

S2.1 Seismic observations of fine-scale heterogeneity in Earth's inner core

KEITH D. KOPER AND FELIPE LEYTON

Dept. of Earth and Atmospheric Sciences, Saint Louis University, St. Louis, USA

The discovery of seismic energy apparently backscattered from Earth's inner core strongly implies that heterogeneities with scale lengths of 1-10 km exist within the inner core. The specific nature of the heterogeneities is unclear and possibilities include pockets of partial melt, boundaries between misaligned grains of iron, and the existence of localized chemical impurities. Here we present results from a theoretical study of *PKiKP* coda envelopes synthesized with various single-scattering theories. We find that it is not possible to generate the emergent, spindle shaped *PKiKP* codas that are commonly observed in the distance range of $50^\circ - 70^\circ$ with heterogeneities in the lower mantle, topography on the core-mantle boundary, or topography on the inner-core boundary. Volumetric heterogeneity within the outer portion of the inner core is indeed required to match the observations.

We also review the seismic evidence for inner core scattering and present new observations from a global analysis of precritical *PKiKP* coda waves recorded at small-aperture (10-20 km) arrays. We find an average value of $Q_c \sim 500$ for the *PKiKP* coda waves, implying that scattering attenuation is at least as important, and probably more so, than intrinsic attenuation. Finally, we also find evidence for lateral changes in the scattering strength of the inner core, with the areas beneath Eastern Asia and the Western Pacific having stronger scattering than areas beneath the Atlantic and the Americas. Therefore, there appears to be a rough anti-correlation between scattering and anisotropy in the inner core; however, better geographical sampling is needed to confirm this idea.

S2.2 Constraints from seismic anisotropy on deformation and mineralogy of the lowermost mantle beneath Siberia

JAMES WOOKEY^a, J-MICHAEL KENDALL^a, STEPHEN STACKHOUSE^b, JOHN BRODHOLT^b AND G. DAVID PRICE^b

^a *Department of Earth Sciences, University of Bristol, Bristol, UK*

^b *Department of Earth Sciences, University College London, London, UK*

The discovery of a post-perovskite polymorph of MgSiO₃ in the lowermost mantle has provided a potential explanation for many of the seismic properties of this enigmatic region of the deep Earth. Exploring the efficacy of this phase to explain lowermost mantle anisotropy requires knowledge of its deformation mechanism. Recent work (Cordier et al, EOS, 2005; Oganov et al, Nature, 2005; Miyajima et al, EOS, 2005; Merkel et al, Science, 2006) using different methodologies have suggested three different candidates for the slip system of post-perovskite; however, improved seismological evidence is needed to help discriminate between them. To this end we have assembled a dataset comprising Hindu-Kush events recorded at the NWT-POLARIS array in Northern Canada and Northwest Pacific events recorded on the German Regional Seismic Network. These provide event-station pairs with epicentral distances around 80 degrees. At these distances the S-phase turns just above D", while the ScS phase samples it. This gives us a seismic dataset which images a region of the lowermost mantle beneath Siberia from two different - nearly orthogonal - azimuths. We apply a differential S-ScS shear-wave splitting technique (Wookey et al, GJI, 2005), extended to use array data, to isolate the anisotropic contribution from the lowermost mantle. This technique also enables the resolution of a more general style of shear-wave anisotropy than is usually assumed, and this is augmented by being able to image two azimuths. The shear-wave splitting we measure is incompatible with the simple, radial style of anisotropy generally assumed for D". We quantitatively compare our measurements with estimates of anisotropy for the perovskite and post-perovskite polymorphs of MgSiO₃ determined using ab initio modelling (Stackhouse et al, EPSL, 2005), assuming the candidate slip systems. By assuming a likely deformation direction from the tectonic history of the region we determine that the anisotropy is best explained by post-perovskite LPO with a [-110](110) or [100](010) slip system.

S2.3 Global mantle tomography: limitations and the future

LAPO BOSCHI

Institut für Geophysik, ETH Zürich, Switzerland

Recent, important achievements in the field of global tomography, with potentially important implications on our understanding of the Earth, have been originated from clever applications of a fast technological progress, and/or from the formulation of increasingly accurate theoretical descriptions of seismic phenomena. Tomographic algorithms limited by the ray-theory approximation have been surpassed by efficient finite-frequency methods, based on sophisticated analytical formulations or the numerical integration of the equations of motion, combined with the concepts of adjoint method and backpropagation. Accuracy and resolution of global tomographic images can be quantified more precisely than in the past, computing directly the corresponding full resolution and covariance matrices. I illustrate a number of tomography exercises where I have applied these new techniques, and use them to explore the issues of model quality and resolution, the selection of appropriate regularization schemes, and the propagation of errors in linearized tomography.

S2.4 A global study of mantle discontinuities using receiver functions

JENNIFER ANDREWS AND ARWEN DEUSS

Bullard Laboratories, Department of Earth Sciences, Cambridge University, UK

The mantle transition zone is a vital region for helping us to understand mantle dynamics, and its discontinuities allow us to form direct links between seismological observations and the theory and experiments of high temperature and pressure mineral physics. We have therefore processed receiver functions for 50 of the GSN network stations in two frequency bands (0.01-0.2Hz and 0.02-0.5Hz), to study the global nature of the mantle discontinuities. The signals from the ‘410’ and ‘660’ discontinuities are ubiquitous and strong and we see no clear evidence for other global discontinuities. In our higher frequency band, the upper mantle shows a consistently greater number of signals than the lower mantle, with possible signals from upper mantle interfaces such as the Lehmann and X discontinuities near 220 and 350km depths. At a few stations we observe a signal within the mantle transition zone, near 500km depth, but mostly the signal from the ‘520’km discontinuity is absent. This is true for regions where it is observed in other data types such as SS precursors (Deuss & Woodhouse, 2001). We see some signals from the lower mantle in the region 850-1050km, but no feature appears at a globally uniform depth. The signals from the ‘660’ region appear to be complex. In agreement with previous studies (Peterson et. al., 1993, Simmons & Gurrola, 2000), we see both very broad and multiple peaks near this depth. When processed at slightly higher frequencies, many of the broad peaks also resolve into multiple peaks, suggesting a widespread role for phase changes in the non-olivine component of a pyrolite mantle (possibly the garnet to pyroxene transition). The relations between multiple phase transitions at this depth may be instrumental in constraining mantle conditions and hence help to distinguish between different modes of mantle dynamics.

