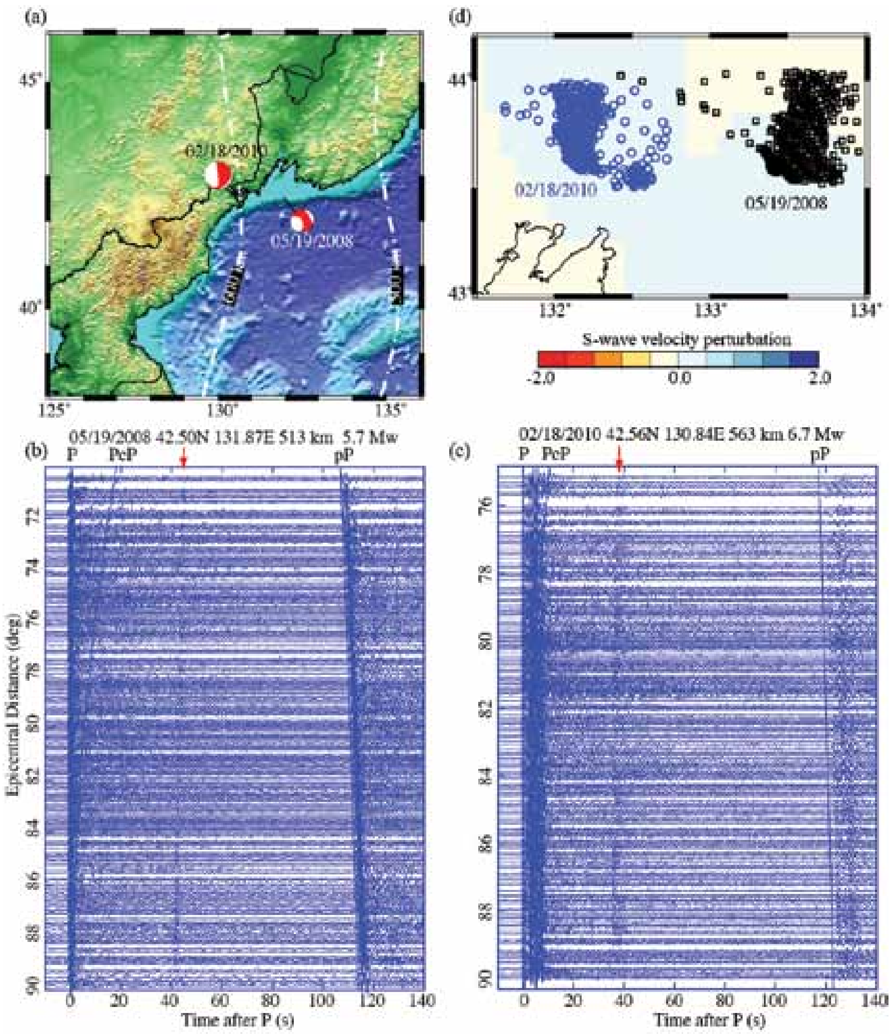
Observation of a Mid-Mantle Discontinuity beneath Northeast China from S to P Converted Waves Recorded by the USArray Stations

Fenglin Niu *(Department of Earth Science, Rice University)*

Strong and localized seismic discontinuity and reflectors have been observed in the lower mantle at various depths beneath western Pacific subduction zones [Niu and Kawakatsu, 1997; Kaneshima and Helffrich, 1999; Castle and Creager, 1999; Niu et al., 2003]. The lateral extension of these anomalous structures, however, is not well constrained. The information may hold the key to the understanding of the nature of these seismic structures as well as the related mantle processes. The USArray opens a new window for "viewing" and mapping these seismic anomalies. We found a clear later phase ~35-42 s after the direct P wave at most of the USArray recordings of two deep earthquakes that occurred near the border between east Russia and northeast China. The measured incident angle and arriving direction of this arrival suggest that it is an S to P wave converted at ~1000 km below Earth's surface. The mid-mantle discontinuity has a lateral dimension of greater than 200 km and 50 km along the EW and NS direction, respectively. It dips toward the east by ~12 degrees. The discontinuity is located in a region with a slightly higher P- and S-wave velocity, suggesting that the discontinuity is likely related to the subducted Pacific slab. One possible explanation is the breakdown of hydrous magnesium silicate phases, which is observed to be stable in cold environment at uppermost lower mantle pressure condition.



(a) Geographic locations of the two deep earthquakes near the border of China, Russia, and North Korea. White dashed lines indicate the Wadati-Benioff zone. (b) A portion of the USArray records of the 05/19/2008 deep earthquake. Theoretical travel times of the iasp91 model for the major expected body wave arrivals are indicated by straight lines. Note a clear phase between 40 and 45 s after the direct P arrival (indicated by red arrows) can be seen in most of the individual seismograms. The phase has a slightly negative slowness compared to the P wave. (c) same as (b) for the 02/18/2010 event. Not that in this case the unknown phase arrives at 35-40s after the direct P arrival, a few seconds earlier than those observed from the 05/19/2008 event. (d) Geographic distribution of the S to P conversion points from the 05/19/2008 (black squares) and the 02/18/2010 (blue circles). S-wave velocity perturbations at ~1000 km depth from Grand (2002) is also shown.

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Core-Mantle Boundary Heat Flow

Thorne Lay *(Department of Earth and Planetary Sciences, Univ. California Santa Cruz),* **John Hernlund** *(Department of Earth and Planetary Sciences, Univ. California Berkeley),* **Bruce A. Buffett** *(Department of Earth and Planetary Sciences, Univ. California Berkeley)*

The current total heat flow at Earth's surface, 46 ± 3 TW (10**12 J/s), involves contributions from secular cooling, radiogenic heating from decay of U, Th and K, heat entering the mantle from the core, and various minor processes such as tidal deformation, chemical segregation and thermal contraction. Over the past decade, estimates of the heat flow across the core-mantle boundary (CMB), or across a chemical boundary layer above the CMB, have generally increased by a factor of 2 to 3, yielding values in the range 5-15 TW from independent considerations of core temperature, geodynamo energetics, buoyancy flux of lower mantle thermal plumes, and direct temperature determinations in the lowermost mantle enabled by relating seismic velocity discontinuities to a laboratory-calibrated phase change in magnesium-silicate perovskite ($MgSiO_3$) (*Lay et al., 2008*). Relative to earlier ideas, the increased estimates of deep mantle heat flow indicate a more prominent role for thermal plumes in mantle dynamics, more extensive partial melting of the lowermost mantle in the past, and a more rapidly growing and younger inner core and/or presence of significant radiogenic material in the outer core or lowermost mantle.

