'source encoding' technique to facilitate the calculation of the gradient of a misfit function independent of the number of sources or receivers. The method requires only two numerical simulations per iteration: one source-encoded forward simulation and one source-encoded adjoint simulation. Importantly, for practical applications, each source does not need to be recorded by all receivers. The encoded forward and adjoint wavefields do not need to be decoded, nor is there a need to calculate or store intermediary stationary contributions to the gradient. We present the preliminary results of regional source-encoded waveform inversion across North America and Eurasia.

Second, we discuss proper uncertainty quantification (UQ) in waveform inversion. In theory, UQ is related to the inverse Hessian (or the posterior covariance matrix). Even for common geophysical inverse problems, its calculation is beyond the computational and storage capacities of the largest high-performance computing systems. We amend the Broyden–Fletcher–Goldfarb–Shanno (BFGS) algorithm to perform UQ for large-scale applications. To facilitate retrieval of the inverse Hessian, we combine BFGS with randomized singular value decomposition to determine a low-rank approximation of the inverse Hessian. Setting the rank number equal to the number of iterations makes this solution efficient and memory-affordable, even for large-scale problems. Furthermore, based on the Gauss-Newton method, we formulate different initial, diagonal Hessian matrices as pre-conditioners for the inverse scheme and compare their performances in elastic FWI applications. We present preliminary results of UQ in global adjoint tomography.

Towards the Geologic Parameterization of Seismic Tomography

Oral Presentation, Sunday, 30 October, 9:30 AM

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Seismic tomography is a cornerstone of geophysics and has led to a number of very important discoveries about the interior of the Earth. However, seismic tomography remains plagued by the large number of unknown parameters in most tomographic applications. This leads to the inverse problem being underdetermined and requiring significant non-geologically motivated smoothing in order to achieve unique answers. While this is acceptable when using tomography as an explorative tool in discovery mode, it presents a significant problem to use of tomography in distinguishing between acceptable models since typically none of the models considered are fit by the tomographic results, even when uncertainties are accounted for. To address this challenge, when seismic tomography is to be used for model selection purposes, we advocate that the tomography be explicitly parameterized in terms of the geologic models being tested instead of using more mathematically convenient formulations like voxels, splines or spherical harmonics. Our proposition has a number of technical difficulties associated with it, with some of the most important ones being the move from a linear to a nonlinear inverse problem, the need to choose a geologic parameterization that fits each specific problem and is commensurate with the expected data quality and structure and the need to use a supporting framework to identify which model is preferred by the data. In this contribution, we present simple toy examples of our proposed geologic tomographic parameterizations, explain the challenges in moving towards more realistic examples and discuss the technical difficulties and how they may be overcome. While it may take many years for the scientific program suggested here to reach maturity, we believe it is necessary to take steps in this direction if seismic tomography is to develop from a tool for discovering plausible structures to one in which distinct scientific inferences can be made regarding the presence or absence of structures.

Imaging the Crustal Velocity Structure Beneath Sikkim Himalaya Using Ambient Noise Tomography

Poster 8, presented Sunday, 30 October

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With an aim to understand the seismic structure, lithospheric deformation and seismicity in the Indian plate beneath Sikkim Himalayas; a dense network of 27 broadband seismic stations, deployed across the Higher Himalayas, Lesser Himalayas and the Himalayan foreland basin, has been monitoring the seismic activity in and around Sikkim since April 2019. Using the data recorded between April 2019 and December 2021, we have used the computationally efficient MSNoise software to obtain the cross-correlation functions (CCFs) between sensor pairs. The dispersion curves obtained from the stacked CCFs by using the Frequency Time Analysis (FTAN), were further processed using the Ambient Noise Surface Wave Tomography (ANSWT) algorithm to generate the 2D Rayleigh and Love wave group velocity tomography maps at various periods (3.5 s, 5 s, 10 s, 20 s and 30 s). From the group velocity maps obtained, we observe that the Himalayan foreland basin is characterized by lower group velocities due to the sedimentary cover. In the Lesser Himalayas we observe a transition from lower to higher velocities as the subsurface rock-type changes from clastic sediments to meta-sedimentary rocks. The relatively higher velocities observed in the Higher Himalayas can be attributed to the high grade crystalline rocks. The group velocity maps reveal a significant reduction of velocity at higher periods (20 s) and then a jump back to higher velocity at 30 s, implying the presence of a low velocity layer at that depth. The complexity in the crustal architecture in this segment of the Himalayan collision zone is thus exhibited by the drastic variations in group velocity, both vertically and laterally.

