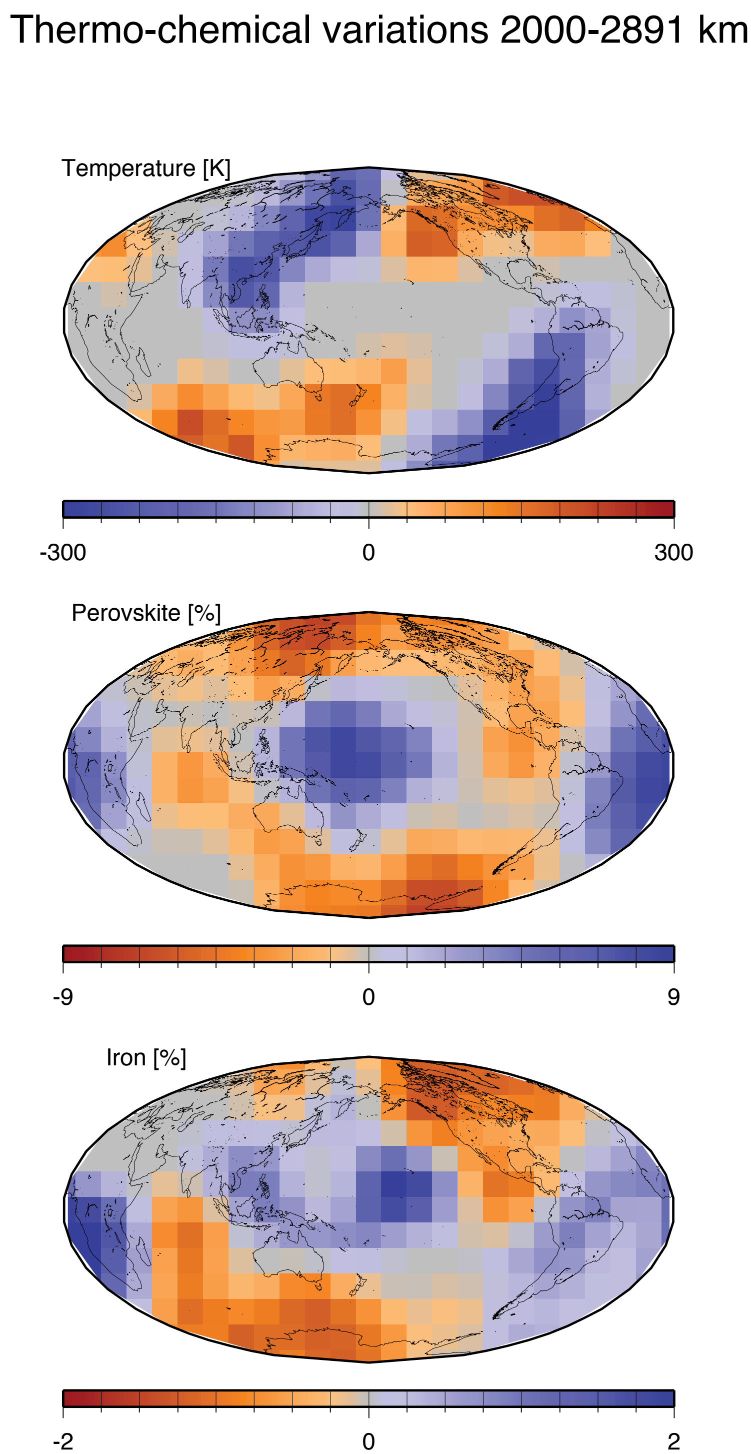
Chemical Heterogeneity in the Mantle: Inferences from Seismology, Mineral Physics and Geodynamics

Jeannot Trampert *(Utrecht University)*, **Frederic Deschamps** *(ETH Zurich)*, **Paul Tackley** *(ETH Zurich)*

Probabilistic Tomography allows us to infer robust probability density functions (pdfs) for long wavelength models of bulk-sound and shear wave speed, density and boundary topography in the mantle. Using appropriate depth-dependent sensitivities, these pdfs can be converted into likelihoods of variations in temperature, perovskite and iron content throughout the mantle (Trampert et al., 2004). The sensitivities are calculated using full uncertainties in mineral physics data and, more importantly, in the thermo-chemical reference state of the mantle. We find that bulk-sound speed (density) variations are an excellent proxy for perovskite (iron) variations, and that shear-wave speed is not highly correlated to temperature as is often assumed. Compositional variations are essential to explain the seismic, gravity and mineral physics data. In particular, the regions of low shear-wave velocity in the deep mantle (> 2000 km) beneath Africa and the Pacific, usually referred to as superplumes, are mainly due to an enrichment in iron, which makes them denser than the surrounding mantle. We performed statistical comparisons between these contributions and some chosen models of thermo-chemical convection. We find that a stable and ubiquitous layer of dense material is unlikely to be present at the bottom of the mantle. Models containing piles explain the observation significantly better (Deschamps et al. 2007).