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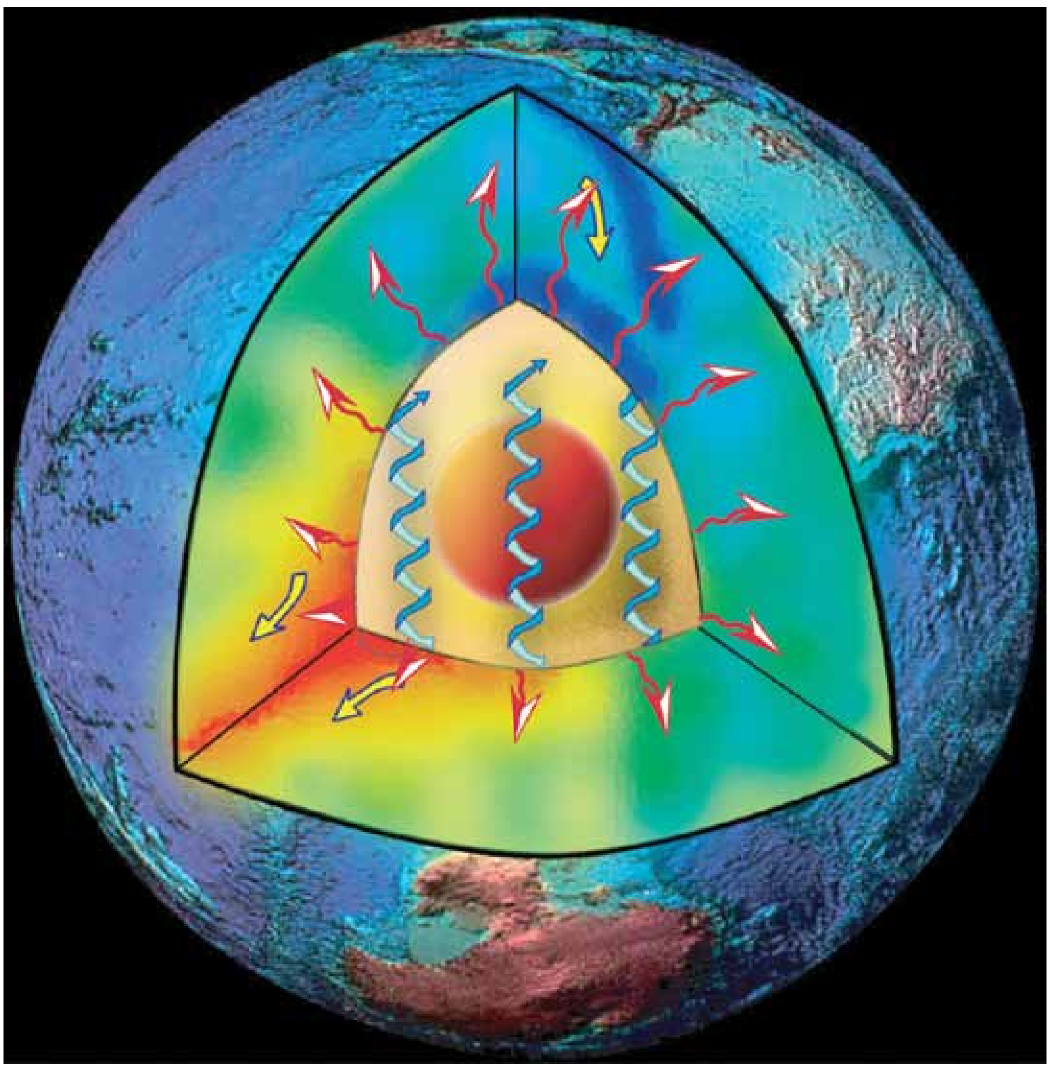
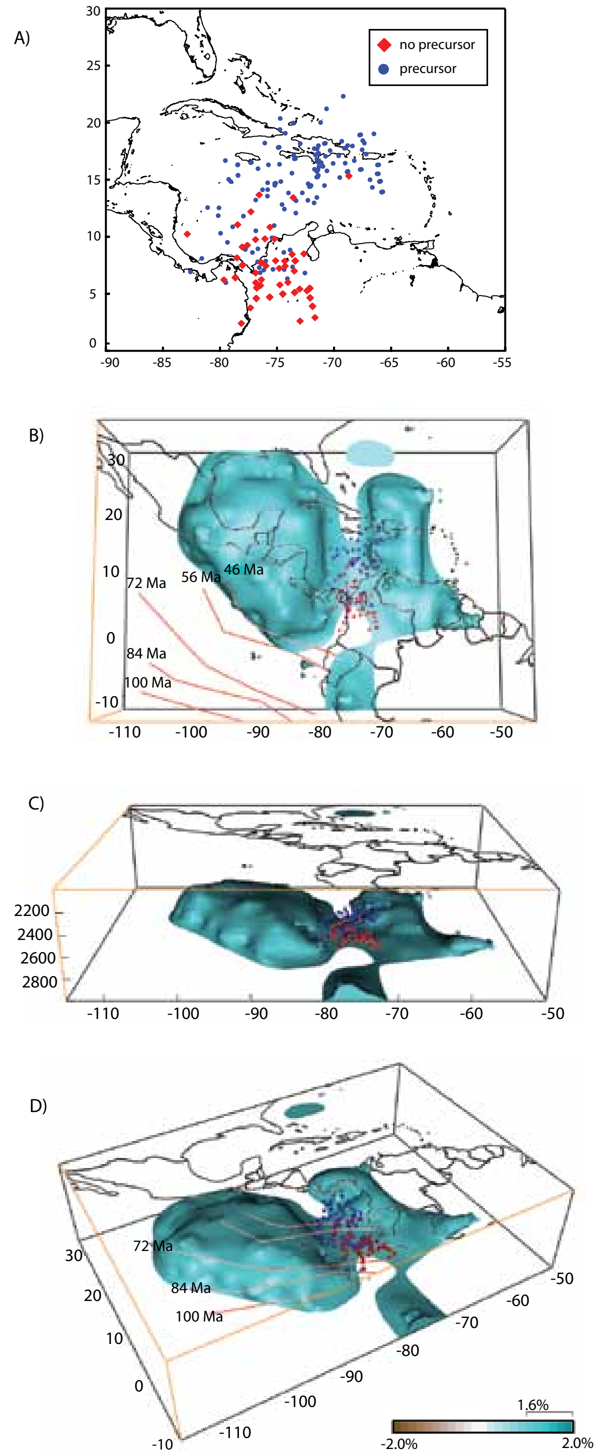


Cut-away Earth schematic indicating dynamic regimes in the mantle and core, along with variation in heat flux through the core-mantle boundary. Heat flux from the core into the mantle (represented by red arrows) is highest in areas cooled by downwellings, and lowest in hot upwelling regions.