S2.5 D” structure for P and S-waves using source and receiver arrays

JEREMY CHALONER, CHRISTINE THOMAS AND ANDREAS RIETBROCK

Department of Earth and Ocean Sciences, University of Liverpool, Liverpool, UK

A simplified migration method is used to investigate D” structure under the Gulf of Tonkin off the coast of Vietnam, using earthquakes in the Philippines recorded at the KNET and GHENGIS arrays in the Tien-Shan region. 10 earthquakes are recorded at between 5 and 15 stations. These earthquakes have bounce points at the core-mantle boundary (CMB) covering a lateral extent of 3 degrees. We find evidence for the presence of a reflector in D” with height varying between 290 and 190 km above the CMB. We

interpret this as a discontinuity in P and S-wave velocities. The apparent height of the discontinuity above the CMB is the same for both P and S-waves. The polarities of the reflected waves suggest that the discontinuity represents a decrease in V_P and an increase in V_S , consistent with recent calculations of the properties of the post-perovskite phase transition. There is also a suggestion of the presence of a second reflector closer to the CMB. Synthetic seismograms, produced using the reflectivity method, are used to test the robustness of the processing method in order to determine its sensitivity to variations in the background 1D velocity model used to perform the migration.

Subsequently, we extend the migration technique to using source arrays. This technique requires multiple seismic events with similar source mechanisms, so we used recordings of the French nuclear tests on Mururoa in 1995-96 recorded in North America, sampling D'' beneath the eastern Pacific. A discontinuity in P and S-wave velocity was also found here.

S2.6 Investigating the lowermost mantle using migrations of long-period S-ScS data

KIT CHAMBERS^a AND JOHN H. WOODHOUSE^b

^a *Dept. of Earth Sciences, University of Bristol, Bristol, UK*

^b *Dept. of Earth Sciences, University of Oxford, Oxford, UK*

Knowledge of structure in the lowermost mantle is of central importance to our understanding of mantle processes such as the nature of the thermo-chemical boundary layer, mantle mixing and the distribution of compositional heterogeneity, plume formation, and core-mantle coupling. Despite this, the lower mantle is poorly understood. Recent seismological investigations have either concentrated on the use of travel time and amplitude data to retrieve detailed structure over small regions or used global travel time datasets to constrain very long wavelength structure. This study attempts to bridge the gap between these techniques by applying migration processing methods to a global dataset of seismograms.

Here we investigate the lowermost mantle beneath Alaska and North Central Asia using a phase stripping technique, which removes the *S* and *ScS* phases in order to isolate more subtle arrivals from the lowermost mantle. Two migration methods were applied to locate scattering bodies. The first, a simple backprojection, is useful for identifying regions of strong scattering. The second migration scheme uses weights based on the Generalised Radon Transform (GRT). For the GRT migration, a forward model for the scattered wavefield from a distribution of point heterogeneities was developed using the Born approximation and ray theoretical Green's functions. The influence of biases in the source-receiver distribution as well as the spatial resolution of our results was tested by computing synthetic datasets using various distributions of point scatterers and the forward model for the scattered wavefield.

Our results suggest the presence of a variety of structures in the lowermost mantle, including complicated structure near the CMB and a D'' reflector. In some regions our results can be simulated using fairly simple distributions of point scatterers, elsewhere the results require more complicated structures. The results suggest that the D'' reflector is not a globally present feature, nor a continuous surface thus requiring that the D'' discontinuity is caused by either localised structures, such as thermal or chemical heterogeneity, or a global boundary with a variable impedance contrast.

S2.7 Seismic and physical reference models for the Earth's mantle

L. COBDEN^a, F. CAMMARANO^b AND S. GOES^a

^a *Department of Earth Science and Engineering, Imperial College London, UK*

^b *Berkeley Seismological Laboratory, University of California Berkeley, USA*

An accurate one-dimensional physical model of the mantle lays the foundations for understanding the dynamics and evolution of the Earth's interior, and provides a reference against which three-dimensional structures can be described quantitatively in terms of the dynamically important variables, temperature and composition. The simplest possible physical model for the mantle is one with constant chemical com-

position, convecting as a whole. This results in a structure with thin boundary layers at the top and bottom, and an adiabatic temperature gradient in between. Previous modelling studies have indicated that it is difficult to reconcile such a structure with seismic data, when it is assumed that the chemical composition is pyrolytic and the temperature profile follows a 1300°C adiabat (Cammarano et al., EPSL 232, 2005). One possible explanation for this result is that the actual thermal structure of the mantle deviates from a 1300°C adiabat. We test this possibility, by designing a set of 1-D thermal structures which cover a range of potential temperatures and temperature gradients. These structures lie within limits imposed by the values of inferred MORB-source temperatures and mineral phase-transition temperatures. For each structure, we generate a large number of synthetic velocity models, using datasets of mineral parameters which lie within published uncertainty bounds. We employ several different methods to extrapolate the mineral parameters to high temperatures and pressures. We then calculate the proportion of velocity models per structure whose seismic behaviour gives a close fit to real, global seismic data. This allows us to assess which thermal structures are most consistent with seismic observations, and whether or not a 1300°C adiabat is the best representation of average mantle temperature structure. We find that none of the mantle thermal profiles which are seismically plausible are simultaneously geodynamically feasible. This implies that seismic reference models are probably being influenced by three-dimensional variations in chemistry.

