A seismological constraint on the asthenosphere: mapping radial anisotropy with multi-mode surface waves

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Lateral heterogeneity and anisotropy in the upper mantle can be well constrained by seismic surface waves that have been widely used in the construction of 3-D shear wave models on global and regional scales. It is well known that there are significant differences in the typical thickness of the lithosphere between oceans and continents. In oceanic areas with typical lithospheric thickness of about 80-100 km, seismic structure in the lithosphere and asthenosphere can be constrained by the fundamental-mode surface waves. Recent surface wave models have revealed anomalous radial anisotropy under the lithosphere beneath Pacific Ocean (e.g., Nettles & Dziewonski, 2008, JGR). To the contrary, in continental areas, particularly under cratons, the thickness of the lithosphere reaches much deeper (~ 200 km), at which the fundamental modes lose their sensitivities. Therefore, higher-mode information is inevitable to map the seismological structure in the lithosphere and asthenosphere beneath continental regions. A recent high-resolution 3-D model in Australian continent using multi-mode surface waves (e.g., Yoshizawa, 2014, PEPI; Yoshizawa & Kennett, 2015, GRL) have revealed the existence of anomalous radial anisotropy (SH > SV) in the asthenosphere, which may manifest the effects of strong shear under the fast-drifting continent.

One of the advantages of using multi-mode surface waves for constraining shear wave models in the upper mantle is that we can map the spatial distribution of the lithosphere-asthenosphere transition and anisotropic properties in the upper mantle by using Rayleigh and Love waves simultaneously. We have investigated the resolving power of multi-mode surface waves for the lithosphere-asthenosphere system and radial anisotropy through a variety of synthetic experiments as well as practical applications to the observed data in continental and oceanic regions, focusing particularly on the Australian continent.

The spatial distribution of the lithosphere-asthenosphere transition (LAT) can be well constrained by multi-mode surface waves, although they are inherently less sensitive to the sharpness of the boundary or interface, unlike body waves/receiver functions at shorter periods. LAT can be estimated from the depth of either the negative peak of vertical velocity gradient and/or the slowest shear wave speed beneath the lithosphere, which provides a plausible depth range of the transition from the lithosphere to asthenosphere.

Seismic models of radial anisotropy (difference in shear wave speeds between SH and SV waves) derived from simultaneous inversions using both Rayleigh and Love waves tends to be affected by the choice of independent parameters for inversions. Theoretically, we may use either set of model parameters for the representation of radially anisotropic shear wave speeds; i.e., (A) Vsv and Vsh, or (B) Vsv and Xi [=(Vsh/Vsv)^2], but in the practical applications, they cause non-negligible influences on the resultant radial anisotropy models, mainly due to the intrinsic differences in the Love-wave sensitivity kernels to these independent parameters. Our synthetic experiments suggest the former parameterization with [Vsv, Vsh] would be preferable particularly when the radial anisotropy with SH>SV is caused by anomalously slow SV wave speeds, like those found under the fast drifting plates such as the Pacific and Australian plates.

Keywords: surface waves, asthenosphere, anisotropy

The behavior of super-weak asthenosphere in the Cascadia Subduction Zone, a perspective from seismic tomography

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Observations around the base of oceanic lithospheres reveal an abrupt seismic velocity decrease and electrical conductivity increase with depth, perhaps suggesting a pervasive thin, weak layer at the top of the asthenosphere. The behavior of such a layer at subduction zones remains largely unexplored. We use on and offshore seismic experiments to generate a tomographic model that reveals a strong low-velocity feature beneath the subducting Juan de Fuca slab along the entire Cascadia Subduction Zone. A simple geodynamic argument shows that a thin, weak, buoyant layer beneath the oceanic lithosphere will accumulate at the hinge of the subducting slab, and we propose that the low-velocity feature we observe may result from this accumulation.

Keywords: Asthenosphere, Tomography, Viscosity, Subduction

Upper Mantle Rheology From Postseismic Deformation of the 2013 M_w 8.3 Okhotsk Earthquake

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The upper mantle rheology at depths within a few hundred kilometers has been well studied through shallow great megathrust earthquakes. However, understanding of the mantle rheology at greater depths, such as in the vicinity of the transition zone, has been limited by the lack of direct or indirect measurements. The largest well-recorded deep earthquake with magnitude M*w* 8.3 occurred within the subducting Pacific plate at ~600 km depth beneath the Okhotsk Sea on May 24, 2013. Twenty-seven continuous GPS stations in this region recorded coseismic displacements of up to 15 mm in the horizontal direction and up to 20 mm in the vertical direction. Within three years after the earthquake seventeen continuous GPS stations underwent transient westward motion of up to 8 mm/yr and vertical motion of up to 10 mm/yr. The geodetically delineated postseismic crustal deformation thus provides a unique opportunity to study the three dimensional heterogeneity of the mantle rheology and properties of the subducting slab at great depths. We have developed three-dimensional viscoelastic finite element models of the 2013 Okhotsk earthquake to explore these questions. Our initial model includes elastic continental and oceanic lithosphere, an elastic subducting slab, a viscoelastic continental upper mantle and a viscoelastic oceanic upper mantle. We assume that the upper mantle is characterized by a bi-viscous Burgers rheology. For simplicity, we assume that the transient Kelvin viscosity is one order of magnitude lower than that of the steady-state Maxwell viscosity. Our preliminary models indicate that the viscosity of the upper mantle at depths 410-660 km is at the same order of the upper mantle at shallower depths. Viscosity at greater depths is at least 10^{22} Pa s. The subducting slab may be still elastic at depths >410 km or be viscoelastic with a viscosity no less than 10^{22} Pa s.