Localized Seismic Scatterers Near the Core-Mantle Boundary beneath the Caribbean Sea: Evidence from PKP Precursors

Meghan S. Miller *(University of Southern California),* **Fenglin Niu** *(Rice University)*

The nature of the core-mantle boundary (CMB) region, the D", has been a focus of research for decades because it is a crucial part in understanding the evolution of geodynamics and whole earth structure. The D" region is very heterogeneous and has complicated seismic structures that require involvements of both chemical and thermal processes. One representative and well studied area is Central America and Caribbean, where the D" region is featured by a well defined seismic discontinuity underlain by anisotropic and higher velocity materials. Here we used seismic phase arrivals from earthquakes in the Western Pacific recorded by broadband seismic stations in northern South America and the Caribbean to investigate the core-mantle boundary and the D" region beneath the central Caribbean plate. We identified precursors to the PKP phases in 14 events, which can be explained by a region of heterogeneous scattering located above the CMB beneath the central Caribbean plate. The seismic scatterers are localized to the vicinity between approximately 5°N to 20°N and -80°W to -65°W. Other similar distance events that display no precursors, interpreted to have traversed non-scattering regions on the core-mantle boundary, lie to the south and southwest of the identified cluster of seismic scatterers. We found that the small-scale seismic scatterers are not uniformly distributed, are concentrated, and are surrounded by relatively fast shear velocity perturbations in the lower mantle imaged with global seismic tomography. The fast velocity perturbations may be residual slab from the subducted Farallon plate and the scatterers to the east-northeast of the high velocity material could be remnants of heterogeneous material, perhaps former basaltic crust, that has been transported ahead or on top of the subducted slab material as it impacts and bends at the core-mantle boundary.



A) Map of the Caribbean region showing the calculated points of ray paths exiting the core and entering the mantle. Blue circles indicate the events with precursors, with a good (> 5) signal to noise ratio and red diamonds indicate the events with no evident precursor, which also have a good (> 5) signal to noise ratio. B-D) Tomographic images of the lower mantle (Grand, 2002) with isosurfaces of 1.6% shear velocity perturbation and greater. The exit points are also plotted with the images showing the localization of the scatterers and their relationship to the surrounding high velocities. The red lines (and ages) are the estimated Farallon plate boundaries from plate and kinematic reconstructions between 100 and 46 Ma (Pindell et al., 2005).

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Constraints on Lowermost Mantle Anisotropy beneath the Eastern Pacific from SKS-SKKS Splitting Discrepancies

Maureen Long *(Yale University)*

Measurements of the birefringence of SKS and SKKS phases are commonly used to infer seismic anisotropy and flow in the upper mantle beneath a seismic station. Comparisons of SKS and SKKS splitting for stations around the globe have demonstrated that in 95% of cases, SKS and SKKS phases for the same event/station pair yield the same splitting parameters [Niu and Perez, 2004] In an important minority of cases, however, these measurements diverge, and in this case the difference in splitting must be attributed to anisotropic structure in the lower mantle far away from the receiver side. Strongly discrepant SKS-SKKS splitting has been observed at broadband stations in western Mexico and California [Long, 2009]. In particular, strong SKKS splitting with fast polarization directions near ~60° and delay times of up to ~ 3 sec is observed for a group of raypaths that sample the lowermost mantle beneath the eastern Pacific Ocean. The region most likely to cause the observed discrepancies is the deepest mantle, as this is the least similar portion of the SKS/SKKS path. Because there is considerable seismological evidence for anisotropy in the D" layer, and because there is laboratory and seismological evidence that the bulk of the lower mantle is seismically isotropic, my preferred interpretation of the anomalous SKKS splitting observed in western North America is that it is due to complex anisotropy in the D" region at the base of the mantle. The anomalous SKKS splitting appears to delineate a region of fairly uniform azimuthal anisotropy in the D" layer beneath the eastern Pacific; this anisotropy coincides geographically with a sharp lateral gradient in isotropic S wavespeed structure at the base of the mantle. One possible model to explain the observations invokes a broad region of high-strain deformation associated with the impingement of the Farallon slab upon the CMB beneath North America, inducing the LPO of lowermost mantle minerals to produce a region of anomalous D" anisotropy at its edge.

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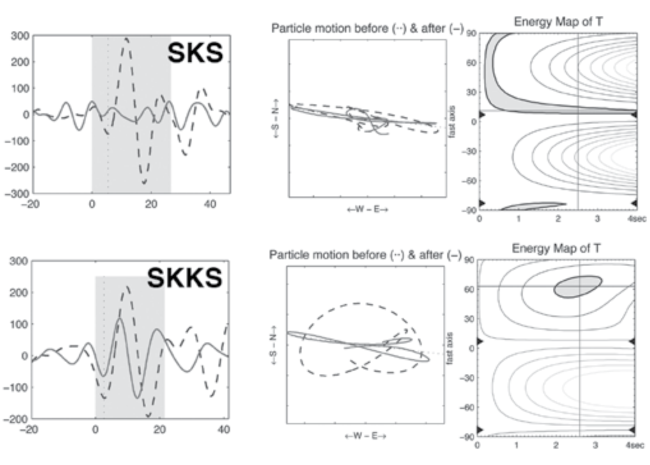
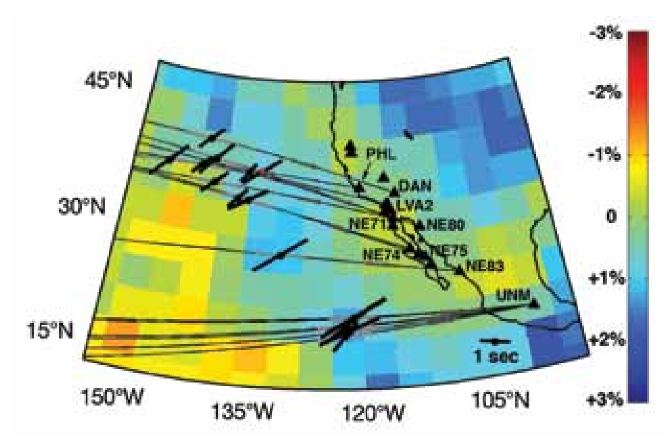


An example of an anomalous SKS-SKKS splitting measurement at station UNM. Columns show the radial (dashed) and transverse (solid) components of the phase (left panel), the initial (dashed) and corrected (solid) particle motion (center panels), and the energy map of the transverse component (right panels). The SKS phase (top row) exhibits null or near-null splitting, while the SKKS phase (bottom row) exhibits well-constrained splitting parameters of $\varphi = 63°$, $\delta t = 2.6$ sec.