Mean anomalies of temperature, perovskite and iron in the lowermost mantle. Grey areas represent anomalies which are smaller than one standard deviation and therefore not robust.

References

Trampert J., Deschamps F., Resovsky J., Yuen D., 2004. Probabilistic tomography maps chemical heterogeneities throughout the lower mantle, *Science, 306*, 853-856.

Deschamps F., Trampert J., Tackley P.J., 2007. Thermo-chemical structure of the lower mantle: seismological evidence and consequences for geodynamics, in Superplume: beyond plate tectonics', edited by D.A. Yuen, S. Maruyama, S.I. Karato, and B.F. Windley, Springer, p. 293-320.

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Moving Seismic Tomography Beyond Fast and Slow to Thermo-Chemical/Mineralogical Modeling

Christine Houser *(University of California Santa Cruz)*

The current reach and extent the Global Seismic Network (GSN) provides the seismic data needed to determine the seismic structure of the entire mantle. In fact, with the large amount of data available through the GSN, there is now enough confidence in the imaged seismic structure that we can begin to interpret seismically slow and fast regions in terms of temperature, chemistry, and mineralogy. The shear velocity (Vs) and compressional velocity (Vp) as well as normal modes are combined with their respective sensitivities to temperature and composition to map out variations in temperature (T), the mole fraction of iron (XFe), and the mole fraction of perovskite (XPv) near the core-mantle boundary (Houser et al., 2008). Since the phase transformation of perovskite to post-perovskite is temperature dependent, the temperature maps are used to determine where post-perovskite may exist at the bottom of the mantle [*Houser 2007*]. Thus, global seismic tomography is moving beyond slow and fast to a thermo-chemical understanding of the mantle in order to address Grand Challenge #9 "How do temperature and composition variations control mantle and core convection?".

References

Houser, C., Masters, G., Shearer, P., Laske, G. (2008) Shear and compressional velocity models of the mantle from cluster analysis of long-period waveforms, *Geophys. J. Int., 174* (1), 195-212.

Houser, C. (2007) Constraints on the presence or absence of post-perovskite in the lowermost mantle from long-period seismology,Post-Perovskite: The Last Mantle Phase Transition, Geophysical Monograph Series 174, K. Hirose, J. Brodholt, T. Lay, D. Yuen editors, American Geophysical Union.

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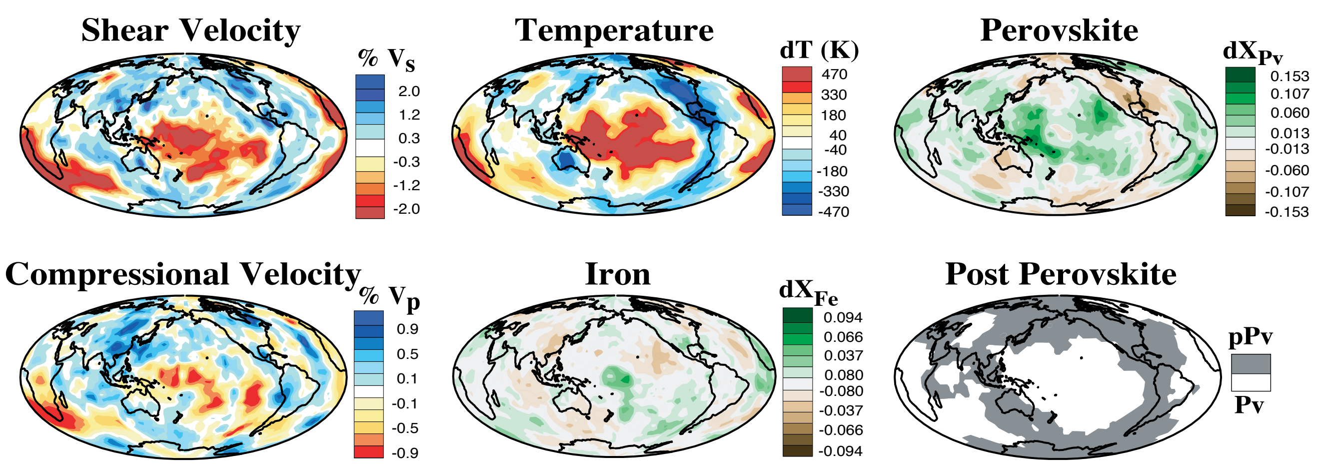
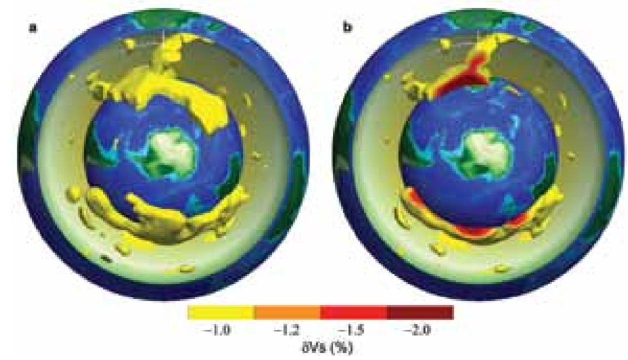


Shear and compressional velocity maps from the layer extending 200 km above the core-mantle boundary from the seismic tomography models HMSL-S and HMSL-P (Houser et al., 2008). Temperature and chemistry heterogeneity are shown using a scale such that the maximum/minimum translates to a -2%/+2% shear velocity anomaly. The temperature map is used to predict which regions may be cold enough to support the perovskite (Pv) to post perovskite (pPv) phase transition (Houser 2007).