Keywords: Upper mantle rheology, Postseismic deformation, Finite element method, Subduction zone, Numerical modeling, Burgers rheology

Anisotropy in the Pacific asthenosphere from inversion of a surface-wave dispersion dataset

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We present a three-dimensional model of the anisotropic velocity structure of the Pacific upper mantle, including lithosphere and asthenosphere. The presence of seismic anisotropy in the oceanic upper mantle provides information about the geometry of flow in the mantle, the nature of the lithosphere-asthenosphere boundary, and the possible presence of partial melt in the asthenosphere. Our dataset consists of fundamental-mode dispersion for Rayleigh and Love waves of 25-250 s with paths crossing the Pacific Ocean. We invert the phase anomaly measurements directly for three-dimensional anisotropic velocity structure. Our models are radially anisotropic and include the full set of elastic parameters that describe azimuthal variations in velocity (e.g. *Gc, Gs*). We find large radial anisotropy with $v_{sh} > v_{sv}$ in the asthenosphere of the central Pacific. There is a distinct contrast in the elastic properties of the asthenosphere between the Pacific and Nazca plates, across the East Pacific Rise. We also investigate lateral variations in azimuthal anisotropy throughout the Pacific asthenosphere and find that there are many locations where the anisotropy fast axis does not align with absolute plate motion, suggesting the presence of small-scale convection or pressure-driven flow beneath the base of the oceanic plate.

Keywords: anisotropy, surface waves, Pacific

Upper mantle structure beneath the Pacific Ocean revealed by land and seafloor broadband observations

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Seismic tomography studies have revealed the structures and dynamics of the Earth's interior. However, spatial resolution of the oceanic region is worse compared to the continental region caused by sparse distribution of the land seismic stations.
In last 20 years, our Japanese seafloor broadband observation groups have conducted several temporary seafloor seismic array observations using broadband ocean-bottom seismographs (BBOBSs) in the Pacific Ocean. Total number of BBOBSs we used is more than 100. U.S. groups have also conducted the seafloor seismic array observations in the Pacific Ocean, and seismograms recorded by their BBOBSs are available from IRIS data center.
These BBOBS data enable us to improve the spatial resolution of the Pacific region.
We analyze three-dimensional shear wave velocity structure in the upper mantle beneath the Pacific region using land and seafloor seismic data by surface wave tomography method.
We have used a surface wave tomography technique in which multimode phase velocities of the surface wave are measured and inverted for a 3-D shear wave velocity structure by incorporating the effects of finite frequency effect and ray bending.
Checkerboard resolution tests suggests that spatial resolution is about 1000 km in the eastern Pacific Ocean but is about 600 km in the western Pacific Ocean.
Large scale heterogeneity of the upper mantle in our obtained model is consistent with previous tomography models. Strong radial anisotropy can be seen in the central Pacific at depths of 100 - 200 km and weak anisotropy can be seen around the subducting slab area.
In the western Pacific Ocean, fastest anomalies are not beneath the oldest seafloor region but beneath southeastward of the Shatsky rise.
Depths of negative peak of velocity gradient, which may be used as a proxy to the depth of lithosphere-asthenosphere boundary, have an age-dependence in young seafloor but is about 80 km in old seafloor (older than 100Ma).

Keywords: surface wave tomography, BBOBS, lithosphere-asthenosphere boundary, upper mantle

Imaging the Pacific Lithosphere Discontinuities at ~60 km using SS Precursors and Constraints on Defining Mechanism

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Oceanic lithosphere provides an ideal location to decipher the nature of the lithosphere –asthenosphere system which is vital to our understanding of plate tectonics. Although a thermally defined plate explains many first order observations such as bathymetry and heat flow. Observations of sharp mantle discontinuities are not well-understood. Here we use SS precursors to image the discontinuity structure across the Pacific Ocean using 24 years of teleseismic data. We image a sharp velocity discontinuity (3 –15% drop over < 21 km) at 30 –59 km that increases in depth with age from the ridge to at least ~36 ±9 My according to conductive cooling along the 1100 °C isotherm. The discontinuity is imaged at a depth of 35 –80 km for seafloor > 36 My. The shallow discontinuity at ~60 km is laterally continuous across most of the Pacific. It has recently been suggested that discontinuities in this depth range may be explained by an increase in radial anisotropy with depth. We evaluate the potential for an anisotropic variation to explain the discontinuities. We test surface wave depth resolution of radial anisotropy and estimate the apparent isotropic seismic discontinuities that could be caused by a change in radial anisotropy scattered wave imaging using synthetic seismograms. We find strong surface wave azimuthal anisotropy at 0 –50 km depth at an example case near the East Pacific Rise (EPR) implies a strong shallow radial anisotropy if caused by aligned olivine. An additional strong increase in anisotropic strength with depth from 50 –100 km is not supported. We find that neither an increase in radial anisotropy with depth caused by aligned olivine or frozen-in compositional layering can easily explain the observations from scattered waves. Another mechanism such as melt or composition may be required. The strength and pervasiveness of the boundary suggests that it is likely related to the lithosphere –asthenosphere boundary.