S2.8 Structural transitions in the inner core: implications for solidification

VERNON F. CORMIER

Physics Department, University of Connecticut Storrs, USA

Combined results of modeling inner core-penetrating seismic body waves suggest an inner core model consisting of 3 separate regions, which may differ only in fabric. These regions are (1) an uppermost region of 20 to 100 km thickness that highly attenuates PKIKP waves, nearly isotropic, with significant lateral variation that may be related to lateral variations in the initial solidification process of the inner core; (2) a middle region from 100 km to 700 km depth from the inner core boundary, with increasing anisotropy, decreasing attenuation, and smaller lateral variations in elasticity and attenuation; (3) an innermost inner core below 700 km depth (500 km radius) with much stronger anisotropy, little or no attenuation or scattering, possibly consisting of a more perfectly aligned fabric of much larger iron crystals compared to the regions above it. The transitions between these regions may occasionally appear sharp due to the effects of grazing incidence to gradient transitions of heterogeneous fabric. Significant lateral variations characterize the uppermost inner core. A transition in P velocity, intrinsic and/or scattering attenuation, and anisotropy is detectable between longitude 20° W to 140° E, concentrated in an equatorial zone between 35° S beneath the Indian Ocean to 60° N underneath Asia. This uppermost region seems to be correlated with a region of strong magnetic secular variation and may represent newly solidified core in an area where vigorous compositional convection in the outer core coincides with the new crystal growth in the inner core. An apparent correlation of anomalies in the inner-core boundary region structure with core-mantle boundary structure may be difficult to reconcile with a consistent rate of differential rotation between the inner core and mantle. The transition to the innermost, strongly anisotropic, region of the inner core must be spread out over 50-100 km to agree with observations of PKIKP waveforms. This deepest transition may eventually be explained by as yet unknown processes of flow and re-crystallization in the inner core, and hence not require distinct episodes of inner core formation.

S2.9 The nature of the 660 km discontinuity from global seismic observations of SS and PP precursors

ARWEN DEUSS^a, SIMON A.T. REDFERN^a, KIT CHAMBERS^b AND JOHN H. WOODHOUSE^b

^a *Bullard Labs, University of Cambridge, UK*

^b *Dept. of Earth Sciences, University of Oxford, Oxford, UK*

The 660 km discontinuity, which separates the Earth’s upper and lower mantle, has been detected routinely on a global scale in underside reflections of precursors to SS waves. The characteristics of this discontinuity determine the convective style of the mantle, distinguishing potentially between whole-mantle and layered-mantle convection. The key question is whether this discontinuity is caused by a phase transition in olivine or by a change in chemical composition. Answers have been sought in seismology by studying the detailed seismic characteristics of this discontinuity and comparing them with predictions from mineral physical models of the mantle.

Here, we report observations of this discontinuity in many different regions, using precursors to PP waves. The apparent absence of the 660 km discontinuity in previous seismic studies of PP precursors has posed major problems for models of mantle composition. We find a complicated structure, showing single and double reflections ranging in depth from 640 km to 720 km, that requires the existence of multiple phase transitions in olivine and garnet at the base of the mantle transition zone. The results are consistent with a pyrolite mantle composition, but require additional lateral variations in temperature and/or minor elements such as Al in the mantle transition zone. This will influence lower mantle slab penetration and upwelling of plumes differently from region to region. Thus, the characteristics of the 660 km discontinuity and its impedance contrast can no longer be taken as a global constant when modelling mantle convection.

S2.10 New constraints on inner core structure from differential waveform analysis of PKP core phases at global scale

RAPHAEL GARCIA ^a, SÉBASTIEN CHEVROT ^b AND HRVÖJE TKALČIĆ ^c

^a *Equipe Etudes Spatiales et Planétologie, Institut de Physique du Globe de Paris, UMR7154 CNRS, Paris, France*

^b *Laboratoire de Dynamique Terrestre et Planétaire, UMR5562 CNRS, France*

^c *Atmospheric, Earth and Environment Sciences, Lawrence Livermore National Laboratory, USA*

PKP waveforms are the main source of information regarding lowermost mantle and core seismological structures. An extension of our previously developed Simulated Annealing algorithm to analyze body waves is presented. It allows us to resolve the interference between the different PKP phases and their corresponding depth phases (pPKP and sPKP), which makes possible to process shallow earthquakes previously discarded, and thus to improve the sampling of the deep Earth. The algorithm is applied to various PKP waveform data sets in order to retrieve differential travel times and amplitude ratios of the core phases, and to demonstrate its efficiency. The introduction of shallow event data confirms the hemispherical pattern of the inner core anisotropy and the increase of the inner core quality factor with depth. An anti-correlation is found in the upper 300 km of the inner core between differential travel time residuals and amplitude ratios. This anti-correlation can only be explained by a high attenuation of fast rays inside the inner core. Relative amplitude ratios and waveforms of core phases are also analyzed in order to detect inner core discontinuities below the inner core boundary. We demonstrate that relative amplitude ratios are highly sensitive to velocity discontinuities inside the inner core. Consequently the absence, at global scale, of both marked features on DF/AB amplitude ratios at large epicentral distances and secondary DF arrivals on stacked waveforms exclude the presence of a discontinuity in the inner core at global scale. Unfortunately, the low number of polar data does not allow to reach a signal to noise ratio good enough to perform such an analysis for anisotropic rays paths.

S2.11 Global shear velocity heterogeneity in the lowermost mantle based on finite-frequency traveltimes tomography with multiscale parameterization

SHU-HUEI HUNG ^a, LI ZHAO ^b, LING-YUN CHIAO ^c AND BAN-YUAN KUO ^b

^a *Department of Geosciences, National Taiwan University, Taiwan*

^b *Institute of Earth Sciences, Academia Sinica, Taiwan*

^c *Institute of Oceanography, National Taiwan University, Taiwan*

We present the global distribution of shear velocity heterogeneity in the D'' region of the lowermost mantle constrained by a joint inversion of differential S (or diffracted S)-SKS and ScS-S travel time residuals measured by long period shear waveforms. We compare the velocity models derived from different forward theories and parameterization approaches. Infinite-frequency ray theory, ray-based finite-frequency theory, and normal mode-based finite-frequency theory are utilized to compute the Fréchet derivatives of observed residual data with respect to three-dimensional S-velocity perturbations. We obtain the 3-D velocity models through regular grid parameterization with *a priori* correlation constraints as well as multiscale wavelet-adaptive parameterization having variable resolutions subject to the data sampling conditions. The tradeoffs between model variance and data misfit are assessed to compare different types of the models at the same χ^2 values. The most distinct difference among the comparative models lies in the parameterization and regularization scheme invoked in the inversion. While all the optimal solutions reveal the dominance of long-wavelength, degree-2 variations at the base of the mantle, there exists a dissimilarity between the ray obtained models and finite-frequency ones using the multiscale parameterization. The two finite-frequency models indicate better lateral correlations and similar root-mean-squared amplitude variations of velocity perturbations in the bottom 200 km of the mantle. Moreover, the multi-scale inversion yields significantly lower model variances and improves the resolution in good informative regions, leading to essentially different velocity heterogeneity within the D'' layer beneath Siberia between the ray-based and finite-frequency models.