On the Sensitivity of Local-scale Full-waveform Ambient Noise Inversion to Global Noise Sources

Poster 60, presented Sunday, 30 October

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Full-waveform ambient noise inversion uses interstation cross-correlations of seismic ambient noise to image noise sources and Earth structure. Usually, this method exploits the noise generated by the oceans, resulting in regional to global spatial sensitivity. Consequently, local-scale studies must consider this large sensitivity or the resulting models might be biased. In this work, we conduct synthetic experiments to show the consequences of ignoring global noise sources on local-scale noise source inversions.

Our experiments involve 33 stations of a local seismic array located on the west coast of Mexico, near the Pacific ocean. We efficiently model "observed" noise cross-correlations on the secondary microseism period band (5 to 10 s) using a database of three-hour-long Green's functions stored at the Earth's surface and a noise source model obtained from significant wave height maps. To show the consequences of ignoring global noise sources, we carry two noise source inversions, one with a global and the other with a local computational domain. In both cases, we assume the Earth's structure is known. Due to the limited sensitivity of the seismic array, the global-domain inversion only recovers the noise distribution near the stations. Meanwhile, the local-domain inversion provides a similar result but with overestimated noise power, as it compensates for the energy generated by the omitted noise sources. These results indicate that the computational domain of local-scale studies must be carefully defined to include global noise sources and avoid biases.

Full-waveform Tomography of the African Continent

Poster 42, presented Sunday, 30 October

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We present a full-waveform inversion of the African plate. Starting from the first generation of the Collaborative Seismic Earth Model, we invert seismograms that are filtered to a minimum period of 35 s and compute gradients using the adjoint state method.

In contrast to conventional waveform inversions, our approach uses dynamically changing mini-batches that approximate the gradient of the larger dataset at each iteration. This has three major advantages, (1) It results in a reduced computational cost for model updates and the inversion, (2) It enables using larger datasets, without increasing iteration costs and (3) it becomes trivial to assimilate new data, as the new data can simply be added to the complete dataset from which mini-batches are sampled.

We perform 130 mini-batch iterations and invert waveforms from 397 unique earthquakes at a cost of approximately 10 iterations with all data. We clearly image tectonic features such as the Afar triple junction as well as slow zones below areas with dynamic topography, such as the Tibesti and Hoggar mountain ranges, that have been difficult to distinguish in earlier works.

Finally, we introduce a new strategy to assess model uncertainty. The final model is deliberately perturbed and additional mini-batch iterations are performed to test if the model returns to its prior converged state. This test uses real data instead of artificially generated synthetic data without requiring assumptions about the linearity of the inverse problem.

New Global Models of 3D Mantle Density From Recent Normal Mode Measurements

Poster 25, presented Saturday, 29 October

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Constraints on the 3D density structure of Earth's mantle provide important insights into the nature of seismically observed features, such as the Large Low Shear Velocity Provinces (LLSVPs) in the lower mantle under Africa and the Pacific. The only seismic data directly sensitive to density variations at all depths inside the mantle are long-period normal modes: whole Earth oscillations that are observed after large earthquakes (Mw ≥ 7.5). However, their sensitivity to density is weak compared to the sensitivity to velocity and previous studies have presented conflicting density models of the lower mantle, showing either entirely light (Koelemeijer et al. 2017) or entirely dense (e.g. Ishii & Tromp 1999, Trampert et al. 2004) LLSVPs with respect to the reference model. Recently, Lau et al. (2017) have used tidal tomography to show that Earth's body tides prefer entirely dense LLSVPs.

A large number of new normal-mode splitting function measurements has become available since the last density models of the entire mantle were published. Here, we present our new models of 3D mantle velocity, density and discontinuity topography, obtained from the inversion of these recent normal-mode measurements using a Hamiltonian Monte Carlo algorithm, which also provides us with model uncertainties. We find a large high-density region in the bottom-300 km of both LLSVPs, while the remaining LLSVP material has a lower-than-average density. These findings are confirmed by the density model obtained from the direct inversion of normal-mode spectra. Our model's partially dense LLSVPs imply that they are at least partially compositionally distinct, as temperature variations alone cannot decorrelate seismic velocity and density. Furthermore, we compare our density model to the density structure obtained from a range of models of thermochemical convection and assess whether our density model can distinguish between different thermochemical scenarios.