Keywords: lithosphere-asthenosphere, radial anisotropy, melt, SS precursor, seismic, ocean lithosphere

Regional-scale variation of the lithosphere-asthenosphere system beneath the old Pacific ocean basin revealed by NOMan seafloor array observation

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We analyzed records of broadband ocean bottom seismometers (BBOBSs) in two areas in northwestern Pacific Ocean: area A (130Ma) and area B (140Ma) in northwest and southeast of Shatsky Rise. The BBOBSs are deployed by the Normal Oceanic Mantle (NOMan) project from 2010 to 2014. This study focuses on one-dimensional S-wave velocity (V_{SV}) structures in the oceanic lithosphere and asthenosphere by the array analysis of surface Rayleigh waves at a period range of 5—100 s.
The method for surface-wave analysis is cross correlation of ambient noise at periods shorter than 30 s and array analysis of teleseismic waves at longer periods. Although the detail of analysis is almost same as the previous studies for different areas in Pacific Ocean (Takeo et al. 2013, 2014, 2016), we improved two points to adjust to the small array size and strong azimuthal anisotropy in our study areas. We first changed the method of phase-velocity measurement for teleseismic waves. Since the array size is small compared to the wavelength, the frequency smoothness of dispersion curve must be increased to reduce uncertainty. In this study, we obtained "smooth" phase-velocity measurements for each teleseismic event by trying various S-wave velocity structures and searching for the best phase-velocity measurement corresponding to the best fitting structure. We then simultaneously estimated isotropic phase velocity and its azimuthal anisotropy for both teleseismic and ambient-noise analyses to avoid the bias of strong azimuthal anisotropy to isotropic measurements.
As a result of above modifications, we obtained improved isotropic and azimuthally anisotropic one-dimensional V_{SV} models beneath two areas from Moho to a depth of 100—200 km. Despite of small difference in seafloor ages, V_{SV} in area A is 2% smaller than that in area B at a depth range of 80—200 km even after correcting the effect of azimuthal anisotropy. This difference reveals the strong and small-scale variation in the oceanic asthenosphere, which might support the existence of small-scale convection beneath old oceanic lithosphere. The azimuthal anisotropy is stronger in the top of lithosphere than below, which may suggest larger shear accumulation during the seafloor spreading when Pacific plate was created 130—140 Ma ago. In area B, however, the fastest azimuth is not perpendicular to magnetic lineation, suggesting mantle flow not fully driven by the seafloor spreading at the mid ocean ridge.

From Melt Percolation in the upper mantle to the Lithosphere Asthenosphere Boundary

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A strong geophysical signal is observed at the lithosphere-asthenosphere boundary (LAB). It can be explained by the presence of melt but the degree of melting predicted by petrological models seems to small to produce a signal able to match the observed one. We believe that melt migration is the missing process. To investigate this question, we have tested the effect of H_2O and CO_2 on the melting via a new thermodynamical model and coupled it to a two-phase mechanical model. It allows to simulate the motion of melt and mantle compaction in response to their density contrast. We conclude that it leads to episodic melt focusing that explain most geophysical observations so far attributed to the LAB. The magnitude of the LAB geophysical signal must be related to up-welling motion in the asthenosphere implying that up-welling is common but not a universal rule since several regions display a very weak or no LAB signal.

Keywords: Melt Percolation, Lithosphere Asthenosphere Boundary (LAB), Numerical modelling

Simple plate cooling model is no longer applicable to the upper mantle beneath the northwestern Pacific: Evidence from marine magnetotellurics

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The old oceanic lithosphere and asthenosphere beneath the northwestern Pacific Basin cannot be interpreted by the lithospheric age difference under a framework of the simple cooling of thermally conductive homogeneous mantle. This surprising result is now more definitely constrained by the electrical conductivity structure models obtained for four areas: northwest (Area A) and southeast (Area B) of the Shatsky Rise, off the Bonin Trench (Area C) and off the Japan Trench (Area D) where the representative lithospheric ages of these areas are 130, 140, 147, and 135 Ma, respectively. The marine magnetotelluric (MT) data were collected through several projects in the areas during the last decade. The 1-D electrical conductivity structure models of the upper mantle representing the areas were estimated by the state-of-art method that takes account for the effect of coast line and seafloor topography which can distort the electric and magnetic field significantly. The 1-D models show a highly resistive upper layer and a conductive zone, which are typical feature of the oceanic upper mantle and can be interpreted as the cool lithospheric mantle and warmer asthenospheric mantle. The significant difference among the four areas was found in the thickness of the resistive layer. The depth that electrical conductivity increases more than 0.01 S m^{-1} is ~90 km, ~100 km, ~190 km, and ~150 km for Area A, Area B, Area C, and Area D, respectively. The thermal structures for the ages representing the four areas predicted from a lithospheric cooling model are not different from each other very much and therefore such thermal model cannot reproduce the difference in the conductivity structures observed. It is necessary to introduce more dynamic processes such like small-scale convection, melt migration associated with the lithospheric flexure, and influence of plume associated with the Shatsky Rise formation. Observational evidence from the present marine magnetotellurics is one of the key issues for understanding the lithosphere-asthenosphere system (LAS) in the northwestern Pacific.

Keywords: marine magnetotellurics, electrical conductivity, oceanic upper mantle, plate cooling, Northwestern Pacific

Electrical conductivity constraints on the origin of the oceanic asthenosphere

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Recent seafloor magnetotelluric (MT) surveys have imaged the electrical conductivity structure of the oceanic upper mantle. Most regions show high conductivities (0.02 to 0.2 S/m) between 50 and 150 km depths that are inconsistent with dry mantle. Instead, the conductivity observations require either volatiles stored in nominally anhydrous minerals or the presence of interconnected partial melts, leading to dramatically different interpretations on the origin of the asthenosphere. To determine which mechanism is more plausible, I apply several competing empirical models to estimate an upper bound on the conductivity of hydrated oceanic mantle in a thermodynamically self-consistent framework. The results indicate that a subset of the MT observations exceed the maximum conductivity of hydrated mantle regardless of which empirical model is applied.