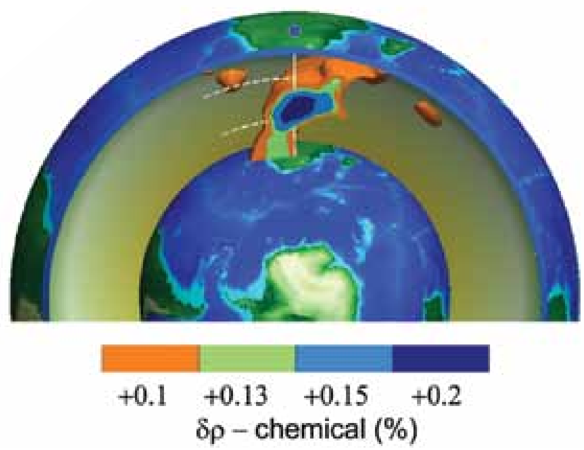
Mantle Heterogeneity and Flow from Seismic and Geodynamic Constraints

Nathan Simmons *(Lawrence Livermore National Laboratory),* **Alessandro Forte** *(Universite de Quebec),* **Stephen Grand** *(University of Texas at Austin)*

Images of mantle heterogeneity are most commonly in the form of seismic velocity since seismic waves are the most direct mantle probe. Although these static images provide general patterns of heterogeneity in the mantle, it is difficult to directly translate them to mantle flow for a variety of reasons. Some reasons include the inherent non-uniqueness of tomographic inversion and the uncertainties in the mineral physics parameters linking seismic velocity to density perturbations which are the driving force behind mantle flow. In attempts to overcome these obstacles, we have developed tomographic images of the mantle through simultaneous inversion of shear-wave constraints and a suite of convection-related observations including the global free-air gravity field, tectonic plate divergences, dynamic surface topography and the excess ellipticity of the core-mantle boundary. The convection-related observations are interpreted via viscous-flow response functions and density perturbations are internally linked to velocity heterogeneity with mineral physics constraints. This joint inversion procedure has allowed us to directly investigate many hypotheses regarding the style of mantle flow as well as the sources of mantle heterogeneity since the process effectively removes biases inherent to pure seismically-derived models. We conclude that temperature variations likely dominate shear-wave and density heterogeneity in the non-cratonic mantle. However, notable compositional anomalies are detected, most strongly within the African superplume structures [*Simmons et al. 2006, 2007, 2009*]. Time-dependent flow calculations from the jointly-derived density models provide evidence that the (usually) minor compositional anomalies play an important dynamic role, particularly beneath the African plate. The static density models have also been used in dynamic flow calculations that predict anomalous flow patterns that coincide with known tectonic features including the New Madrid Seismic Zone [*Forte et al., 2007*], the Colorado Plateau [*Moucha et al., 2008*], and several features within the African plate [*Forte et al., 2010*]. Collectively, these observations lend support to the validity of jointly-derived images of mantle heterogeneity.



Model showing contoured slow shear velocity anomalies with corresponding density and thermal anomalies(Simmons et al., 2007). The density anomalies here are inferred assuming heterogeneity is due solely to temperature anomalies.



To fit geodynamic data with the thermal model shown in figure 1 additional density anomalies are needed as shown here. The "Africa Superplume" is unique in the required high chemical density anomaly needed to fit the geodynamic data.

References

Forte, A. M., N. A. Simmons, R. Moucha, S. P. Grand, and J. X. Mitrovica, 2007, Descent of the ancient Farallon slab drives localized mantle flow below the New Madrid seismic zone, *Geophys. Res. Lett., 34*, doi: 10.1029/2006GL027895.

Moucha, R., A. M. Forte, D. B. Rowley, J. X. Mitrovica, N. A. Simmons, and S. P. Grand, 2008. Mantle convection and the recent evolution of the Colorado Plateau and the Rio Grande Rift valley, *Geology, 36*, 439-442, doi:10.1130/G24577A.1.

Simmons, N., A. Forte, and S. P. Grand, 2006. Constraining mantle flow with seismic and geodynamic data: A joint approach, *Earth Planet. Sci. Lett., 246*, 109-124, doi:10.1016/j.epsl.2006.04.003.