Shear wave splitting parameters (black bars) attributed to D" anisotropy for anomalous SKKS phases are plotted at the midpoint of their D" paths. The colors indicate isotropic S wavespeeds at the base of the mantle from the model of Houser et al. [2008] as a % deviation from the reference model.

Constraints on Lowermost Mantle Mineralogy and Fabric beneath Siberia from Seismic Anisotropy

James Wookey *(University of Bristol, UK),* **J-Michael Kendall** *(University of Bristol, UK)*

Seismic anisotropy is an important tool for studying the nature, origin and dynamics of the lowermost mantle (D"). Here we present analysis of the seismic anisotropy beneath Siberia from shear-wave splitting measured in ScS phases. Data come from two near-perpendicular raypaths (Hindu-Kush to Northern Canada and the Kuril Arc to Germany; both at ~80 degrees epicentral distance) with close ScS reflection points on the Core-Mantle boundary (CMB). We apply differential S-ScS splitting to minimise contamination from the source and receiver side upper mantle. The two raypaths show different ScS splitting times and fast shear-wave orientations, incompatible with the VTI style of anisotropy inferred for much of the lowermost mantle. The availability of data at two azimuths give us an opportunity to better understand D" anisotropy than in previous studies. For example, the results provide the first accurate measurement of the dip of the symmetry plane. Several mechanisms have been suggested to explain lowermost mantle anisotropy, including the lattice-preferred orientation of lower mantle minerals such as perovskite or post-perovskite, or the shape-preferred orientation of inclusions of melt. In order to infer the flow regime implied by these mechanisms we use elasticities from published deformation experiments to forward model shear-wave splitting. Tomography of the region suggests a north-south trend in the geodynamics, and a model incorporating post-perovskite with a [100](010) slip system or aligned melt inclusions are most naturally compatible with such a trend. This may suggest a connection with remnant slab material from past subduction in the north Pacific.

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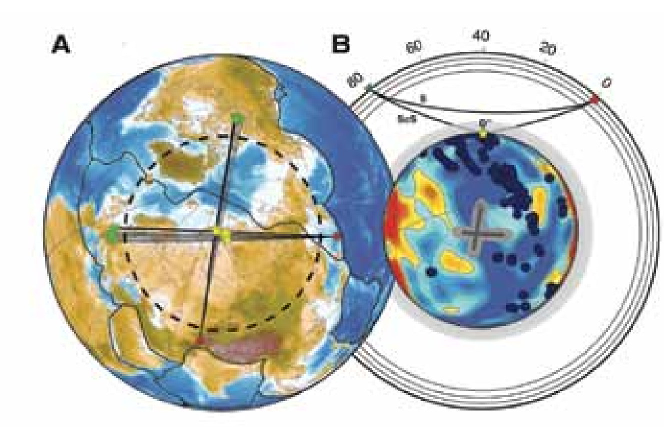
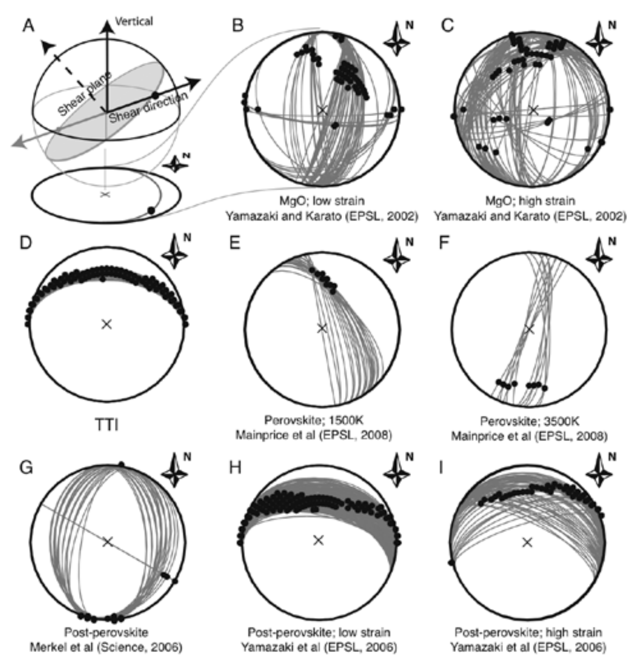
Acknowledgements: Data came from the CNSN and SZGRF datacentres. JW was supported by a NERC fellowship grant.



Raypaths and bouncepoints for data used in the study. Panel A shows the great-circle paths for the phases studied, from Hindu-Kush and Kuril Arc events (circles) to POLARIS and GRSN stations (triangles). Stars mark the reflection point of ScS: for both paths these are very close. Panel B shows the variation of shear-wave speed at the CMB from Masters et al (2000) (blue colours are faster than average) and the predicted location of paleosubducted slab material from Lithgow-Bertelloni and Richards (1998) (blue cirles). The grey region shows the approximate Fresnel zone of the ScS phases in the lowermost mantle. Also shown are the S and ScS raypaths; S turns above D$''$ whilst ScS samples it.