S2.12 Mean-term tectonomagnetic effects from intermediate and deep focus earthquakes

FARSHED H. KARIMOV

Institute of EQ Engg&Seismology, Academy of Sciences, Tajikistan

Stress dynamics is transforming to tectonomagnetic anomalies through rocks magnetisation response and electric currents stipulated by electrokinetic effects. An experience of tectonomagnetic effects' observation in Central Asia region evidences that deep and intermediate focus earthquakes in Hindu-Kush seismic zone hypocentred in 200-400 km depth generate mean-term bay-like anomaly in local geomagnetic field variations on sites distant at 300-500 km aside within middle and far zones. The anomalies' time durations are about days through month.

Bay-like shapes of the anomalies seemingly reflect the elasticity-plasticity mechanism for stress accumulation and release. The larger is the magnitude M , i.e. the power of the preparing earthquakes the larger are the time T and space R scales of the relevant anomaly. The time duration of the anomalies in the middle zone and short time anomalies in the far zone can be the result of stresses time travel from the near zone to the observational site.

The comparison of duration anomalies in the near, middle and far zones shows that tectonic stresses are traveling from the focus preparation zone with the speed about 1-10 km per day. The mosaic shaped tectonomagnetic anomalies space distribution reflects rather inhomogeneous tectonic stresses distribution in the preparing focus.

S2.13 Observations of anomalous out of plane phases beneath the Cocos plate

TADASHI KITO, CHRISTINE THOMAS AND ANDY HEATH

Dept. of Earth and Ocean Sciences, Jane Herdman Laboratories, University of Liverpool, Liverpool, UK

Subducted slabs have been detected deep into the lower mantle by looking at tomographic images, however, other seismic detections of subducted slabs at present are sparse. We search for out-of-plane anomalous arrivals of seismic waves to detect subducted slabs in the mid- and lower mantle: these anomalous arrivals propagate from the source to a structure in the mantle (e.g. a subducted slab) reflect at the surface of this structure in the mid- or lower mantle and from there propagates to the stations. Since we select earthquakes where the direct wave does not interact with a subduction zone other than originating in it, these anomalous arrivals will display a backazimuth deviation and therefore arrive as

out-of-plane waves. At this stage we use broadband data recorded in California from intermediate- and deep focus events in South America which were analysed with seismic array techniques. The data were filtered with a low pass filter of 1s to avoid high frequency noise. All traces were deconvolved with the P beam to get simple waveforms. The direct P waves and depth phases have been subtracted from the data to avoid contamination of these phases. First, we performed a slowness and backazimuth analysis of small time windows to identify the out-of-plane waves. In order to locate the reflection points of the observed out of plane phases within the entire mantle a migration method was applied to the observed and corresponding synthetic data using a dense 3D grid. Several out-of plane arrival have been detected that arrive from the direction of central America and have likely been reflected at the subducting Cocos plate.

S2.14 Heterogeneities of the Earth's solid core from PKiKP coda waves

D.N. KRASNOSHCHIEKOV, P.B. KAAZIK AND V.M. OVTCHINNIKOV

Institute of Dynamics of Geospheres of the Russian Academy of Sciences, Moscow, Russia

We report new data on PKiKP coda waves recorded after USSR and China underground nuclear explosions (UNEs) at distances of PKiKP precritical reflection. To detect PKiKP coda waves we use source arrays consisted of Semipalatinsk UNEs registered by a station, and China explosions recorded by seismic arrays. This new enhanced dataset confirms absence of a constant depth global isotropic reflector all through 300 km below the ICB. In the same time, presence of local reflectors in some portions of the outermost inner core is evidenced by detection of distinct arrivals with expected slowness and backazimuth calculated from the array data. This demonstrates laterally non-homogeneous nature of the outermost inner core likewise it was observed for its surface. The research described was made possible in part by contribution from the President Grant MK-1600.2005.5.

S2.15 Modeling transition zone structure using multiple seismic discontinuity phases

JESSE F. LAWRENCE AND PETER M. SHEARER

IGPP, Scripps Institution of Oceanography, UCSD, La Jolla, CA, USA

Mantle transition zone discontinuities reflect and convert different amounts of seismic energy depending upon the wave type and incidence angle. In this study we use multiple seismic discontinuity phase observations to characterize the structure of the mantle transition zone. SS-precursors (SdS underside reflections) have long been used to resolve global impedance contrasts at about 410 km, 520 km, and 660 km depth. A recent global analysis of P-to-S converted phases (Pds) yields an average transition zone thickness (~ 242 km) and a pattern of lateral variations very similar to SdS results. While some individual stations may record P520s phases, globally the P520s phase is incoherent. Global analysis of PP-precursors (PdP underside reflections) demonstrates that while P410P and P510P have expected amplitudes, P660P has a very low amplitude, as noted by Estabrook and Kind (1996). The effects of interfering waves arriving simultaneously with P660P can be minimized by examining the radial component rather than the vertical component. Yet, even without interfering signals, P660P has a surprisingly low amplitude. We globally stack Pds, SdS, PdP, and Ppdp (topside P reflections) in order to constrain a best-fitting 1-D model of shear velocity, compressional velocity and density that explains all of the observed amplitude variations. Waveform modeling indicates that the 410-km discontinuity represents a large contrast in V_s ($\sim 6\%$), V_p ($\sim 5.5\%$), and density ($\sim 6\%$); at 520 km, V_p ($\sim 1.5\%$) and density ($\sim 2.3\%$) increase whereas V_s does not ($< 0.3\%$); at 660 km, V_s ($\sim 5\%$) and density ($\sim 4.5\%$) increase significantly whereas V_p has a small contrast ($\sim 1\%$) above a steep bottom-side gradient. This model of V_p , V_s , and density can be compared to elastic constants obtained through experimental and theoretical studies to infer the rheological and chemical state of the mantle.