Simmons, N., A. Forte, and S. P. Grand, 2007, Thermochemical structure and components of the African superplume, *Geophys. Res. Lett., 34*, doi:10.1029/2006GL028009

Simmons, N., A. Forte, and S. P. Grand, 2009, Joint seismic, geodynamic and mineral physical constraints on three-dimensional mantle heterogeneity: Implications for the relative importance of thermal versus compositional heterogeneity, G*eophys. J. Int., 177*, 1284-1304, doi:10.1111/j.1365-246X.2009.04133.x

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A Three-Dimensional Radially Anisotropic Model of Shear Velocity in the Whole Mantle

Mark Panning *(University of Florida),* **Barbara Romanowicz** *(University of California, Berkeley)*

We present a 3-D radially anisotropic S velocity model of the whole mantle (SAW642AN), obtained using a large three component surface and body waveform data set primarily recorded on IRIS GSN stations. An iterative inversion for structure and source parameters was performed based on Non-linear Asymptotic Coupling Theory (NACT). The model is parametrized in level 4 spherical splines, which have a spacing of ~8°. The model is parameterized with isotropic shear velocity and the radial anisotropic parameter ξ (VSH^2/VSV^2). The model shows a link between mantle flow and anisotropy in a variety of depth ranges. In the uppermost mantle, we confirm observations of regions with VSH > VSV starting at ~80 km under oceanic regions and ~200 km under stable continental lithosphere, suggesting horizontal flow beneath the lithosphere. We also observe a VSV > VSH signature at ~150–300 km depth beneath major ridge systems with amplitude correlated with spreading rate for fast-spreading segments. In the transition zone (400–700 km depth), regions of subducted slab material are associated with VSV > VSH , while the ridge signal decreases. While the mid-mantle has lower amplitude anisotropy (<1 per cent), we also confirm the observation of radially symmetric VSH > VSV in the lowermost 300 km, which appears to be a robust conclusion, despite an error in our previous paper which has been corrected here. The 3-D deviations from this signature are associated with the large-scale low-velocity superplumes under the central Pacific and Africa, suggesting that VSH > VSV is generated in the predominant horizontal flow of a mechanical boundary layer, with a change in signature related to transition to upwelling at the superplumes. The included figure shows the isotropic and anisotropic signature in the core-mantle boundary region, showing the strong blue (VSH > VSV) signature in most regions with deviations generally associated with the low velocity superplumes. This work was originally published in Geophysical Journal International [*Panning and Romanowicz, 2006*].

References

Panning, M., and B. Romanowicz (2006), A three-dimensional radially anisotropic model of shear velocity in the whole mantle, *Geophys. J. Int., 167*, 361–379.

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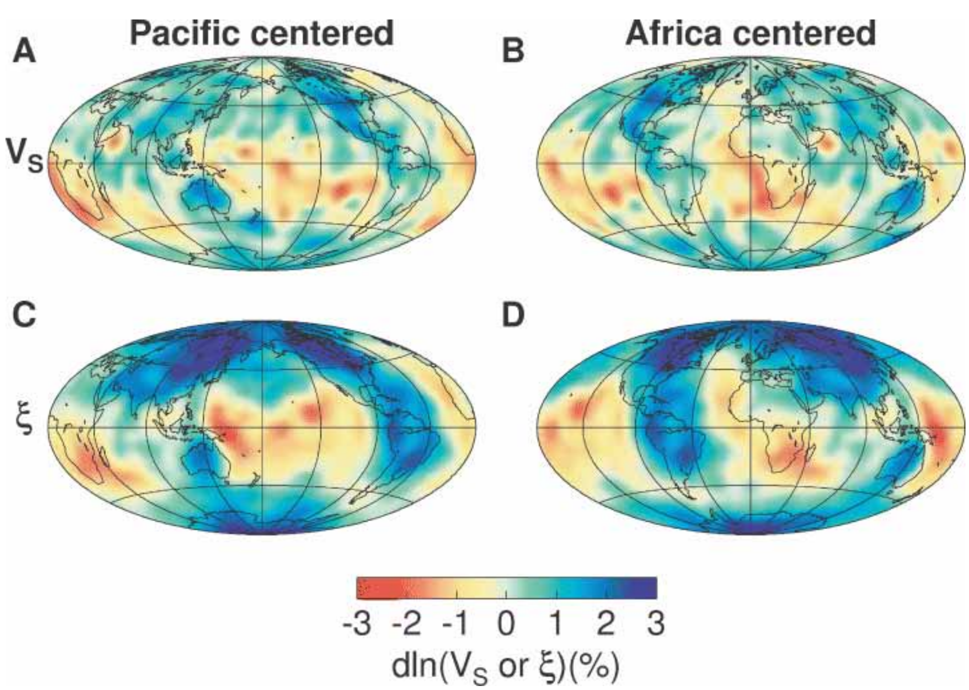


VS (A, B) and ξ structure (C, D) at a depth of 2800 km centered under the central Pacific (A, C) and Africa (B, D).