New Imaging Strategies for Constraining Arbitrarily Oriented Upper Mantle Anisotropic Fabrics With Teleseismic P- and S-wave Delay Times

Poster 1, presented Saturday, 29 October

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Teleseismic travel-time tomography remains one of the most popular methods for obtaining images of Earth's upper mantle. However, despite extensive evidence for a seismically anisotropic mantle, assuming an isotropic Earth remains commonplace in such imaging studies. This assumption can result in significant imaging artifacts which in turn may yield misguided inferences regarding mantle dynamics. Using realistic synthetic seismic datasets produced from waveform simulations through elastically anisotropic geodynamic models of subduction, we show how such artifacts manifest in teleseismic P- and S-wave tomography models. The anisotropy-induced apparent anomalies are equally problematic in both shear and compressional body wave inversions and the nature of the shear velocity artifacts are dependent on the coordinate system in which the delay times are measured. In general, the isotropic assumption produces distortions in slab geometry and the appearance of large sub- and supra-slab low-velocity zones. We summarize new methods for inverting P- and S-delay times (independently and jointly) for both isotropic and anisotropic heterogeneity through the introduction of three anisotropic parameters that approximate P and S propagation velocities in arbitrarily orientated hexagonally symmetric elastic media. Through a series of synthetic tomographic inversions, we demonstrate that teleseismic P- and S-wave delay time data can resolve complex anisotropic heterogeneity expected in environments such as subduction systems. Moreover, including anisotropic parameters into the inversions improves the reconstruction of true isotropic anomalies. Particularly important to the removal of erroneous velocity structure is accounting for dipping fabrics as many imaging artifacts remain when simpler azimuthal anisotropy is assumed.

Full-3D Inversion of Slowness Vectors Measured Across Seismic Arrays

Oral Presentation, Saturday, 29 October, 1:30 PM

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Full three-dimensional tomography (F3DT) is a computationally demanding technique to image Earth structure by iteratively assimilating waveform constraints into 3D seismic velocity models. We seek to improve F3DT estimates of near-surface crustal structure by measuring frequency-dependent slowness perturbations across regional seismic networks and inverting these differential slowness data for subarray structure. The specific problem we address is how to calculate the Fréchet kernels that relate 3D velocity perturbations to 2D slowness perturbations using the full Rytov theory; i.e., without the local 1D approximation often assumed in Helmholtz tomography. Such vector-valued kernels can be written as linear combinations of scalar-valued spatial kernels for single-station phase-delay measurements. We test our methodology on waveforms from regional earthquakes recorded by the Southern California Seismic Network (SCSN). We calculate synthetic waveforms for the CVM-S4.26 F3DT model (Lee et al., 2014) up to 0.25 Hz using the Hercules Toolchain of Tu et al. (2006), focusing on station arrays in the Los Angeles region. We measure single-station phase-delays using a GSDF procedure adapted to the array geometry, and we linearly combine their Fréchet kernels to obtain kernels for the centroid phase delay and the two components of the slowness vector. We show that, for arrays of 25 stations (separation of ~2 km) recording earthquakes at epicentral distances of 200 km, the low-frequency slowness kernels are fairly localized in the vicinity of the array, and that the sensitivity of the slowness perturbations to near-source and along-path structure, as well as source location, is substantially reduced relative to the centroid phase-delay kernel. Kernels for both the radial and transverse components show a dipole-like structure, in which, the values go from negative to positive, reflecting their sensitivity to the first moment of the phase-delay field.

Exploring the Outermost Outer Core With Full-waveform Modeling

Poster 68, presented Sunday, 30 October

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One of the most challenging problems in geophysics is imaging Earth's deep interior. In this work, we aim to address the challenges in imaging the outermost outer core using SKS & SmKS phases with ray-based methods and explore the extension to the full-waveform inversion (FWI).