S2.16 Spectral-element based seismograms as a basis for diffracted-phase tomography

TARJE NISSEN-MEYER^a, ALEXANDRE FOURNIER^b AND F. A. DAHLEN^a

^a *Dept. of Geosciences, Princeton University, USA*

^b *Laboratoire de Géophysique Interne et Tectonophysique, Université Joseph-Fourier, Grenoble, France*

We aim at extending global tomography to include traveltimes from any phases in a broadband seismogram such as those caused by diffraction, triplications, or caustics. Provided we have high-frequency (≤ 1 Hz) and quality data, we note that the inclusion of core-diffracted arrivals (e.g. P_{diff}) shall drastically improve coverage and resolution of 3-D images of the sparsely sampled D'' region.

To accomplish this, we need to calculate exact Fréchet sensitivity kernels based on solving the full wave-propagation problem. While known for a while, this idea is still computationally intractable in 3-D, facing major simulation and storage issues (up to 10^{18} Bytes) when global waveforms up to 1 Hz are considered. To circumvent these limitations, we devise a method which is based upon exploring symmetry considerations of the seismic-wave radiation patterns, thereby collapsing 3-D wave propagation to a series of six equivalent 2-D problems, subject to different (multipole) source types while accounting for the full 3-D complexity of sensitivity kernels. As no existing wave-propagation algorithm meets the requirements, we develop a dedicated 2-D spectral-element method for spherically symmetric earth models as needed to compute the Green functions underlying the sensitivity kernels. The method has been extensively tested against a variety of reference solutions for simplistic settings such as elastostatics, source radiation, wave propagation and energy conservation upon a homogeneous solid, exposing very high accuracy and efficiency. We present some of these validation tests and address optimal grid generation, parallelization and the discretization of a PREM background model for up to 1 Hz waveforms. These waveforms will then form the backbone in using diffracted-wave arrival times for tomographic inversions from which we anticipate lowermost mantle images with unprecedented detail and sharpness.

S2.17 High temperature anomalies oceanward of subducting slabs at the 410-km discontinuity

MASAYUKI OBAYASHI, HIROKO SUGIOKA, JUNKO YOSHIMITSU AND YOSHIO FUKAO

Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology, Japan

Our P-wave whole mantle tomography revealed a low velocity region oceanward of the Northern Honshu slab of the Pacific plate at depths around the 410-km seismic discontinuity. Resolution tests and scrutiny of the travel time residuals for the ray paths passing through the low velocity region indicate that this anomaly is a resolvable feature and not an artifact due to the strong slab anomalies. The existence of the slow anomalies is also supported by the analysis of the P wave records from the J-array (a large-aperture seismic array in Japan) for a Bonin earthquake. The P arrivals to Northern Honshu (at epicentral distances of 13-20°) are strongly triplicated because of the 410-km discontinuity. The later arrivals along the retrograde branch, where ray paths pass through the low velocity region, are anomalously slow. Comparison of the observed and synthetic waveforms indicates not only slow anomalies but also depression of the 410-km discontinuity. This depression represents the direct evidence for the low velocity zone of primarily thermal origin. An excess temperature of 200 K and the associated fractional melt of less than 1 % can explain both the results of the tomographic and waveform analyses.

S2.18 Whole mantle V_P/V_S tomography

SATOKO OKI, YOSHIO FUKAO AND MASAYUKI OBAYASHI

IFREE/JAMSTEC, Japan

Understanding of tomographic image in terms of dynamics of the Earth's interior requires knowledge of what causes lateral variation of seismic wave velocities. One way of distinguishing origins of heterogeneity

is to compare observed tomographic velocity anomalies to those predicted by mineral physics. The purpose of this study is to model three-dimensional V_P/V_S ratio variation which is suitable to be measured for laboratory experiments but rarely derived seismologically. Modeling is made using broadband S - P differential travel times, which carry P and S information along similar ray paths with little bias from origin time determinations. The V_P/V_S tomographic model so derived can be directly compared to laboratory measurements.

Picking S wave arrival is in general a difficult task, which is often overcome by waveform correlation technique. Since our primary interest is S - P differential travel time, rather than S arrival time, we cross-correlate the observed S waveform with that synthesized from the observed P waveform by correcting the attenuation effect, which is characterized by two parameters t^* and f_0 . The reference frequency f_0 is conventionally set to 1 Hz, with which we, later, found a systematic discrepancy of about 0.5 s between the cross-correlated and handpicked S - P times. This discrepancy disappears when the reference frequency is taken to be 2 Hz, indicating that 2 Hz is more appropriate than 1 Hz as the reference frequency of teleseismic body waves. We obtained about 15,000 S - P times using this reference frequency.

V_P/V_S tomography can be modeled by the use of measured S - P times and highly-resolved P tomography of *Fukao et al.*, [2001]. The consistency of our handpicked P times and the predicted travel times of their model enables us to solve for V_P/V_S diffraction as a linear inverse problem. Using the result of the obtained V_P/V_S tomography and the P velocity model, a three-dimensional S distribution can be derived as $V_S = V_P / (V_P/V_S)$. These models are compared to each other to find regions which, for instance, are anomalously slow in S wave, yet are very different in terms of V_P/V_S ratio. We also apply our inversion technique to obtain a three-dimensional distribution of R , the ratio of fractional S -velocity perturbation to fractional P -velocity perturbation.