Global Mantle Anisotropy and the Coupling of Free Oscillations

Caroline Beghein *(University of California at Los Angeles),* **Joseph Resovsky** *(Roosevelt Academy, The Netherlands),* **Robert D. van der Hilst** *(Massachusetts Institute of Technology)*

Seismic anisotropy can be generated by large-scale deformation, and therefore provide us with a unique way of constraining mantle dynamics. However, because its detection below ~300 km depth remains challenging, it is unclear whether and what kind of seismic anisotropy is present in the deep upper mantle and transition zone. Due to their sensitivity to structure throughout the entire mantle, the Earth's free oscillations, or normal modes, constitute a unique source of data to constrain large-scale mantle seismic anisotropy. While isolated mode multiplets have been widely used in the literature to constrain Earth's large-scale structure, little attention has been given to mode coupling, which can occur due to Earth's rotation, ellipticity, and three-dimensional (3-D) isotropic and anisotropic structure.

Mode coupling measurements require high quality long-period seismic data. Few such measurements have been made so far, but we were able to take advantage of an existing small data set composed of 0Tl-0Sl+1 coupled mode multiplets [Beghein et al., 2008]. They had been measured by Resovsky and Ritzwoller [1995] for spherical harmonic degrees 2 and 4, and corrected for the effect of rotation and ellipticity. These multiplets have high sensitivity to shear-wave radial anisotropy and to six elastic parameters describing azimuthal anisotropy in the deep upper mantle and transition zone. They constitute therefore a potential new source of data to constrain anisotropy at these depths.

We first attempted to fit the degree two measurements using existing isotropic and transversely isotropic mantle models. However, the signal could not be explained by any of these models. After correction for the effect of crustal structure and mantle radial anisotropy, we tested whether the remaining signal could be explained by azimuthal anisotropy. We explored the model space with a forward modeling approach to identify the most likely azimuthal anisotropy models and associated model uncertainties. We determined that, although the variance was large, a robust azimuthal anisotropy signal could be extracted from the data. In addition, we showed that the data tend to slightly favor the presence of azimuthal anisotropy below 400 km depth.

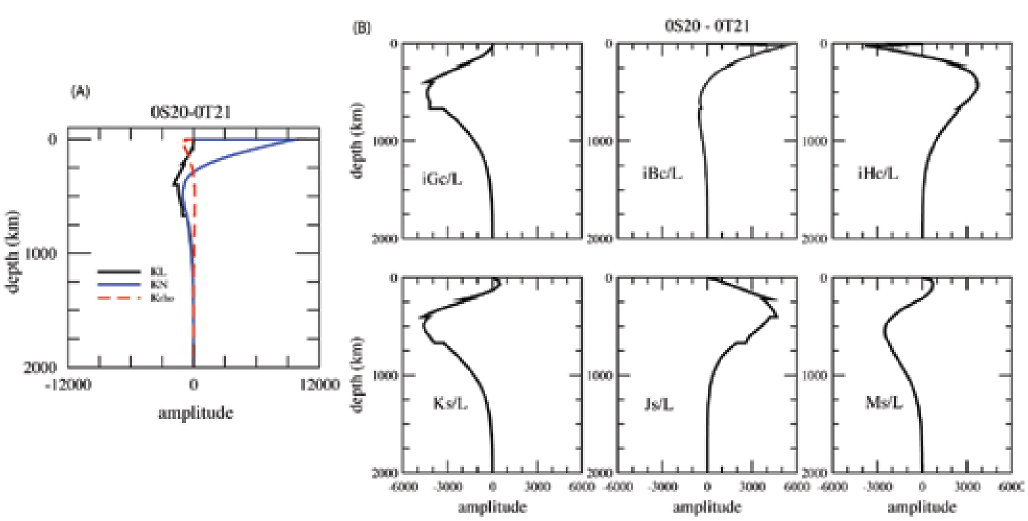
While the depth extent and distribution of the anisotropy were not well constrained due to parameter tradeoffs and a limited coupled mode data set, it is clear that mode coupling measurements constitute a promising tool to study deep mantle anisotropy. In addition, because some of the elastic parameters that can lead to mode coupling do not affect surface wave phase velocities, coupled free oscillations complement surface wave data, and have the potential to provide new and unique constraints on other elastic parameters, yielding a more complete description of Earth's elastic structure. In the future more coupled mode measurements could help us discriminate between different compositional models of the mantle [Montagner and Anderson, 1989].

References

Beghein, C., Resovsky, J., and van der Hilst, R.D., The signal of mantle anisotropy in the coupling of normal modes, *Geophys. J. Int., 175*, 1209-1234, 2008.

Montagner, J.P., and Anderson, D.L., Petrological constraints on seismic anisotropy, *Phys. Earth Planet. Int., 54*, 82-105, 1989.

Resovsky, J., and Ritzwoller, M., Constraining odd-degree Earth structure with coupled free-oscillations, *Geophys. Res. Lett., 22*, 2301-2304, 2005.