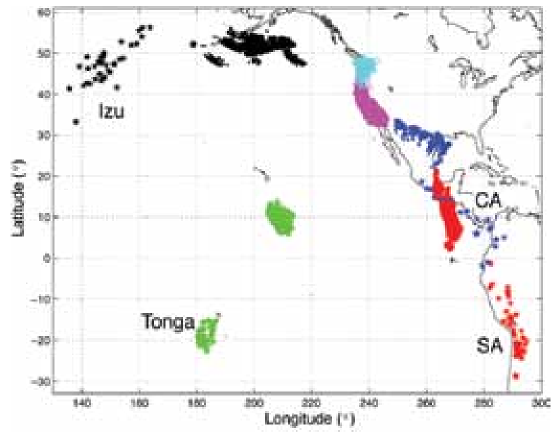


Orientations of candidate elastic models which fit the shear-wave splitting observed beneath Siberia. Panel A is a cartoon showing how to interpret the other panels. Plots are upper hemispheric projections of the shear plane (grey arcs) and direction (black circles) predicted by matching orientations of different elastic tensors to the polarisations observed in the data. North is up the page, as indicated, and normal to the page is vertical (i.e., radially in the Earth). The elastic tensors tested are: B and C, an LPO of MgO; D, an ideal TTI medium; E and F, $MgSiO_3$ perovskite at 1500K and 3500K; G, post-perovskite LPO using $MgGeO_3$; H and I, post-perovskite LPO using $CaTiO_3$.

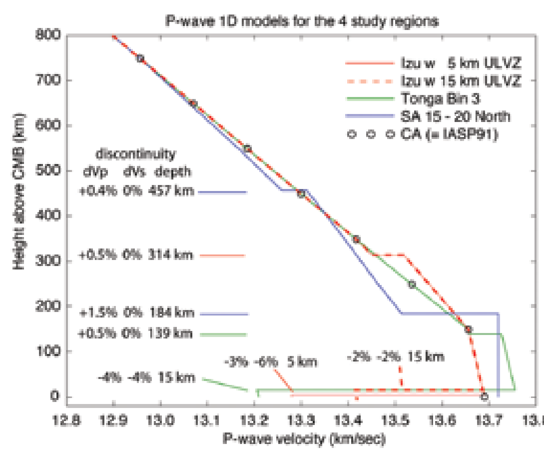
Localized Double-Array Stacking Analysis of PcP: D" and ULVZ Structure beneath the Cocos Plate, Mexico, Central Pacific, and North Pacific

Thorne Lay *(University of California Santa Cruz)*, **Alexander R. Hutko** *(U. S. Geological Survey, NEIC)*, **Justin Revenaugh** *(University of Minnesota)*

A large, high quality P-wave data set comprising short-period and broadband signals sampling four separate regions in the lowermost mantle beneath the Cocos plate, Mexico, the central Pacific, and the north Pacific is analyzed using regional one-dimensional double-array stacking and modelling with reflectivity synthetics. A data-screening criterion retains only events with stable PcP energy in the final data stacks used for modelling and interpretation. This significantly improves the signal stacks relative to including unscreened observations, allows confident alignment on the PcP arrival and allows tight bounds to be placed on P-wave velocity structure above the core-mantle boundary (CMB). The PcP reflections under the Cocos plate are well-modelled without any ultra-low velocity zone from 5 - 20° N. At latitudes from 15 – 20° N, we find evidence for two P-wave velocity discontinuities in the D" region. The first is ~182 km above the CMB with a δlnVp of +1.5%, near the same depth as a weaker discontinuity (<+0.5%) observed from 5 - 15° N in prior work. The other reflector is ~454 km above the CMB, with a δlnVp of +0.4%; this appears to be a shallower continuation of the joint P- and S-wave discontinuity previously detected south of 15° N, which is presumed to be the perovskite to post-perovskite phase transition. The data stacks for paths bottoming below Mexico have PcP images that are well-matched with the simple IASP91 structure, contradicting previous inferences of ULVZ presence in this region. These particular data are not very sensitive to any D" discontinuities, and simply bound them to be <~2%, if present. Data sampling the lowermost mantle beneath the central Pacific confirm the presence of a ~15-km thick ultra-low velocity zone (ULVZ) just above the CMB, with δlnVp and δlnVs of around -3 to -4% and -4 to -8%, respectively. The ULVZ models predict previous S-wave data stacks well. The data for this region indicate laterally varying Vp discontinuities in D", with one subregion having a δlnVp of 0.5% 140 km above the CMB. Beneath the north Pacific, the PcP arrivals are compatible with only weak ULVZ (δlnVp ~ 0 to -3%), and there is a weak D" reflector with δlnVp = 0.5%, near 314 km above the CMB. These results indicate localized occurrence of detectable ULVZ structures rather than ubiquitous ULVZ structure and emphasize the distinctiveness between the large low shear velocity province under the central Pacific and circum-Pacific regions.



Map of PcP data stacking configurations; earthquake epicenters (stars), recording stations in western North America (triangles), and PcP midpoints (small dots). The red, blue, green, and black colour earthquakes and midpoints are the South America (SA), Central America (CA), Tonga, and Izu data sets, respectively. The CA events were recorded by University of Washington short period-stations (cyan triangles), all other data sets incorporate broadband and short-period data from the TriNet, SCSN and NCSN networks (magenta triangles). All data shown have been screened to ensure a stable PcP detection in individual event stacks. About a third (half) of the Tonga (Izu) data are a screened subset of the data used by Revenaugh and Meyer (1997).



Summary of P-wave velocity structures for the four study regions. The discrepancy in depth between the observed and synthetic PcP stack (when using the direct P-wave as the reference phase) was matched for each region. We do not model the absolute travel times of the P-waves, so the absolute velocities are not constrained. Perturbations from the reference 1D model are so small that relative depths of discontinuities are well constrained. This is not the case when modelling S-wave data. Our modelling has little sensitivity to density contrasts or the sign or magnitude of dVp/dZ, however for some source-receiver geometries, there is some sensitivity to abrupt changes in dVp/dZ (Hutko et al. 2008). All discontinuities were modelled as sharp discontinuities. Distributing the velocity changes at the discontinuities across some depth can reduce the effective reflection coefficient by varying degrees, depending on the source-receiver geometry.

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Anti-Correlated Seismic Velocity Anomalies from Post-Perovskite in the Lowermost Mantle

Thorne Lay *(University of California Santa Cruz),* **Alexander R. Hutko** *(University of California, Santa Cruz),* **Justin Revenaugh** *(University of Minnesota),* **Edward J. Garnero** *(Arizona State University)*

Earth's lowermost mantle has thermal, chemical, and mineralogical complexities that require precise seismological characterization. Stacking, migration, and modeling of over 10,000 P- and S-waves that traverse the deep mantle under the Cocos plate resolves structures above the core-mantle boundary (CMB). A small -0.07 ± 0.15% decrease of P-wave velocity (Vp) is accompanied by a 1.5 ± 0.5% increase in S-wave velocity (Vs) near a depth of 2570-km. Bulk-sound velocity (Vb = [Vp²–4/3Vs²]**½) decreases by –1.0 ± 0.5% at this depth. Transition of the primary lower mantle mineral, (Mg1-x-y FexAly)(Si,Al)O3 perovskite, to denser post-perovskite is expected to have negligible effect on the bulk modulus while increasing the shear modulus by ~6%, resulting in local anti-correlation of Vb and Vs anomalies; this explains the data well.