Seismic Image of a Thermo-Mechanical Channel at the base of Oceanic Lithosphere

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The plate tectonics theory is based on the existence of a rigid lithosphere floating over a ductile asthenosphere, forming the most prevalent plate boundary on earth, lithosphere asthenosphere boundary (LAB), but the nature of the LAB remains elusive. Surface wave tomography has been used to define the LAB but the vertical resolution is rather poor. Recently, receiver function methods have been used to image the LAB, but the resolution is still on 10 km with a very limited sub-surface sampling. Using ultra-deep seismic reflection technique, here we show the image of the LAB across the St Paul Fracture zone in the Equatorial Atlantic Ocean, consisting of two reflections. The depth of the upper reflector gradually increases from 70 km at 40 My to 80 km at 70 My, consistent with the plate cooling model of the lithosphere. It has a negative polarity with a velocity decrease of 7.5% and follows the 1150º Isotherm. The second reflector lies 15 to 10 km below, has a positive polarity, requiring an increase in velocity of 6.5%, and follows the 1250º isotherm. We suggest that these two reflectors define a thermo-mechanical channel (TMC), containing about 1.5% of melt with reduced viscosity, whose thickness decreases with age. The highly viscous TMC would decouple the tectonically driven lithosphere with the convecting mantle below.

Keywords: Plate Tectonics, Lithosphere Asthenosphere Boundary, Melt

Origin of asthenosphere inferred from polycrystal anelasticity

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Asthenosphere is observed as seismic low velocity and high attenuation zone. However, temperature of such region is, for the most part, below the solidus temperature of dry mantle peridotite. This suggests that seismic wave velocity is significantly reduced in the absence of melt or in the presence of a very small amount of melt stabilized by volatiles. Effects of partial melting on the seismic velocity and attenuation have long been studied within the framework of the direct effect of the melt phase, such as poroelastic effect. Because the direct effect is small for very small melt fraction, it is difficult to explain the relatively large velocity reduction in the asthenosphere.

Rock anelasticity, which can cause low velocity by grain boundary sliding without melt, has been considered as a key to solve this problem (e.g., Karato, 1993; Faul and Jackson, 2005). However, due to the difficulty of high temperature experiment, we have had a limited understanding of rock anelasticity at the seismic frequencies. Recent experimental studies by using a rock analogue (organic polycrystals) has revealed that polycrystal anelasticity is significantly enhanced from just below the solidus temperature in the absence of melt (Takei et al, 2014; Yamauchi and Takei, 2016). Importantly, the amplitude of this `pre-melting effect' is large even for the samples which can produce very small amounts (~0.4-0.5 %) of melt at the solidus temperature (Yamauchi and Takei, 2016). Therefore, the newly recognized effect can remove the difficulty to explain the seismic observations without melt or with very small amount of melt indicated by the thermal and geochemical studies.

Using the temperature and seismic structures of the Pacific mantle, Priestley and McKenzie (2006, 2013) captured a steep reduction in Vs just below the dry peridotite solidus. The new anelasticity model including the pre-melting effect can explain this steep reduction qualitatively and almost quantitatively (Yamauchi and Takei, 2016), whereas the other models cannot. Seismic discontinuity, which is attributed to the lithosphere-asthenosphere boundary (LAB), can be also explained by the pre-melting effect without invoking melt (Yamauchi and Takei, AGU fall meeting 2016). The new model is not sensitive to the existence or non-existence of a very small amount of melt, but is sensitive to the existence or non-existence of volatiles because of their strong effects on the solidus temperature. Possible mechanism causing the pre-melting effect is a disordering transition of grain boundary. Therefore, the new anelasticity model suggests that the mechanical properties of the asthenosphere are controlled by the dynamic properties of the grain boundary at near-solidus temperatures.

Keywords: anelasticity, polycrystal, grain boundary, partial melt

Estimation of electrical anisotropy in the oceanic upper mantle from seafloor magnetotelluric array data

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Electrical anisotropy in the oceanic upper mantle could provide important clues on mantle structure and dynamics if it is confirmed from observational data. Seafloor magnetotelluric (MT) data are useful to estimate electrical anisotropy in the oceanic upper mantle, but should be carefully treated partly because maximum anisotropic signal may not be so large (half an order of magnitude in electrical conductivity) and there is always trade-off between intrinsic anisotropic effects and effects of a large-scale lateral heterogeneity including bathymetric variations and coast effects. One promising method to estimate electrical anisotropy from seafloor MT array data is first to obtain a 1-D isotropic model through iterative correction for bathymetric distortion, and then to estimate anisotropy as deviations from the 1-D isotropic model. We first investigate the performance of this method through a series of synthetic modeling using plausible 1-D anisotropic models for the Normal Oceanic Mantle project area in the northwestern Pacific. The synthetic modeling includes forward modeling using the 1-D anisotropic models with and without bathymetry and inversion with iterative bathymetric correction to data produced from the 1-D anisotropic models underlying a 3-D real bathymetry. After the synthetic test, we apply the method to an observational array data obtained during the Normal Oceanic Mantle project in the northwestern Pacific. We will show and discuss results of the application in the presentation.

Layered seismic anisotropic structure of the subducting asthenosphere in the Cocos subduction zone

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Previous studies of the seismic anisotropy in the subslab mantle of the Cocos subduction zone show that the fast directions are in general parallel (~30 degrees) to the absolute plate motion (APM). Such APM-parallel pattern can be interpreted as the a-axis of olivine being aligned by the shear stress associated with the moving plate.To better understand the relationship between anisotropy and mantle flow, we collected S waves from the Cocos slab recorded by the stations located on the Pacific plate. Our results show that fast directions predominantly align at N65E, or 30 degrees clockwise from the direction of the APM, and that the delay time of our source-side anisotropy is much larger than previously reported. We also found that both of the splitting parameters have $\pi/2$ periodicity. We model the periodic distribution using 2 layer anisotropic structure with E-type olivine fabric, for which the fast direction remains the same at all incident angles to satisfy the basic assumption of the 2 layer modeling. The best-fit model shows that the upper and lower layers are characterized by a fast direction of 30 and 65 degrees, respectively, with delay time ratio about 1:2~3. The upper layer immediately entrained by the slab is "normal" descending and the lower layer is oblique in subduction. The mechanism behind this double layer subduction of the asthenosphere is under investigation.