S2.19 Detection of subducted crustal material in the mid-mantle from asymmetric PP reflections

SEBASTIAN ROST^a, EDWARD J. GARNERO^a AND QUENTIN WILLIAMS^b

^a *Department of Geological Sciences, Arizona State University, USA*

^b *Department of Earth Sciences, University of California Santa Cruz, USA*

The high-frequency P-wavefield contains precursory energy to PP, a P-wave once reflected at the free surface, that is often used to study the structure of the upper mantle. Besides underside reflections from upper mantle discontinuities additional energetic arrivals with shorter travel times than PP can be detected in the 90 to 110 deg distance range. These have been identified to originate from asymmetric reflections at the surface in the distance range of the upper mantle P-wave triplication, i.e., about 20 deg from source or receiver. Using array data from the Canadian Yellowknife Array (YKA) and a frequency-wavenumber analysis, we measure the complete slowness vector for PP and all precursors for 21 strong earthquakes in the western Pacific in the distance range from 95 to 115 deg. We identify 116 PP precursors that are not related to mid-point reflections from upper mantle discontinuities, i.e., asymmetric and off great-circle path PP precursors. We apply a ray-theoretical backtracing algorithm to map distinct reflection locations in the mantle that uniquely match observed PP precursor slowness, backazimuth, and traveltimes. We find that many precursors likely originate from shallow depths less than 200 km. However, almost one half of all precursors are mapped to depths below 400 km, extending to 1000 km depth, beneath W/SW Pacific subduction zones. The deep reflectors are highly correlated with seismically fast zones in tomographic models, and thus are likely related to subduction processes. Our mineral physical modeling shows that at depths deeper than 660 km, the harzburgite to basalt interface is associated with a 5% impedance contrast. This contrast can explain the observed precursor amplitudes. The harzburgite-basalt interface is expected to be less altered by magmatic and metasomatic alteration during subduction relative to the basalt-perovskite boundary where the impedance contrast is slightly lower, but crucially depends on the silica content of the basalt. As silica is readily transported by devolatilizing fluids and hydrous magmas, we expect that the impedance contrast of the basalt-pyroxene interface will be reduced relative to that theoretically calculated for unaltered basalt at these depths. Therefore, our data likely shows evidence for the remnants of the oceanic Moho material down to depths

of at least 1000 km beneath two major subduction zones in the Pacific. These results further confirm the hypothesis that oceanic lithosphere penetrates into Earth's lower mantle.

S2.20 Imaging the 410-km discontinuity structure beneath the Central Pacific using PP-precursors

NICHOLAS SCHMERR, EDWARD J. GARNERO AND SEBASTIAN ROST
Department of Geological Sciences, Arizona State University, USA

Using precursory energy to the seismic phase PP, we map the local topography of the 410-km discontinuity in the central Pacific and also search for other mantle reflectors in this region. The underside reflection of PP energy off discontinuities is sensitive to the topography and the impedance jump on these boundaries, and provides a powerful probe for understanding mantle dynamics, elastic structure, and composition. To achieve this, we geographically bin and stack approximately 7000 broadband seismograms obtained from various data centers such as IRIS and the CNSN. The bouncepoints of these seismograms sample a region in the central Pacific extending over 4500×4500 km, centered on the Big Island of Hawaii. Data are stacked along predicted move-outs for underside reflections from different upper mantle depths. Stacks show significant contamination when including records at distances known to contain interfering phases. We explore the effects on resulting topography of correcting for different predictions of upper mantle heterogeneity. The sharpness of the 410 phase boundary, as well as scale lengths of topography, are investigated by pre-stack low-pass filtering data at different corner frequencies. Our results are compared to 410 topography recently imaged by a dataset of 4500 SS precursors that samples the same area. In contrast to the S-wave dataset, we do not observe underside P-wave reflections off the 660-km discontinuity, consistent with previous P studies. The pattern of relief on the 410-km discontinuity agrees with our previous SS results, although the PP dataset exhibits an increase in the peak-to-peak amplitude of topography by 10-20 km. Weak P reflections from the depths of 520 and 220 km are detected in some of the stacking bins, but do not appear to be continuous across our study region, consistent with the S-wave results. We explore possible scenarios consistent with a non-detection of the 660-km discontinuity in the PP dataset with synthetic modeling. These include a split or double 660, a drop in the PREM impedance contrast across the boundary, or various velocity structures such as gradients. A drop in impedance across the 660 best explains the non-detection of this precursor, consistent with results from previous studies.

S2.21 Geothermal study in Central Kyzylkum desert (Western Uzbekistan)

OLGA SIDOROVA
National University, Tashkent, Uzbekistan

It is a known fact that the heat being the main form of transformation and transfer of the Earth's inner energy determines such fundamental parameter as the temperature of depths which in its turn influences the physical properties of depth, their phase conditions, metamorphic processes and other fundamental properties of the Earth. At present time, no complex of geophysical researches is acknowledged as complete, if the study of heat flows is not included. Heat flow is defined as the total of temperature's gradient varies from place to place, heat flow is more stable deep characteristic and appears to the facet where experiment and theory combine. In Central Kyzylkum a big volume of complex geothermal explorations has been carried out. A unique aspect of the Central Kyzylkum metallogenic province is that deep crystal intrusions have been imaged there by the Soviet Union's Deep Seismic Sounding (DSS) program. This data set has been analyzed with geothermal measurements. It has been found that zones of seismic transparency with low numbers of seismic reflections can be easily identified with a moving filter, and that these transparent zones coincide with zones of density variation and possible alteration. Features of the seismically suggested intrusions of the Central Kyzylkum province have significance for the pattern of hydrothermal convection heat from the intrusions might produce. When magmas invade the middle and upper crust, adjacent pore waters are heated and caused to convectively circulate. The convection

is strongest at the margins of the sill where the horizontal thermal gradients that drive convection are greatest (Cathles et.al., 1997).