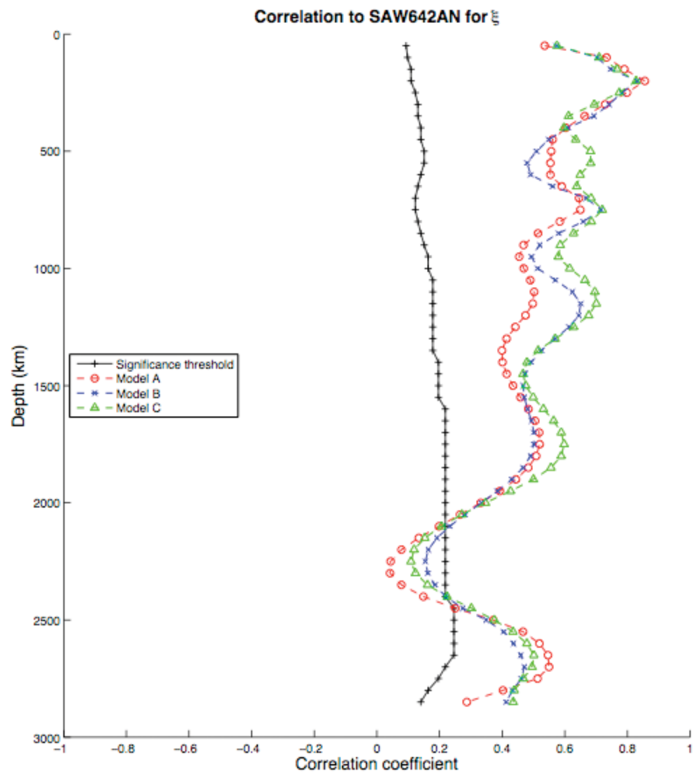


Sensitivity kernels of coupled modes 0S20-0T21 for (A) elastic parameters related to S-wave radial anisotropy and (B) elastic parameters describing azimuthal anisotropy.

The Importance of Crustal Corrections in the Development of a New Global Model of Radial Anisotropy

Mark Panning *(University of Florida)*, **Vedran Lekic** *(Brown University)*, **Barbara Romanowicz** *(University of California, Berkeley)*

Accurately inferring the radially anisotropic structure of the mantle using seismic waveforms requires correcting for the effects of crustal structure on waveforms. Recent studies have quantified the importance of accurate crustal corrections when mapping upper mantle structure using surface waves and overtones. Here, we explore the effects of crustal corrections on the retrieval of deep mantle velocity and radial anisotropy structure. We apply a new method of non-linear crustal corrections to a 3 component surface and body waveform dataset derived primarily from IRIS GSN data, and invert for a suite of models of radially anisotropic shear velocity. We then compare the retrieved models against each other and a model derived from an identical dataset, but using a different non-linear crustal correction scheme. While retrieval of isotropic structure in the deep mantle appears to be robust with respect to changes in crustal corrections, we find large differences in anisotropic structure that result from the use of different crustal corrections, particularly at transition zone and greater depths. Furthermore, anisotropic structure in the lower mantle, including the depth-averaged signature in the core-mantle boundary region, appears to be quite sensitive to choices of crustal correction. Our new preferred model, SAW642ANb, shows improvement in data fit and reduction in apparent crustal artifacts. We argue that the accuracy of crustal corrections may currently be a limiting factor for improved resolution and agreement between models of mantle anisotropy. The included figure shows the correlation for the anisotropic portion of a suite models developed with the new crustal corrections with that of SAW642AN, which was developed with the same dataset but a different implementation of non-linear crustal corrections. The new model, SAW642ANb is freely available through the website http://www.clas.ufl.edu/users/mpanning/SAW642ANb.html. This work is currently in revision for publication in the Journal of Geophysical Research [*Panning et al., 2010*].



Correlation of the ξ models A, B, and C (red, blue, and green dashed lines, respectively) to SAW642AN (derived from the same dataset with different crustal corrections) up to spherical harmonic degree 24. The black line shows the 95% confidence threshold for significant correlation. Correlations for ξ throughout the mantle are lower than those for isotropic shear velocity which generally are 0.8 or above throughout the mantle.

References

Panning, M.P., V. Lekic, and B.A. Romanowicz (2010), The importance of crustal corrections in the development of a new global model of radial anisotropy, *J. Geophys. Res.*, in revision.