Keywords: Subslab anisotopy, Cocos subduction zone, asthenosphere

Radial anisotropy as "bodywave-surface wave discrepancy"

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The lithosphere-asthenosphere system (LAS), especially beneath the ocean, is known to have pronounced radial anisotropy (transverse isotropy with vertical symmetry axis, VTI), but its physical origin is not well understood. Radial anisotropy in the mantle has been often associated with "Rayleigh/Love wave discrepancy", but it could be also due to other factors. Recently, Kawakatsu et al. (2015) and Kawakatsu (2016a,b) have introduced a new fifth parameter in VTI system that describes the incidence angle dependence of bodywaves. Rayleigh wave dispersion has a strong sensitivity to this parameter (Kawakatsu, 2016b), and thus it can also affect the strength of radial anisotropy.

Song and Kawakatsu (2012) has demonstrated how bodywaves that enter the LAS with different incident angles can be used to constrain asthenospheric anisotropy. Also the reflection/conversion efficiency at the G-discontinuity depends on the fifth parameter in a peculiar way. Thus bodywaves can provide additional information about radial anisotropy of the LAS, and it is possible to view radial anisotropy as "bodywave-surface wave discrepancy" through the new parameter, \eta_k. Lateral change of the strong asthenospheric anisotropy may be due to this effect.

Constraints on mantle flow in the oceanic upper mantle from a high-resolution estimate of seismic velocities in the central Pacific

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Observations of seismic anisotropy in ocean basins are important for constraining deformation and melting processes in the upper mantle. The NoMelt OBS array was deployed on relatively pristine, 70-Ma seafloor in the central Pacific with the aim of constraining upper-mantle circulation and the evolution of the lithosphere-asthenosphere system. Azimuthal variations in Rayleigh-wave velocity suggest strong anisotropic fabric both in the lithosphere and deep in the asthenosphere, with the asthenospheric flow driven by either small-scale convection or large-scale lateral pressure-gradients, and little deformation related to plate motion. To further evaluate these mechanisms, we combine Love waves derived from high-frequency ambient noise (5-10 s period) and earthquakes (20-100 s period) with body-wave travel times to further constrain fabric and flow in the oceanic mantle. High-frequency Love waves require positive radial anisotropy (Vsh > Vsv) and azimuthal anisotropy with a strong 4-theta azimuthal signal in the upper 30 km of the mantle, consistent with the high-resolution Rayleigh-wave anisotropy, but inconsistent with estimates from global models. Forward modeling of multi-mode Love waves traversing the array from three strong earthquake sources suggests that the positive radial anisotropy (Vsh > Vsv) extends through the asthenosphere. Taken together, the Love- and Rayleigh-wave anisotropy suggests that olivine fabric can explain the anisotropic signature of the lithosphere-asthenosphere system, and melt or other exotic mechanisms are not required. To further evaluate the processes producing asthenospheric fabric, we measure teleseismic P- and S-wave multi-channel delay times to constrain lateral velocity variations beneath the array. Finite-frequency sensitivity kernels provide the mapping of the delay times to velocity variations in the asthenosphere. We will specifically test for the presence of lateral velocity variations within the asthenosphere that are consistent with small-scale convection. At minimum, we will place bounds on the maximum plausible temperature variations allowed by the data. Taken together, the surface- and body-wave modeling will provide a unique, high-resolution picture of seismic structure and mantle flow within the oceanic lithosphere-asthenosphere system.

Keywords: asthenosphere, seismic anisotropy, mantle flow

Waveform modeling of BBOBS data for old oceanic lithosphere-asthenosphere system

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Analysis for a base of lithosphere, at nearly 100 km depth, is still difficult because of a lack in observation data which contain a pure information for the lithosphere-asthenosphere system (LAS). Recent developments in seafloor in-situ observation and waveform analysis enable to determine more detailed structure of the LAS. In this study, we modeled broadband seismic waveforms of outer-rise earthquakes occurring after the Tohoku earthquake around the Japan trench that are observed by 5 broad-band ocean bottom seismometers(BBOBSs) at the northwest pacific seafloor; the traveling paths of these seismic waves are entirely within the old (~130Ma) ocean LAS, and can be used to constrain the average 1-D velocity structure under ’ normal ocean’ . Because the observation data contain much short-period noise, the waveforms need to be applied appropriate bandpass filters: periods 6-100s for P wave, 33-100s for Rayleigh wave, and many octave-range filters for Love wave. We compared observed and synthetics waveforms, and then adjusted our model. Very preliminary analysis indicated that (1) crust is 3% faster in P wave or 0.5 km thinner than the PA5 model (Gaherty et al., 1999), (2) LID is 20km thicker or 2% slower than PA5, but (3) the model has still strong trade-off between crust thickness and crust velocity, and between LID thickness and LID velocity. As a result, the depth of lithosphere-asthenosphere boundary (LAB) or G-discontinuity is not constrained uniquely. Further analysis for multiply bounced S-waves (e.g., ScS, SS, SSS) should constrain more detailed structure for the depth.