We first analyze the effect of the 3D crust and mantle on core phases and assess the accuracy of mantle corrections commonly applied to them in ray-based studies. We computed synthetic waveforms for ~50 global CMT earthquakes using the 3D wave propagation solver SPECFEM3D_GLOBE for various models: 1) isotropic PREM, 2) 3D mantle model S40RTS with 3D crustal model Crust2.0, 3) S40RTS with PREM crust, 4) global adjoint models GLAD-M15 & GLAD-M25 where the crust and mantle were inverted simultaneously. We measure the absolute and differential timeshifts between synthetics computed for different Earth models to discriminate the effect of 3D crust and mantle on core phases. We then assess the accuracy of the mantle corrections by comparing the measured time shifts between spectral-element synthetics from 3D models and PREM to those predicted by ray tracing. We observe that finite-frequency effects, 3D mantle and crust, the accuracy of mantle corrections and potential mantle anisotropy may affect travel-time measurements. The isolation of SKS & SmKS phases is not easy due to the interference of multiple phases, which becomes more severe for shallow earthquakes. 1D crust simplifies waveforms; however, timeshifts can still be as large as those from measurements with 3D crust. Full-waveform modeling is the way forward; however, FWI may not be straightforward because of the potential trade-off between the D" region and the outer core, in addition to the complexities coming from the 3D mantle and crust. In the second part of the study, we analyze how FWI works in a 2D setup. We will present our current observations to set up a framework to image the Earth's outer core with 3D full-waveform modeling.

Tomography for Plate Tectonics and Geodynamics: Advances, Open Questions, Future Opportunities

Poster 31, presented Saturday, 29 October

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The plate tectonic revolution of 50 years ago showed that the past state of Earth's surface can be reliably reconstructed from seafloor magnetic anomalies and other constraints. However, at convergent margins the seafloor constraints are subducted and recycled into the mantle. As a result, the most significant uncertainties in current global plate models are along convergent margins, especially within the Pacific-Panthalassan and Tethyan-Himalayan oceanic realms. These uncertainties encompass >50% of the Earth surface by the Early Cretaceous ~115 Ma.

Imaging of the Earth's mantle through seismic tomography has provided a trove of new information for constraining plate tectonics and geodynamics in 4D. The locations, depths and geometries of possible slabs allow competing plate reconstructions to be tested. Structurally-restored slabs from tomography can be used to directly fill plate reconstruction gaps. The tomography may also image plumes, illuminate flow paths and inform us of the thermal and/or chemical properties of the mantle. Here we highlight recent developments in the use of seismic tomography by the plate tectonics and geodynamics community that include: analysis of subducted features within slabs, reconstructing past intra-oceanic subduction zones, global slab catalogs, tomographic vote maps, and use of P-wave resolution filters for geodynamic models. We show the first views of TOMOPAC-22, a tomography-prioritized, circum-Pacific plate reconstruction that we test by assimilation into forward mantle convection models. Finally, I invite discussion of open questions, potential pitfalls for tomographic over-interpretation and future opportunities for collaboration between seismologists, tectonicists and geodynamicists.

Identification of the Meso-Kaynoy Complexes of the Earth's Crust of Azerbaijan by Seismic Tomography

Poster 71, presented Saturday, 29 October

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These studies were carried out within the framework of the international project "Caucasus Section" and are devoted to the redefinition of data on the hypocenters of earthquakes that occurred on the territory of Azerbaijan for the period 2010-2021 yy. (ml>2.0) and calculation of the velocity model of the earth's crust using algorithms that are not included in the mandatory processing when compiling a catalog of seismic events. It should be noted that within the framework of this project, in the territory of the Greater Caucasus (in addition to the main 35 digital stations that operate in real time), 17 additional digital seismic stations were installed. The algorithms used were developed and provided by Missouri Institute Professor (Columbia, USA) Eric Sandvol. In the last decade there have been refinements in model parameterization, 3D ray tracing, inversion algorithm, sharing of local, regional and teleseismic data and addition of transformed and reflected waves to tomographic inversion. Studies have shown that with the help of seismic tomography, reliable data were obtained on the deep structure of the Earth, its thickness, the relative position of the layers, as well as on the tectonic structures identified in the earth's crust. Thanks to a significant increase in the number of seismic stations, it was possible to obtain a large amount of observed seismic material and solve rather complex methodological issues. The calculation results presented in the form of horizontal sections of the spatial model at different depths and in the form of deep sections clearly demonstrate the features of the obtained velocity structures. The features of the occurrence of the Meso-Cenozoic complexes of the earth's crust and a significant velocity heterogeneity of the transition zone of the mountainous region of the Greater Caucasus and the Kura lowland have been established It is important to note that some of the velocity interfaces obtained were associated with different stress states of matter at depth and with the imposition of secondary metamorphism processes.