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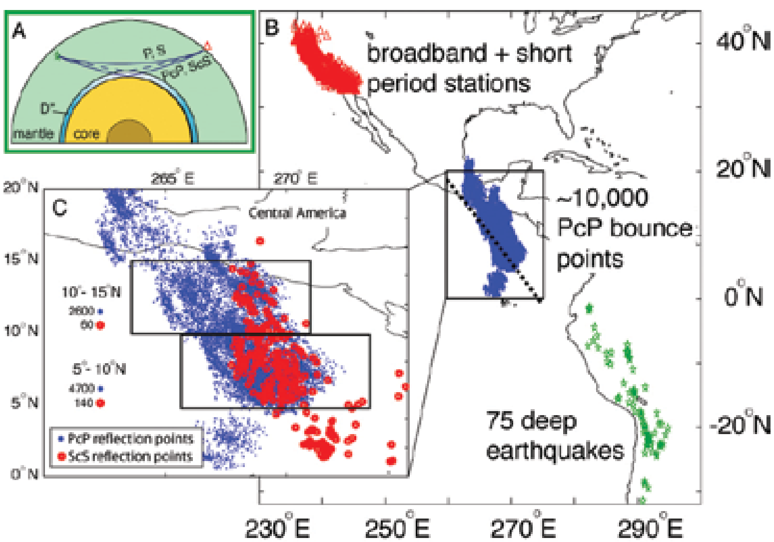
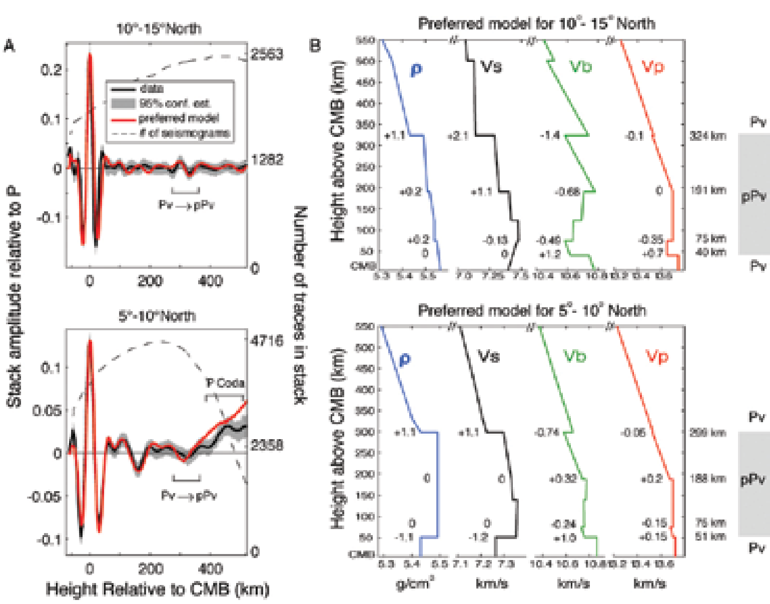


(A) Earth cross-section with representative raypaths for direct (P/S) and CMB reflected (PcP/ScS) phases, and any reflections from deep mantle discontinuities (dashed). The D" region structure in the lowermost mantle is the focus of this study. (B) Map indicating the study configuration, involving 75 earthquake epicenters (green stars), seismic stations (red triangles) and surface projections of PcP core-mantle boundary (CMB) reflection points (blue dots). The dashed line shows the surface trace of a cross-section made through the migration image volume in the lower mantle (Fig. 3). The inset map (C) shows both PcP and ScS CMB reflection points and two data bins where these overlap, used in waveform stacking analysis.



(A) P-wave double array stacking results for two 5° latitudinal bins beneath the Cocos Plate. The solid black line shows the data stack amplitude relative to the direct *P* amplitude. The grey shaded region is the 95% confidence interval of the stack from bootstrap re-sampling, and the dashed line is the number of seismograms contributing to the data stack at a particular depth (right scales). Above 400 km the stack for 5-10°N is contaminated by *P* coda. The red lines are stacks of synthetic seismograms generated from our preferred models. The synthetics were sampled to match the source-receiver geometry and had the same processing as the data. (B) Elasticity models obtained by modeling the data: ρ is density (gm/cm^3), V_s is S-wave velocity (km/s), V_b is bulk-sound velocity (km/s) and V_p is P-wave velocity (km/s). Percent changes in these parameters are shown at first-order discontinuities at the indicated depths. The depth range likely to contain post-perovskite (pPv) is indicated on the right.

Waveform Modeling of D" Discontinuity Structure

Michael S. Thorne (University of Utah), **Edward J. Garnero** *(Arizona State University),* **Thorne Lay** *(University of California, Santa Cruz),* **Gunnar Jahnke** *(Ludwig Maximilians University, Munich, Germany),* **Heiner Igel** *(Ludwig Maximilians University, Munich, Germany)*

The 3-D velocity structure of the deep mantle has been inferred from imaging procedures such as migration, tomography, stacking, and waveform modeling, all which utilize localized 1-D reference structures. As these methods often have limiting assumptions it is essential to assess to what extent 3-D solution models are self-consistent with the imaging procedures from which they were produced; this is possible through synthesizing waveforms in laterally varying media. We use a 3-D axi-symmetric finite difference algorithm (SHaxi) to model SH-wave propagation through cross-sections of recent 2- and 3-D lower mantle models along a north-south corridor roughly 700 km in length beneath the Cocos Plate. Synthetic seismograms with dominant periods up to 3 sec are computed to assess fit of 3-D model predictions to data. Model predictions show strong waveform variability not observed in 1-D model predictions. It is challenging to predict 3-D structure based on localized 1-D models when lateral structural variations are on the order of a few wavelengths of the energy used. Iterative approaches of computing synthetic seismograms and adjusting model characteristics by considering path integral effects are necessary to accurately model fine-scale D" structure.