Super-weak asthenosphere in light of plate motions and azimuthal anisotropy

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Plate motions and azimuthal seismic anisotropy from surface waves are consistent with a strong, oceanic lithosphere that is predominantly dragged by slabs, and weakened upon subduction. Plates are underlain and sustained by a moderately weak asthenosphere, as expected from the temperature and pressure dependence of olivine viscosity for the upper mantle. However, recent observations from active source seismology, magneto-tellurics, body wave anisotropy, and postseismic surface deformation can be interpreted to imply the existence of a very weak channel of low viscosity material, potentially decoupling plates, not unlike a plume-fed asthenosphere scenario in several ways. Here, I explore the implications of such a decoupling channel for plate driving forces as well as observations of seismic anisotropy. The thickness and viscosity reduction of the channel are expected to trade off with each other, and plate motions are sensitive to the lateral extent of this super-weak asthenosphere. While there is some ambiguity of plate motion metrics with the strength of slabs, seismic anisotropy is expected to be sensitive to how shear is localized with depth. The overall good fit of azimuthal anisotropy patterns to flow model predictions brakes down for a number of the more extreme lateral and depth-dependent viscosity scenarios. This may imply that weakening mechanisms may not apply globally under plates, but are rather limited to isolated regions, perhaps associated with melt-rich pockets that have limited connectivity.

Keywords: asthenosphere, plate motions, azimuthal anisotropy

Significance of sediment reverberations on receiver functions of broadband OBS data

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We attempted to estimate the depth of the lithosphere-asthenosphere boundary (LAB) and velocity contrast at LAB with a receiver function (RF) analysis of waveform data observed by a broadband ocean bottom seismometer (BBOBS) installed in the northwest Pacific Ocean under the OHP project. Beneath the station (WPAC), thickness and several physical properties of the sediment layer were revealed from a boring core (Kanazawa *et al.*, 2001, *Proceedings of the Ocean Drilling Program, Initial Reports*). The oceanic crustal structure was precisely estimated by a seismic experiment (Shinohara *et al.*, 2008, *PEPI*). Using waveform data observed at the bottom of a borehole just beneath WPAC, depth of the LAB and S-wave velocity contrast at LAB were estimated to be 82 km and 7.2%, respectively (Kawakatsu *et al.*, 2009, *Science*; Kumar *et al.*, 2011, *JGR*).
We calculated P-wave RFs (PRFs) and S-wave RFs (SRFs) from teleseismic waveforms, and obtained averaged PRF and SRF. To calculate RFs, a Gaussian low pass filter, $G(\omega)=\exp(-(\omega/2\alpha)^2)$, was applied. We obtained four pairs of PRF and SRF with different values of α, 0.25, 0.5, 1.0, and 2.0. We synthesized PRF and SRF using the known structural parameters revealed from the studies shown above. However, the synthetic PRF and SRF cannot explain the observed ones. The synthetic PRF has several peaks caused by reverberation of S-wave in the sediment layer with larger amplitudes than the observed one. Amplitude of the first peak of the synthetic SRF is much larger than that of the observed one.
We showed that the observed PRF can be explained when we assume attenuation and velocity gradient of S-wave in the sediment layer in addition to the known parameters. Although the observed SRF cannot be explained even if we assume them, we showed that they can be explained when we calculate an SRF from synthetic waveforms added with large noise. Velocity gradient and attenuation of S-wave in the sediment layer and noise are necessary to be taken into account for explaining RFs obtained from BBOBSs.
The observed waveforms would contain noise that largely changes amplitude of SRF, and it is difficult to constrain subsurface structure from SRFs. Only from PRF, we searched structural parameters from the ocean bottom to the asthenosphere, where attenuation and velocity gradient in the sediment layer were contained. The depth of LAB and S-wave velocity contrast at LAB are constrained to be 73-129 km and 6-25%, respectively. Thick sediments beneath WPAC (377 m; Kanazawa *et al.*, 2001) would make the analysis difficult. New BBOBSs have been developed to reduce noise (*e.g.* BBOBS-NX: Shiobara *et al.*, 2013, *IEEE J. Ocean Engineering*). At other stations, where the condition is better, the parameters might be constrained better.

Keywords: receiver function, oceanic sediments, broadband ocean bottom seismometer

The impact of temporal stress variations, dynamic disequilibrium, and asthenospheric channels on the initiation of plate tectonics

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We use 3-D numerical experiments and 1-D thermal history models to study the impact of dynamic thermal disequilibrium, asthenospheric channels, and large temporal variations of normal and shear stresses on the initiation of plate tectonics. Previous models that explored plate tectonics initiation from a steady state, single plate mode of convection concluded that normal stresses govern the initiation of plate tectonics. Using 3-D spherical shell mantle convection models in an episodic regime allows us to explore larger temporal stress variations than can be addressed by considering plate failure from a steady state stagnant lid configuration. The episodic models show that an increase in convective mantle shear stress at the lithospheric base initiates plate failure. In this out-of-equilibrium and strongly time-dependent stress scenario, the onset of lithospheric overturn events cannot be explained by boundary layer thickening and normal stresses alone.

Moreover, we empirically find that the period increases with a decrease in "channel number MN", which we define as $MN=eta_A/(d_A)^3$ (here eta_A is the non-dimensional channel viscosity and d_A the ratio between channel thickness and mantle depth). Therefore, decreasing values of MN move the system toward stagnant lid convection.

At this stage, our results indicate that a decreasing channel number is associated with lower basal shear stress on the plate above, and in that sense, our results are consistent with the idea that basal shear stress, asthenospheric channels, the temporal variation of stresses, and dynamic disequilibrium are critical for initiating plate tectonics.

References. Stamenkovic, V., Höink, T., Lenardic, T. (2016) JGR Planets, 121, 1–20, doi:10.1002/2016JE004994.