Earthquake Tomography Integrated With Gravity Data: An Application From NE-Italy

Poster 57, presented Saturday, 29 October

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We present the results of the comparison between two different strategies for earthquake tomography. The first uses the tomographic software Cat3d, integrated with the software Nnloc for hypocenter estimate. The second uses the software Simulps for the simultaneous inversion of both hypocenters and seismic velocities. Ultimately the models have been adjusted with information obtained from gravity data.

We applied the two solutions to the first arrivals of the P and S waves recorded by OGS and other data from the projects AlpArray and SwathD. Our final goal is to upgrade the available crustal model of NE Italy by improving the resolution and accuracy, in terms of seismic velocity, density and elastic moduli.

The software Cat3d, generally used in active seismic tomography, takes advantage of the inversion algorithms ART and SIRT and other tools to constrain the models, improve their resolution and explore their reliability. Moreover, its 3D ray-tracing algorithm makes it suitable for modeling complex geological structures. Therefore, we decided to explore its potential in the case of passive tomography by including the automatic location of the events with the probabilistic solution given by the Nnloc software. On the other hand, the software Simulps is renowned as one of the most reliable inversion methods for seismological data and was already successfully applied in the study area. Finally, gravity data used within the Sequential Integrated Inversion strategy (SII) allowed us to obtain the 3D density structure, assess the tomographic inversion results and improve it in areas with a low rate of earthquake occurrence but with homogeneous coverage of gravity stations.

Seismic Wave Modeling in Anisotropic Media With Fracture Sets Using the Finite-difference Rotated Staggered Grid

Poster 9, presented Saturday, 29 October

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Modeling the seismic wave propagation accurately is of importance to seismic imaging and full waveform inversion. Forward modeling through complex anisotropic geometries remains challenging. Currently, the Standard Staggered Grid (SSG), which has the normal and shear components allocated at different points, defines the geometry used in finite-difference modeling. However, applying SSG to modeling of seismic wave propagation through low-symmetry anisotropic media leads to interpolation error and instability. The adaptation of the Rotated Staggered Grid (RSG) is proposed to overcome this problem. RSG has both normal and shear stress components allocated at the same point to avoid half-length of the unit cube interpolation and the derivative between two adjacent points is calculated diagonally using coordinate transform. In this study, we develop a second-order finite-difference modeling scheme using Rotated Staggered Grid based on Devito, an open-source finite-difference modeling software. We have found that RSG not only performs more stably than SSG when calculating elastic wave propagation through complicated anisotropic intact media up to triclinic symmetry with tilted axes, but also enables the incorporation of the prefer-orientated fracture sets.

Our ultimate goal is to better understand the seismic responses through a tilted and highly fractured mylonite sequence observed in an active source borehole seismic experiment near the Alpine Fault, New Zealand. Here, however, we evaluate and compare the performances of SSG and RSG through a hypothetical medium consisting of a fractured and tilted mylonite as part of initial tests.

Adjoint Seismic Tomography of the Antarctic Continent Incorporating Both Earthquake Waveforms and Green's Functions From Ambient Noise Correlation

Poster 40, presented Sunday, 30 October

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High-resolution images of Antarctica's crust and upper mantle structure are needed to better understand both the response of the solid earth to ice mass changes and the geological history of the continent. Although the existing 3D seismic model ANT-20 (Lloyd et al., 2020) has a good regional-scale resolution from the upper mantle to the transition zone, there is a need for a higher resolution of the uppermost mantle of Antarctica. In this study,