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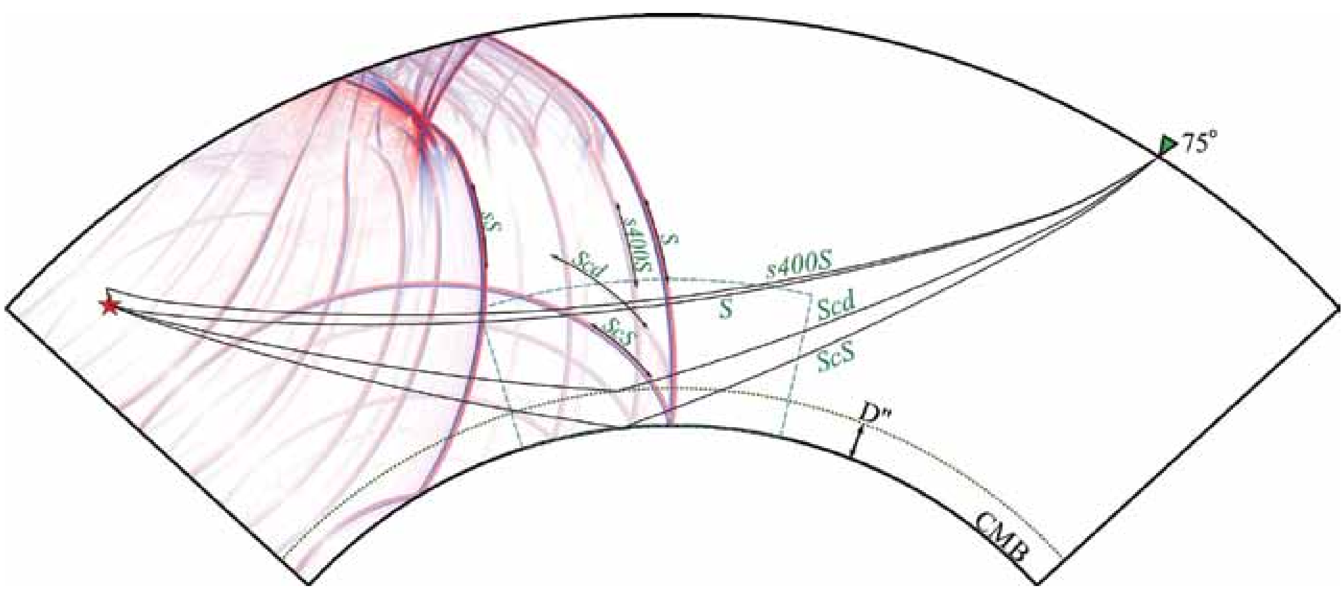

The SH- velocity wave field is shown at propagation time of 600 sec for a 500 km deep event with dominant source period of 6 sec. Selected wave fronts are labeled with black double-sided arrows. Ray paths are drawn in black for an epicentral distance of 75º. The calculation is done for the D" discontinuity (indicated with a dashed green line) model of Fig. 1. Non-linear scaling was applied to the wave field amplitudes to magnify lower amplitude phases.

A Narrow, Mid-Mantle Plume below Southern Africa

Daoyuan Sun *(Carnegie Institution of Washington),* **Don Helmberger** *(California Institute of Technology),* **Michael Gurnis** *(California Institute of Technology)*

Current tomographic models of the Earth display perturbations to a radial stratified reference model. However, if these are chemically dense structures with low Rayleigh numbers, they can develop enormous relief, perhaps with boundaries closer to vertical than radial. Here, we develop a new tool for processing array data based on such a decomposition referred to as a multi-path detector which can be used to distinguish between horizontal structure (in-plane multi-pathing) vs. vertical (out-of-plane multi-pathing) directly from processing array waveforms. We demonstrate the usefulness of this approach by processing samples of both P and S data from the Kaapvaal Array in South Africa. The result displays a narrow plume-like feature emitting from the top of the large African low-velocity structure in the lower mantle. A detailed SKS wavefield is assembled for a segment along the structure's southern edge by combining multiple events recorded by a seismic array in the Kaapvaal region of southern Africa. With a new processing technique that emphases multi-pathing, we locate a relatively jagged, sloping wall 1000 km high with low velocities near it's basal edge. Forward modeling indicates that the plume's diameter is less than 150 km and consistent with an iso-chemical, low-viscosity plume conduit.

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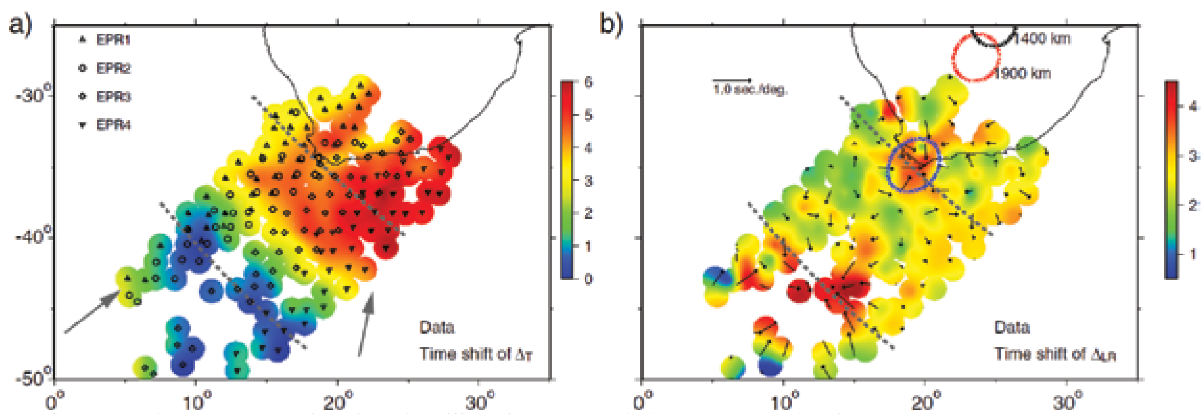
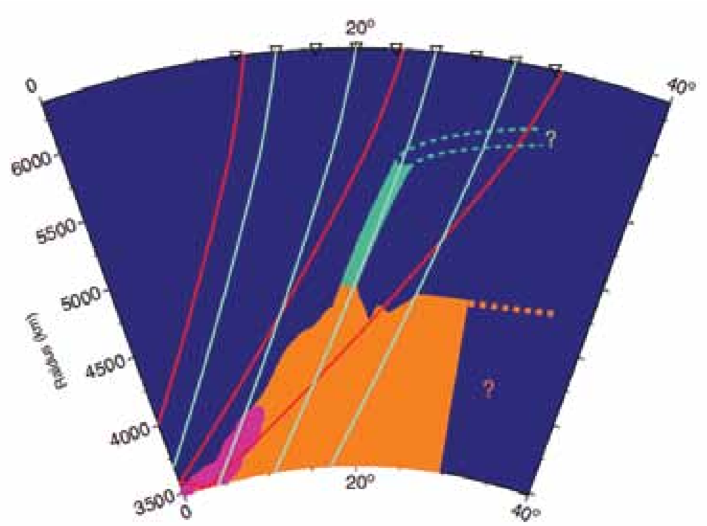
Acknowledgements: The waveform data were obtained from IRIS. This work was supported by NSF grant MCG.00021-NSF.CSEDIFINE.



a) The travel time delay ΔT and b)multi-pathing differential values ΔLR indicate the boundaries of the superdome.