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Keywords: Plate tectonics, Asthenosphere, Stresses, Non Equilibrium, Mantle Convection

Diffusion creep of fine-grained olivine aggregates : Chemical and melt effects

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Since olivine is the major constituent mineral of the earth's upper mantle, flow properties of the upper mantle are often estimated based on flow laws of olivine aggregate which are determined by high-temperature creep experiments. In particular the viscosity of asthenospheric mantle plays a key role on plate tectonics because it decouples solid plates above and convective upper mantle below. Recently, the presence of a small amount of melt at the oceanic mantle asthenosphere has been suggested by some studies on seismic wave, electrical conductivity, and geochemistry (Hawley et al. 2016, Naif et al. 2013, Hirschmann 2010).
The effect of melt on rheology of olivine aggregates at dry conditions, however, has not been understood well yet. Deformation experiments on olivine aggregates synthesized from naturally derived mantle rocks (we refer naturally-derived olivine hereafter) showed that 4% melt-doped samples had a factor of 3 lower viscosity than undoped samples indicating a relatively small melt effect (Hirth and Kohlstedt 1995). Experiments on olivine aggregates synthesized from reagents using sol-gel methods (hereafter we call Sol-gel olivine) showed that the 4% melt-doped samples had a factor of 50 lower viscosity compared to non-doped samples indicating a very large melt effect. These previous studies have difficulties in determination of precise melt effect, 0.5 to 1 vol. % melt was observed even in non-doped naturally-derived samples presumably due to impurities (Hirth and Kohlstedt 1995). The change in viscosity due to adding of melt phase in sol-gel olivine can be due to the effect of impurities at grain boundaries which is known to have a large effect on the strength of polycrystalline oxide (e.g. Yoshida et al. 1997).
In this study, we synthesized olivine aggregates with and without impurities (CaO and Al_2O_3) by using a new technique and conducted high-temperature creep experiment on such synthesized olivine aggregates to investigate effects of chemical composition and presence of the melt phase on the creep properties of olivine aggregates.
The aggregates were prepared by applying vacuum sintering to nano-sized olivine powder synthesized from highly pure and fine-grained (<100 nm) raw powders (Koizumi et al 2010). Olivine aggregates with and without dopants of <1 wt% Al_2O_3, CaO, were prepared. Deformation tests on these samples showed that non-doped samples were deformed by grain boundary diffusion creep mechanism with no major difference in strength between non-doped and impurity-doped samples at temperatures below solidus of impurity-doped samples, while a reduction of a factor of 6 in viscosity was observed in impurity-doped samples with 0.05 vol. % melt at temperatures above solidus. FTIR analysis showed that both synthesized and deformed samples were dry. The strength of the non-doped samples was essentially identical to the aggregates by Faul and Jackson (2007), thus the difference in strength between previous studies can be explained solely by melt effect on olivine rheology.

Keywords: diffusion creep, olivine aggregates, chemical effect, melt effect, rheology

Water sensitivity of the rheology and seismic properties of upper-mantle olivine

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Hydrous, but water-undersaturated, conditions for the fabrication and mechanical testing of synthetic olivine polycrystals have been achieved within internally heated gas-medium high-pressure apparatus. Enclosure of specimens within a Pt capsule rather than the usual Ni-Fe sleeve results in significantly more oxidising conditions and a relatively high water fugacity. Exposure of Ti-doped olivine to these conditions results in the creation and preservation of an extended defect involving Ti/Mg substitution, charge balanced by double protonation of a neighbouring Si vacancy. Fully synthetic solution-gelation derived Fo_{90} olivine, doped with 660-1940 atom ppm Ti/Si, was hot-pressed and then deformed in Pt capsules at 300 MPa confining pressure and temperatures of 1200–1350°C. Due to the enhanced grain growth under hydrous conditions, the samples were at least three times more coarse-grained than their dry counterparts and deformed by power-law creep at differential stresses as low as a few tens of MPa. The data define an essentially linear relationship between strain rate and the concentration of chemically bound hydroxyl, inferred from the intensity of infrared absorption bands at 3572 and 3525 cm^{-1} diagnostic of the Ti-hydroxyl defect. The observed rheology is broadly consistent with the hydrous rheology previously determined for olivine under water-buffered, and therefore saturated conditions. However, in contrast with previous interpretations, we conclude that extrinsic defects (involving the Ti impurity) in olivine play the dominant role in water weakening of the Earth's upper mantle (Faul et al., *EPSL*, 2016). Concerning seismic properties, similarly prepared Ti-doped olivine polycrystals, have been sleeved in Pt for mechanical testing in torsional forced oscillation under water-undersaturated conditions. The observed mechanical behavior is of the high-temperature background type involving monotonically decreasing shear modulus and increasing dissipation with increasing oscillation period and increasing temperature. The modulus dispersion and dissipation, thus measured under water-undersaturated conditions, are markedly stronger than for a similarly prepared specimen, tested dry within an Ni-Fe sleeve under more reducing conditions. The contrasting seismic properties of the hydrous and dry specimens suggest an important role for the chemical environment (changes of f_{O2} and f_{H2O}) in the viscoelastic relaxation responsible for reduced seismic wave speeds and attenuation in the Earth's asthenosphere (Cline et al., *Nature Geoscience*, submitted).