S2.22 Deep thermo-chemical slabs beneath the Americas identified from P and S wave tomography, plate history reconstruction and mineral physics

E. STUTZMANN ^a, J. MATAS ^b, Y. REN ^a, R. VAN DER HILST ^c AND J. BESSE ^a

^a *Institut de Physique du Globe de Paris, France*

^b *Ecole normale supérieure de Lyon, France*

^c *Massachusetts Institute of Technology, Cambridge, USA*

Slab structure in the deep mantle is investigated from tomographically inferred P- and S-wave velocity anomalies. We have used a waveform cross-correlation technique on broadband data to measure P1-P2 and S1-S2 differential travel times between 2 stations for a given event and PcP-P and ScS-S for given earthquake-station couple. In order to achieve path coverage as similar as possible for both wave types, we have only kept source-receiver configurations for which we could make both P-wave and S-wave differential measurements. Earthquakes and receivers are located along a great circle path from Alaska to South America. We invert the 20,000 P and S wave differential travel times simultaneously to estimate P- and S-wave speeds in $2^\circ \times 2^\circ \times 200\text{km}$ constant velocity blocks.

We interpret slab structures and unravel subduction history by comparing our Vs tomographic images with reconstructed plate motion from present-day up to 100 Ma. In the upper part of the lower mantle we can recognize the imprint of the most recent phase of the plate history. In the lowermost mantle, the large fast anomalies which is most pronounced in the S-wave models can be associated with Late Cretaceous subduction of the Farallon plate beneath the Aleutian islands and most of the Americas, and perhaps with the Phoenix plate beneath the southern part of South America. Near 2000 km depth, the images record the fragmentation of the proto Farallon plate into the Kula plate in the North and the Farallon plate in the North-East since 80 Ma. Around 1000 km depth, we observe separated fast anomalies that we interpret as, from North to South, the Kula-Pacific, the Juan de Fuca, and the Farallon slabs. This interpretation is validated by comparing the volume and length of slabs estimated from the tomographic images and from plate history reconstruction.

In order to understand the differences between the P- and S-wave velocity anomalies associated with slabs, we interpret the lateral variations of seismic velocities in terms of temperature and bulk chemical composition with respect to an average pyrolytic mantle. We consider lower mantle bulk chemistry models composed of five compounding oxides: MgO, FeO, Al₂O₃, CaO, and SiO₂. We use the partial derivatives of V_p and V_s with respect to temperature and chemical composition computed from a recent compilation of elastic parameters for lower mantle minerals. We show that the slabs beneath North America correspond to cold structures and an harzburgitic bulk composition whereas slabs below central and South America may have a different composition. We also show that the effect of Al cannot be neglected in the interpretation.

S2.23 Variability; chemistry or folded-slab

DAOYUAN SUN ^a, DON HELMBERGER ^a AND PAUL ASIMOW ^b

^a *Seismological Laboratory, California Institute of Technology, Pasadena, USA*

^b *Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, USA*

A lower mantle S-wave triplication with a Scd branch is easily observed beneath regions where subduction has occurred. Sidorin et al. (1999) argued that this arrival could be explained by a small phase-change (1.5%) triggered on mapping S-wave tomography into temperature. Its enhanced strength, in particular regions, is then caused by slab-debris induced velocity increases. Dense S_{cd} waveform sampling indicates highly variable behavior which cannot be explained with this simple assumption. Here we introduce a binary system assuming a slab-dominant (Al-rich) and normal ambient (Fe-rich) set of perovskite to

post-perovskite relationship. The slab-dominant ambient height of phase boundary occurs 50 km lower than the normal level to fit the data.

We also investigated the abrupt fading of Scd strength by introducing still more complex phase-transition involving double-boundaries and transition sharpness. Synthetics generated from such maps predict waveform data quite well suggesting some validity. Furthermore, some of this complexity is expected from present knowledge of mineral physics.

S2.24 Toward seismic tomography based upon adjoint methods

CARL TAPE, QINYA LIU AND JEROEN TROMP

Seismological Laboratory, California Institute of Technology, Pasadena, California, USA

We outline the theory behind tomographic inversions based on 3D reference models, fully numerical 3D wave propagation, and adjoint methods, and we illustrate the approach using 2D examples. Our approach involves computing the Fréchet derivatives for tomographic inversions via the interaction between a forward wavefield, propagating from the source to the receivers, and an ‘adjoint’ wavefield, propagating from the receivers back to the source. The forward wavefield is computed using a spectral element method (SEM) and a heterogeneous wave-speed model, and stored as synthetic seismograms at particular receivers for which there is data. We specify an objective or misfit function that defines a measure of misfit between data and synthetics. For a given receiver, the differences between the data and the synthetics are time-reversed and used as the source of the adjoint wavefield. For each earthquake, the interaction between the regular and adjoint wavefields is used to construct finite-frequency sensitivity kernels, which we call *event kernels*. These kernels may be thought of as weighted sums of measurement-specific banana-doughnut kernels, with weights determined by the measurements. The overall sensitivity is simply the sum of event kernels, which defines the *misfit kernel*. The misfit kernel is multiplied by convenient orthonormal basis functions that are embedded in the SEM code, resulting in the gradient of the misfit function, i.e., the Fréchet derivatives. A conjugate gradient algorithm is used to iteratively improve the model while reducing the misfit function. Using 2D examples for Rayleigh wave phase speed maps of southern California, we illustrate the construction of the gradient and the minimization algorithm, and consider various tomographic experiments, including source inversions, structural inversions, and joint source-structure inversions. We also illustrate the characteristics of these 3D finite-frequency kernels based upon adjoint simulations for a variety of global arrivals, e.g., Pdiff, PKIKP, and SKS. Finally, we draw connections between classical Hessian-based tomography and gradient-based adjoint tomography.

S2.25 P and S-wave reflectors beneath Central America

C. THOMAS^a, T. KITO^a, S. ROST^b AND E. GARNERO^c

^a *University of Liverpool, UK*

^b *University of Leeds, UK*

^c *Arizona State University, USA*

Broadband P- and S-waves from earthquakes in South America recorded at Californian broadband stations are analyzed to image lateral variations of the D^{''}-discontinuity beneath the Cocos plate. We apply two array processing methods to the dataset: a simplified migration method to the P-wave dataset and a double-array method to both P-wave and S-wave dataset allowing us to compare results from the two array methods. The double-array method images a deeper reflector in the southern part of the study area with a step-like change to a shallower reflector to the north, as well as evidence for a second (deeper) reflector in the north. Results from a simplified migration agree well with those from the double-array method, similarly locating a large step in reflector depth in a similar location as well as the deeper reflector in the North. Solution structures depend strongly on initial assumptions in the array analyses, e.g. reference phases, source equalization, and signal-to-noise ratio. Possible explanations for D^{''} reflectors at two depths in the same location include the top and bottom of a slab, a folding slab, internal chemical layering in D^{''}, or transformation into and out of the post-perovskite phase. However, comparing waveforms of the reflected waves from both methods suggests a negative velocity contrast for P-waves for the

upper reflector but a positive contrast for S-waves. This is in agreement with results from mineral physics calculations for a post-perovskite phase transition and makes post-perovskite the most likely cause for the observed upper reflector.