we use the ANT-20 model as a starting model. We use double-difference earthquake measurements to improve the resolution near the Antarctica continent. Then, we further enhance the resolution of the upper ~150 km by fitting vertical and transverse Green's functions for interstation propagation calculated from ambient noise cross-correlation. We keep the same earthquake event list and stations as Lloyd et al., 2020 but add new double-difference measurements for the earthquake data set. The dataset for ambient noise correlation is the same as Zhou et al., 2022, which includes all available broadband records collected in Antarctica over the past 20 years. Three-component cross-correlations are calculated and rotated to extract ambient noise surface wave observations for Rayleigh and Love waves. We use the software package SPECFEM3D_GLOBE to carry out an adjoint inversion for an improved 3D earth model, minimizing the nondimensionalized travel-time phase misfit between the observed and synthetic waveforms. The correlated waveforms show an excellent signal-to-noise ratio (SNR) between 15 to 70 s for surface waves. Both correlograms and synthetic waveforms are spectrum-whitened based on the good SNR range to avoid spectral bias introduced by the unknown noise source frequency distribution. The preliminary results indicate weaker negative radial anisotropy in the lower crust and stronger positive radial anisotropy in the uppermost mantle for West Antarctica and part of East Antarctica. With more iterations, smaller-scale detail can be revealed by the new ambient noise data, resulting in a more reliable uppermost mantle and crustal structure

Data Assimilated Full Waveform Inversion of Continuous Seismic Monitoring Data for Tracking the Evolution of CO2 Plumes

Oral Presentation, Sunday, 30 October, 11:05 AM

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Continuously seismic monitoring and even quantifying CO_2 plumes in the subsurface, as well as detecting any potential leakages are crucial for long-term geological carbon storage. The rapid development of time-lapse seismic monitoring instrumentations has made it possible to collect dense time-lapse data and even semi-continuous seismic data. While traditional time-lapse full-waveform inversion (TLFWI) algorithms are designed for sparse time-lapse surveys, these lack of effective temporal constraints on time-lapse data, and, meanwhile, lack of the uncertainty estimation of derived models.

We develop the data assimilated time-lapse full waveform inversion algorithm to process dense time-lapse or even continuous seismic monitoring data. The benefit of using data assimilation is to continuously update the estimated parameters over lapsed time with improved model accuracy. This algorithm consists of two parts: visco-acoustic full waveform inversion (QFWI) and multi-parameter hierarchical matrix powered extended Kalman Filter (mHiEKF). Thus we can construct high-resolution time-lapse velocity and attenuation changes. Three advantages of the algorithm are (1) to pose temporal constrains to retrieve time-lapse information from dense monitoring data by using mHiEKF; (2) to accurately recover high-spatial-resolution velocity and attenuation perturbations using first-order based QFWI; (3) to provide the model uncertainty by estimating their model standard deviation. We demonstrate the validity and applicability of the proposed method with a realistic CO_2 monitoring case derived from Frio-II CO_2 injection sites. The high-resolution time-lapse models of seismic velocity and attenuation derived accurately delineate the evolution of stored CO_2 plume with reduced model uncertainties.

Viscoacoustic Full-waveform Inversion: Theory and Application to Critical Zone

Poster 38, presented Sunday, 30 October

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Seismic wave propagation through the Earth is often described as an elastic process by ignoring the rock anelasticity. However, the anelasticity quantified by seismic attenuation could significantly modulate the characteristics of seismic signals by reducing the amplitude and distorting the phase. Seismic attenuation is particularly sensitive to the existence of fluids (water/gas), differences in mineral composition, fractures and high-temperature anomalies and could serve as a valuable physical constraint of the subsurface.

In this study, we present a viscoacoustic full-waveform inversion (*Q*-FWI) approach for inverting seismic attenuation. The *Q*-FWI adopts the fractional viscoacoustic wave equation for wavefield simulation and is constructed under the adjoint-state method framework to invert both the subsurface velocity and attenuation structures simultaneously. The Hessian information is incorporated into the *Q*-FWI through the L-BFGS method to mitigate the "crosstalk" artifacts between the velocity and attenuation. Synthetic experiments have been conducted to demonstrate that the proposed *Q*-FWI can produce a reliable and independent attenuation model with a feasible computational cost. Finally, we applied the *Q*-FWI to a field dataset acquired from an active-source seismic survey at the Garner Run site of the Susquehanna Shale Hills Critical Zone Observatory. The P-wave attenuation (*Q*p) model shows high-attenuation zones at the shallow depth beneath the hillslopes, which could be caused by the heterogeneity of fluid saturation and porosity. The attenuation asymmetry between hillslopes could provide constraints on subsurface fractures and hydraulic regions.

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