Keywords: olivine rheology, water weakening, seismic wave dispersion and attenuation

Temperature dependency of the electrical grain boundary transport in forsterite aggregates

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The grain-size-dependency on the electrical conductivity of fine-grained forsterite aggregate was found and attributed to grain boundary diffusion of charge carriers as a main conduction mechanism in the aggregate (ten Grotenhuis et al., 2004). Such result indicates that the electrical conductivity measurement can be used to detect physicochemical changes of grain boundaries with changing temperature and bulk chemistry. We conducted impedance measurements on forsterite aggregates with different grain sizes and secondary phases (e.g., forsterite + enstatite and forsterite + diopside) under a gradual change in temperature in order to obtain temperature (*T*) and grain size (*d*) dependency of the electrical conductivity (*s*).
Synthetic samples of forsterite + enstatite (solidus temperature T_m = 1557 C) and forsterite + diopside system (T_m ~ 1350 C) were prepared from the powders of $Mg(OH)_2$, SiO_2 and $CaCO_3$ (50 nm). Impedance measurements were carried out every 2 ~ 5 minutes during annealing at the highest temperature (1300 ~ 1400 C) for 50 hours and during subsequent gradual cooling down to 1000 C.
Impedance measurements of both forsterite + enstatite and forsterite + diopside during their annealing show grain-size-dependency of their electrical conductivities as $s \propto 1/d$, indicating that the electrical conduction mechanisms are grain boundary transport of the charge carriers in both aggregates.
Impedance measurement during the cooling of forsterite + enstatite shows Arrhenius type of temperature dependency of electrical conductivity which changes with temperature ranges such as the dependency well described by activation energy of 240 kJ/mol at 1000 ~ 1150 C, 290 kJ/mol at 1150 ~ 1350 C and 320 kJ/mol at 1350 ~ 1400 C. Forsterite + diopside exhibits stronger temperature dependency than a simple Arrhenius type dependency providing apparent activation energy ranging from 180 kJ/mol to 1000 kJ/mol at temperature from 1000 C to 1350 C (= sample solidus). We will discuss such temperature dependencies based on structural and/or chemical changes of grain boundaries in these systems.

Keywords: Electrical conductivity, Grain boundary, Grain size dependence

Thermal & petrological structure of lithospheric mantle deciphered from xenoliths from Ichinomegata, NE Japan.

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Mantle xenoliths are important sources of information on thermal and petrological structure of lithospheric mantle and its temporal variation. Extraction of such information from xenoliths in arc settings is critical to understand evolution of wedge mantle. However, our knowledge on arc lithosphere is limited because of lack of reliable geobarometers for plagioclase- and spinel-peridotites. We have conducted geothermobarometry on carefully selected pairs of minerals and their chemical compositions, and successfully gained reasonable pressure estimates. This allows us to construct reliable thermal and petrological structure and its temporal variation of the mantle beneath NE Japan arc.
Ichinomegata volcano is a latest Pleistocene maar in Oga peninsula, NE Japan. Peridotite xenoliths occur as inclusion in basaltic to dacitic pyroclastic rocks (Katsui et al. 1979). The MOHO depth beneath Ichinomegata is estimated as 28 km (Zhao et al. 1992), and the depth of lithosphere-asthenosphere boundary (LAB) was estimated to be close to that of Japan Sea (ca. 60 km; Zheng et al. 2011). Eight lherzolite and one wehrlite samples were examined. Three samples contained plagioclase and/or pyroxene-spinel symplectite after plagioclase (Takahashi, 1986), and six samples were spinel-peridotite. They are also grouped into two types: equigranular samples with etching pits on void surfaces indicating a fluid phase, and porphyroclastic samples with interstitial glass suggesting a melt phase.
We analyzed chemical zonings of orthopyroxene and clinopyroxene using EPMA to pinpoint compositional pairs where equilibrium conditions are preserved. Four patterns of the chemical zonings of Ca, Al, and Cr due to temperature (T) changes are distinguished. They indicated 1) simple and gradual T decrease, 2) gradual T decrease followed by rapid and weak T increase, 3) gradual T decrease followed by rapid and strong T increase, 4) faint T increase. The prograde zonings observed in (3) are referred "preheating" in Takahashi (1980). On the basis of the zoning patterns and consideration on diffusional time scale, the most appropriate pairs of chemical compositions and minerals preserving pressure and temperature information just before xenolith extraction were identified for geothermobarometry.
The essential strategy in the choice of geothermobarometers is based on the fact that Al and Cr effects on geothermobarometries are very difficult to evaluate which is actually included in several thermobarometers (e.g. Lindsley 1983; Tayler 1998; Nimis and Taylor 2000; Putirka 2008). This is because response of the solubility of Al and Cr in pyroxene to pressure and temperature changes is different for plagioclase, spinel, and garnet peridotites (Gasparik 2003). We thus used T_{BKN} and $T_{Ca\text{-}in\text{-}Opx}$ (Brey and Köhler 1990), since the effects of Al and Cr contents are less important.
The estimated pressure ranges from 0.7 to 1.6 GPa, which correspond to a depth range from 28 to 54 km (± 6 km), and the estimated temperature ranges from 831 to 1084 °C (± 9 °C). The pressure values are well within the range of lithosphere, and the temperature values are consistent with those of previous studies (e.g. Takahashi 1980; Takahashi 1986; Abe and Arai 2005).
According to the pressure estimate, we can construct thermal and petrologic structure beneath Ichinomegata. Samples derived from the deeper level (1.1-1.6 GPa) were "preheated" (up to 1016-1084 °C), and samples from the shallower depth (0.7-0.9 GPa) stayed at low temperature (832-905 °C) without such "preheating". Systematic depth variations of various features of the xenoliths are identified: the change of Al-phases from plagioclase to spinel, the change of interstitial phases from fluid to melt, and change of microstructure from equigranular to porphyroclastic textures. The consistent depth dependent transitions might correspond to those expected in the thermal and rheological boundary

layers near LAB controlled by wet-solidus.

Keywords: wedge upper mantle, thermal structure, rheological structure