S2.26 3-D seismics of the lowermost mantle: generalized Radon transform imaging with broad band *ScS* waveforms

R. D. VAN DER HILST^a, P. WANG^a, M. V. DE HOOP^b, P. MA^c, L. TENORIO^d AND S. SHIM^a

^a *Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge MA, USA*

^b *Center for Computational and Applied Mathematics, Purdue University, West Lafayette IN, USA*

^c *Department of Statistics, University of Illinois, Champaign IL, USA*

^d *Center for Wave Phenomena, Colorado School of Mines, Golden CO, USA*

We present results of a new method for imaging at and near interfaces in Earth’s deep interior with broadband, three-component seismograms from global seismograph networks. Our approach, which paves the way to 3-D seismo-stratigraphy of the lowermost mantle, is based on inverse scattering and allows the extraction of structural information from large data sets. We construct a generalized Radon transform to map broadband seismogram windows (comprising main arrivals with their coda and precursors) into multiple images of a target structure. The ‘common image-point gathers’ thus produced are subjected to statistical analysis and reveal multi-scale variations in elastic properties near deep interfaces. To enhance radial resolution and allow multi-scale interface analysis, we use both narrow- and wide angle reflections. The statistical analysis is used to enhance the images and to establish the significance of the inferred singularities. We transform $\sim 70,000$ transverse-component *ScS* waveforms into image gathers of the core mantle boundary (CMB) region beneath Central America. The juxtaposition of these image gathers generates 2-D image profiles that clearly reveal contrasts in elasticity near the target depth of the CMB and ~ 280 km above it, with significant topography (several tens of km) on the latter. In addition to what can be regarded as the top of the so called D’’ region, the images also reveal structures closer to the CMB. Not all of these interfaces are laterally coherent. We present lowermost mantle images over a large area beneath Central and North America and discuss the implication for our understanding of D’’ stratification and the presence of single or multiple phase transitions.

S2.27 Onset picking and cross-correlation travel times of finite-frequency wave in heterogeneous media

HSIN-YING YANG AND SHU-HUEI HUNG

Department of Geosciences, National Taiwan University, Taipei, Taiwan

We investigate the efficacy of three seismic travel-time theories, linearized ray theory (LR), generalized ray theory (GR) and Born-Fréchet kernel theory (BK), by conducting numerical forward modeling of acoustic wave propagation through 3-D structures with random velocity perturbations embedded in the homogeneous background medium. The numerical experiment entails systematic comparisons of ground-truth travel-time shifts with those predicted by different theories for the media with various scale lengths (a) and strengths of velocity perturbations (ε) and leads to the following conclusions: (1) For weak perturbations ($\varepsilon < 3\%$), BK is superior to either LR or GR because finite-frequency effects are properly incorporated into travel time predictions (2) For strong ($\varepsilon \geq 3\%$) perturbations with $D \equiv a/\sqrt{\lambda L} \geq 0.5$, where λ and L are the characteristic wavelength and propagation distance respectively, nonlinear GR traces fastest bending paths and leads to better predictions (3) All the three theories break down for strong ($\varepsilon \geq 3\%$) and rough ($D \leq 0.5$) perturbations.

The ground-truth travel time shifts utilized in the comparisons are those determined either from waveform cross-correlation (CC) measurements which include the whole waveforms or from AIC measurements which underline the first swing signals. However, the AIC auto-picker results in earlier arrivals than those

by CC measurements for $D \leq 0.5$ because the lateral-arriving energy predominates the initial-swing signals with the decrease in scale length a and increase in propagation distance L . Moreover, the scatterplot slope of δT_{AIC} versus δT_{CC} for $\delta T > 0$ data only from wave propagation through relatively slow regions is decidedly different from that for $\delta T < 0$ from wave propagation through relatively fast regions. As seismic waves are preferentially bent toward the high-velocity region, higher order effects leading to the fast-slow asymmetry are prominent particularly for large ε and cannot be modeled by LR and BK that explicitly invoke the linearization approximation.

S2.28 Inner core anisotropy investigated with normal modes and body waves

JESSICA IRVING, ARWEN DEUSS AND JENNIFER ANDREWS

Institute of Theoretical Geophysics, Bullard Laboratories, Department of Earth Sciences, Cambridge University, UK

A number of previous studies have confirmed the existence of seismic anisotropy in the earth's inner core. This anisotropic nature has been modelled using free oscillation data with widely varying results, which are formally inconsistent with each other and with data collected using body waves. All of these models have been developed using a self coupling approximation which ignores the significance of coupling of different inner core modes through the anisotropic structure.

We investigate the effect that the inclusion of this coupling would have on four different models [Woodhouse, Giardini & Li (1988), Tromp (1993), Durek & Romanowicz (1999) and Beghein & Trampert (2003)] by comparing the frequency and attenuations of a set of modes which have a significant proportion of their energy in the inner core. The coupling has a strong effect on the frequency and attenuation of the modes studied, and it is found that the changes caused by the coupling are highly dependent on the anisotropy model used. In particular both the size and constituents of the groups of modes which couple together are dependent on the model used. Synthetic seismograms and data are presented to illustrate the differences between self and full coupling approximation and between the different models.

Data from body wave studies can also be used to constrain the anisotropy. At present there are inconsistencies between the body wave and normal mode data which must be resolved. Such information is a prerequisite for the integration of results from seismology and mineral physics to establish the details and causes of inner core anisotropy.