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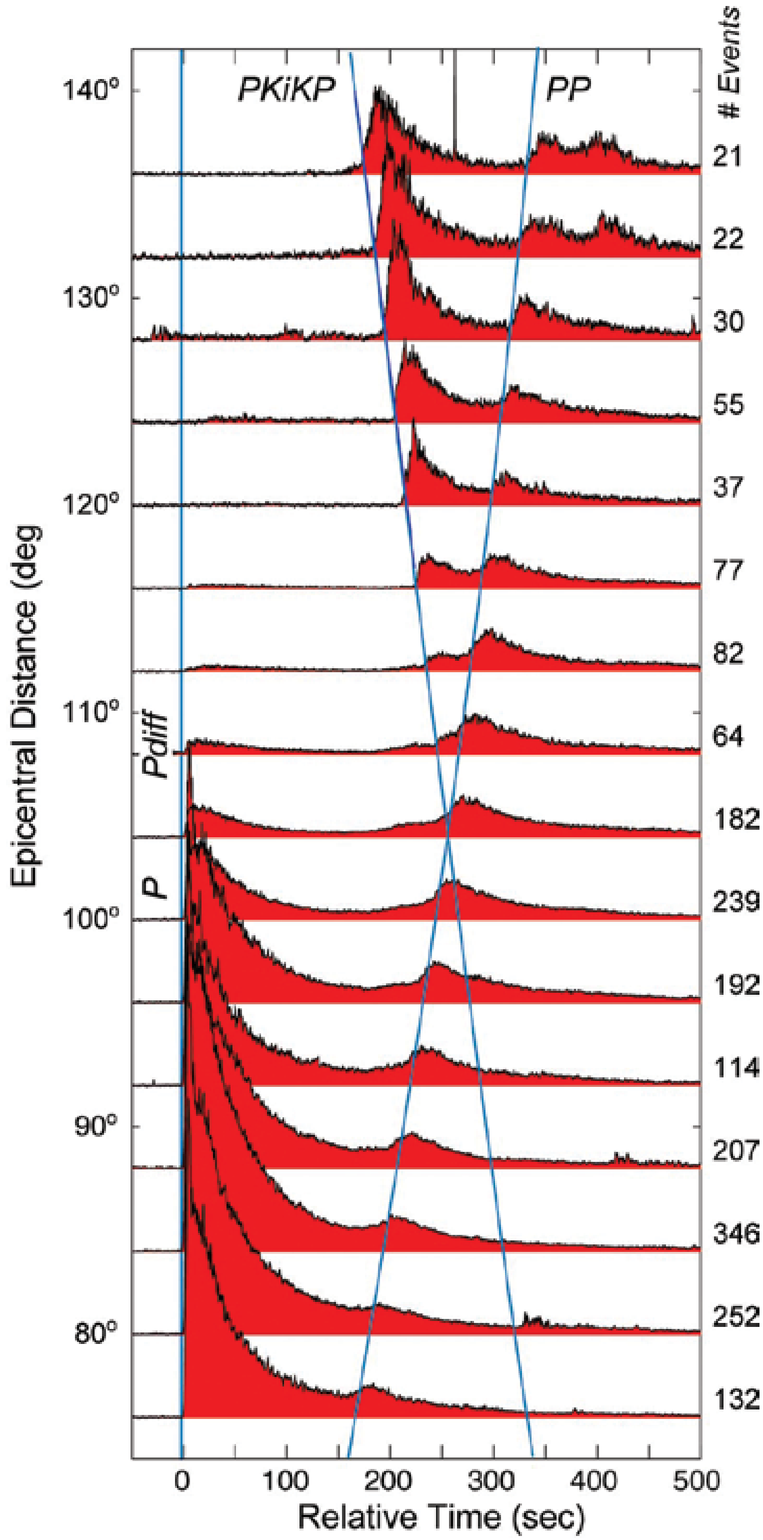
Analysis of the Mantle's Small Scale-Length Heterogeneity

Michael S. Thorne *(University of Utah)*, **Sebastian Rost** *(University of Leeds)*

The scattering of seismic waves from small spatial variations of material properties (e.g., density and seismic wave velocity) affects all seismic observables including amplitudes and travel-times and also gives rise to seismic coda waves. A large amount of the seismic energy observed at high frequencies is contained in these coda waves, and is especially evident in the P-wavefield. Analysis of seismic scattering has provided a means to quantify small-scale seismic properties that cannot be determined through travel-time analysis or ray theoretical approaches. Numerical wave propagation techniques, such as Finite Difference (FD) techniques, have been utilized in analyzing the full waveform effects of the scattered wave field, although application of these techniques has been focused on studies in regional distance ranges.

We examine the seismic coda of the phases P, Pdiff, PP, and PKiKP for events occurring globally recorded at the short period arrays: Yellowknife (YKA) located in northwestern Canada, Eilson (ILAR) located in Alaska, and Gräfenberg (GRF) located in Germany. We model the envelope of the coda wave train using the axi-symmetric finite difference approach PSVaxi. Although, we do not model full 3D scatterer geometries, the 2.5D axi-symmetric approach allows us to reach dominant seismic periods on the order of 2 sec. The result of using 2.5D scatterer geometries is that our scattering strength is smaller than suggested by full 3D geometries, thus producing a conservative estimate to the scattering strength. Using this numerical approach is the first attempt at actually synthesizing waveforms for seismic scattering at the global scale.



Envelope stacks of 2169 events. The data are grouped into 4° epicentral distance bins with the number of events going into each bin listed to the right of the plot window. Data are aligned in time on the P or Pdiff arrival and normalized to unity on the PP arrival. Data are SP, vertical component seismograms, beam formed on the PP slowness.