With a new processing technique that emphases multi-pathing, we find that the plume's diameter is less than 150 km and consistent with an iso-chemical, low-viscosity plume conduit (green). A 2D cross-section sampling the plume is displayed idealized with a uniform reduction of 3% inside the superdome (yellow).

Absence of Ultra-Low Velocity Zones at the CMB

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Seismological studies of Earth's core mantle boundary (CMB) show evidence for heterogeneities and structures on many scales. Among the most enigmatic structures detected at the CMB are ultra-low velocity zones (ULVZs). ULVZs are thin layers of strongly reduced seismic velocities that have been detected at the CMB in several locations. Typical ULVZ thicknesses are on the order of 5 to 40 km with velocity reductions of up to 10 and 30% relative to 1D velocity models for P- and S-waves, respectively. Some studies also indicate strongly increased ULVZ density relative to the surrounding mantle. Several models for ULVZ have been proposed including partial melting of mantle material and iron enrichment of perovskite and/or post-perovskite. The knowledge of the global distribution of ULVZs on Earth is essential for distinguishing between different ULVZ hypotheses. Unfortunately, only a limited number of regions covering roughly half of the CMB area have been probed to date.

Here we use an aftershock of the relatively large Hawaiian earthquake on October 15, 2006 (moment magnitude, Mw ~ 6.7) that was recorded by roughly 1100 stations from several networks in the western United States and Canada. Using core reflected P-waves (PcP) allows the study of a previously unprobed region just north of the large low shear velocity province (LLSVP) beneath the Pacific Ocean. The large amount of high quality stations sampling this patch of CMB allows unprecedented waveform quality to sample the fine scale structure of the CMB.

Stacked seismograms show PcP amplitudes clearly out of the background noise level, but no evidence for a PcP precursor that would indicate ULVZ existence. Synthetic modelling of a large parameter space of ULVZ properties indicates that this region of the CMB is likely devoid of ULVZ, although ULVZs with thicknesses below the vertical resolution level (~5 km) of PcP might exist.

References

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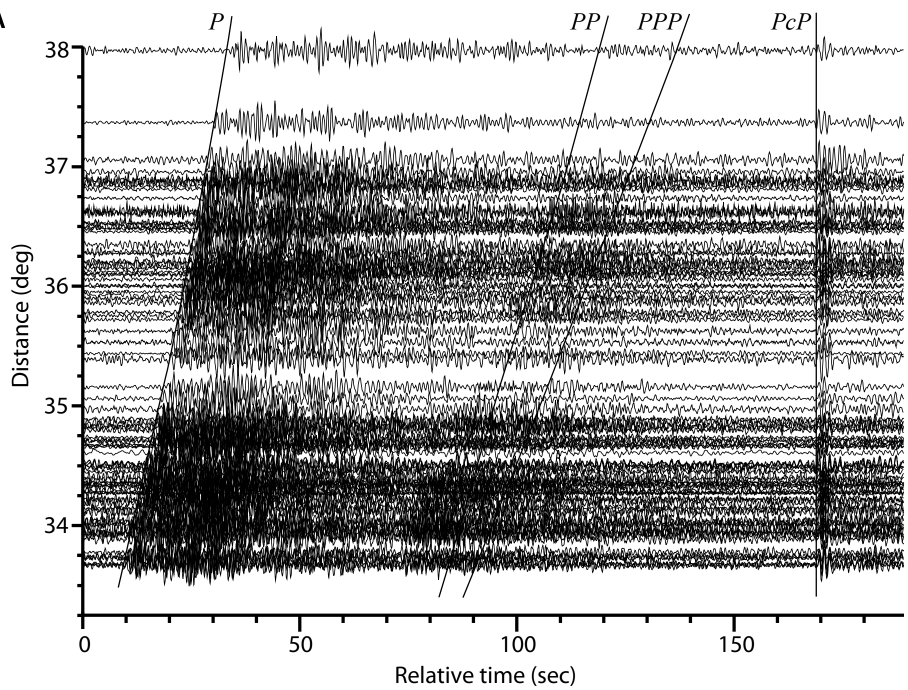
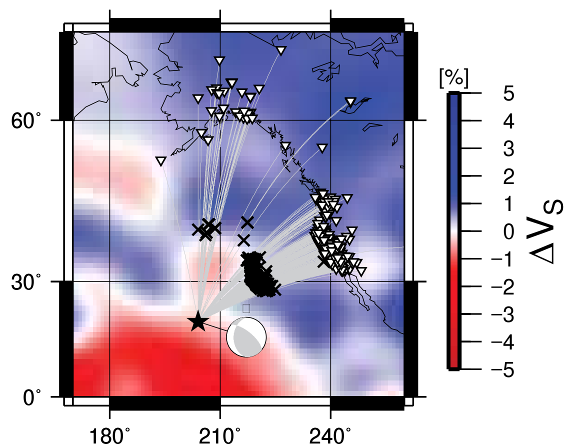
A



B



A) Seismic section (ground velocity) of the recorded aftershock recorded at the Southern California seismic network. Data have been bandpass filtered with corner frequencies of 0.7Hz and 2 Hz. Data have been aligned on the theoretical PcP arrival for IASP91. Theoretical arrival times for several body waves are marked. B) Map of source (star) and receiver (inverted triangle) combination. PcP CMB reflection points are marked by crosses. Background shows S-wave seismic velocities from a tomographic model (Ritsema and van Heijst, 2002). Great circle paths are marked as thin grey lines and the double couple solution for the earthquake is also given.