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