Slabs Do Not Go Gentle

Karin Sigloch *(Ludwig-Maximilians-University Munich, Germany),* **Guust Nolet** *(Geosciences Azur Nice, France & Princeton University),* **Yue Tian** *(Chevron Exploration and Production, San Ramon, CA)*

One of the big surprises from the EarthScope experiment is the extent to which the ancient Farallon plate has fractured into pieces during its 150+ years of subduction history under North America. A first multi-frequency P-wave inversion of USArray data by *Sigloch et al.* [2008] brought sharp contrast to the picture of the North American mantle, through unambiguous resolution of the narrow tears and breaks that separate different episodes of subduction. This was confirmed last year by the S-wave tomography of *Tian et al.* [2009].

The gain in image resolution results from two significant improvements, both accomplished through NSF-funded projects: the dense station deployment of USArray, and the development of finite-frequency tomography. Initially conceived as a theoretical improvement on classical ray theory, finite-frequency tomography has proved its worth in practice. Its advantage over ray tomography increases with station density, making it an ideal tool to exploit the array data. Modeling the frequency dependence of traveltime and amplitudes that is due to wave scattering yields superior resolution, especially in the lower mantle and in very heterogeneous regions.

We have been able to link some of the observed slab breaks to tectonic episodes inferred from surface geology. The origin or surface manifestations of others remain to be understood. These finding may well trigger a change in our thinking about the dynamics of convergent margins. *Nolet* [2009] has observed that in all three regions where station density allows for high-resolution tomography, *i.e.* the western U.S., Italy, and Japan, slabs show effects of tearing and detachment.

References

K. Sigloch, N. McQuarrie, and G. Nolet. Two-stage subduction history under North America inferred from multiple-frequency tomography. *Nature Geosci., 1*, 458-462, 2008.

Y. Tian, K. Sigloch, and G. Nolet. Multiple-frequency SH-wave tomography of the western US upper mantle. *Geophys. J. Int., 178*, 1384-1402, 2009.

G. Nolet. Slabs do not go gently. *Science, 324*, 1152-1153, 2009.

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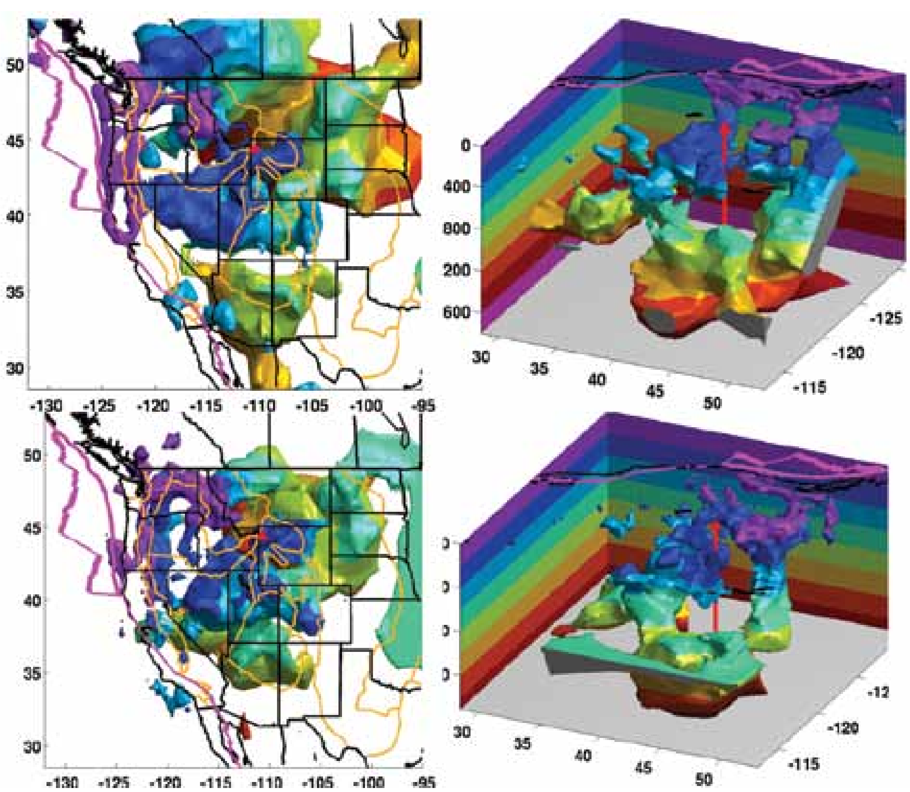

Subducted slab fragments (seismically fast anomalies) in the upper and lower mantle beneath western North America. Contoured 3-D iso-surfaces of the Cascadia subduction system down to 1800 km depth. Color codes for depth and changes every 200 km. Top row shows the P-wave model by Sigloch (2008), bottom row the S-wave model by Tian (2009). Left column shows map views, right column bird's-eye views from north-east. Lithospheric structure is not rendered except close to the trench. The red arrow marks the vertical downward projection of the Yellowstone hotspot. The models show good agreement on details such as a major vertical plate tear that runs from Oregon to Saskatchewan, just north of and parallel to the hotspot track.