# Toward proper characterization of seismic radial anisotropy of the lithosphere-asthenosphere system

*Hitoshi Kawakatsu[1]

1.Earthquake Research Institute, the University of Tokyo

Kawakatsu et al. (2015) recently proposed a new fifth parameter, $\eta_k$ that properly characterizes the incidence angle dependence (relative to the symmetry axis) of seismic bodywaves in a transverse isotropy (TI) system. When existing models of upper mantle radial anisotropy (TI with a vertical symmetry axis) are compared in terms of this new parameter, PREM shows a distinct property. Within the anisotropic layer of PREM (a depth range of 24.4-220km), $\eta_k < 1$ in the top half and $\eta_k > 1$ in the lower half. If $\eta_k > 1$, anisotropy cannot be attributed to the layering of homogeneous layers, and thus requires the presence of intrinsic anisotropy (Kawakatsu, 2016, GJI).

Partial derivatives of surface wave phase velocity and normal mode eigen-frequency for the new set of five parameters indicate that the sensitivity of $\eta_k$ is about twice as large as that of the conventional $\eta$, indicating that $\eta_k$ is more resolved than is usually considered. While sensitivities for (anisotropic) S-velocities are not so changed, those for (anisotropic) P-velocities are greatly reduced. In contrary to Dziewonski and Anderson (1981)'s suggestion, there is not much control on the anisotropic P-velocities; on the other hand the significance of $\eta_k$ for the long-period seismology is clear.

Considering now that a variety of seismic body waves with different incidence angles (receiver functions, multiple S, SS-precursors, SKS, etc.), as well as surface waves and normal-modes, are available to constrain the property of the lithosphere-asthenosphere system, and that the presence of strong radial anisotropy in the suboceanic asthenosphere is well established, we should properly characterize seismic radial anisotropy of the lithosphere-asthenosphere system using the new fifth parameter.

Reference:

Kawakatsu, H., J.-P. Montagner, and T.-R. A. Song (2015), On DLA's η, in The Interdisciplinary Earth: A volume in honor of Don L. Anderson, edited by Foulger et al., PP. 33-38, GSA and AGU.

Kawakatsu, H. (2016), A new fifth parameter for transverse isotropy, Geophys. J. Int., 204, 682-685.

Keywords: seismic anisotropy, PREM, surface wave, body wave

 

# Interstation phase speed measurements of surface waves in the Sea of Japan using broadband seismic arrays

*Ryo Narita[1], Kouta Hamada[1], Kazunori Yoshizawa[2], Hitoshi Kawakatsu[3]

1.Graduate School of Science, Hokkaido University, 2.Faculty of Science, Hokkaido University, 3.Earthquake Research Institute, University of Tokyo

Seismic structure in the crust and upper mantle beneath the Sea of Japan reflects its complex tectonic history including back-arc spreading and the subsequent formation of the Japanese islands. The seafloor topography and the crustal thickness of this marginal sea are quite variable, characterized by several basins and rises. Although the upper mantle structure beneath the Sea of Japan has been investigated with surface wave tomography using permanent broadband seismic networks in Japan and in East Asia by Yoshizawa et al, (2010, PEPI), the horizontal resolution of this earlier model was limited due to the small numbers of ray paths across the marginal sea.

A temporary broadband seismic array, which has recently deployed across Northeast China (NECESSArray) from 2009 to 2011, can be of great help in enhancing the ray coverage across the Sea of Japan, by employing interstation dispersion measurements of surface waves. In combination with the Japanese permanent broadband network (F-net), a large number of interstation phase speeds information across the Sea of Japan can be extracted. In this study, we employ a fully non-linear waveform fitting technique to measure interstation phase speeds using a method developed by Hamada & Yoshizawa (2015, GJI). Through the waveform analysis of the combined data sets in the period range between 20 and 150 seconds, we collected about 5000 new measurements of phase speeds using seismic events with moment magnitude greater than 6.0 during the temporary deployment of NECESSArray (2009-2011). With the additional data set, we are now able to resolve the smaller scale heterogeneity of about 1.5 degrees or less in the Sea of Japan. The updated preliminary phase speed maps of Rayleigh waves show significant fast phase speed anomaly beneath the Japan Basin in the period shorter than 45 s, while, in the longer periods, slow anomalies are found in most areas beneath the Sea of Japan, suggesting relatively thinner lithosphere (about 60 km) compared with the typical oceanic plate like the Pacific. One of the striking features of the new model is that the phase speed maps at shorter period than 45 s shows conspicuous regional variations in the Sea of Japan; i.e., phase speeds beneath southwestern areas, including the Tsushima Basin, tend to be slower, while the northeastern half of the sea, including the Japan Basin, is characterized by faster phase speeds, which may reflect the lateral variations of the lithospheric thickness. Furthermore, a localized fast phase speed anomaly is found beneath the Yamato Rise in the period shorter than 60 s, which may suggest relatively thicker lithosphere of about 80-90 km beneath it.

Keywords: Sea of Japan, Surface waves, Tomography, Phase speed

 

# Anisotropy in the Northwest Pacific oceanic lithosphere inferred from Po/So waves

*Azusa Shito[1], Daisuke Suetsugu[2], Takashi Furumura[3], Hajime Shiobara[3], Takehi Isse[3], Hiroko Sugioka[4], Aki Ito[2], Akiko Takeo[3], Hisashi Utada[3]

1.Institute of Seismology and Volcanology, Kyushu University, 2.Department of Deep Earth Structure and Dynamics Research, Japan Agency for Marine-Earth Science and Technology, 3.Earthquake Research Institute, University of Tokyo, 4.Department of Planetology, Graduate School of Science, Kobe University

Po/So waves, which have a high frequency, large amplitude, and long duration, propagate for large distances across oceanic lithosphere. These waves are generated by multiple forward scattering of P- and S-waves due to small-scale heterogeneities in oceanic lithosphere and P-waves trapped in seawater. To study the origin of such small-scale heterogeneities, we analyzed the azimuthal anisotropy of Po/So waves propagating in the Northwest Pacific.

Seismological observations using Broad Band Ocean Bottom Seismometers (BBOBSs) were conducted in the Northwest Pacific from 2010 to 2014 as a part of the Normal Oceanic Mantle Project. During the experiments, high-quality Po/So waves were recorded from earthquakes in the subducting Pacific plate. We determined travel times of the Po/So waves using an auto-picking algorithm based on an AR model, and estimated the average velocities of the Po/So waves between sources and stations. The average velocities of the Po/So waves traveling in the Northwest Pacific show clear variations as a function of azimuth, as follows:
$V_{Po} = 8.25 + 0.20 \cos 2(x - 153)$,
$V_{So} = 4.71 + 0.04 \cos 2(x - 159)$.
The magnitudes of the anisotropy for Po and So waves velocities are 2.4% and 0.8%, respectively, which are smaller than the results of previous studies for Pn and Sn waves [Shimamura, 1984; Shinohara et al., 2008]. The fast direction is parallel to the past spreading direction of oceanic crust as estimated from magnetic anomalies [Nakanishi et al., 1992], which is roughly consistent with the previous studies [Shimamura, 1984; Shinohara et al., 2008].

We investigate the mechanism of the azimuthal anisotropy of Po/So wave propagation, which should be relating to the generation and evolution of the oceanic lithosphere using a Finite Difference Method (FDM) simulation of seismic wave propagation. We compare observed and calculated Po/So waves, and discuss the mechanism of their azimuthal anisotropy.

Keywords: Po/So waves, anisotropy, oceanic lithosphere

# Possibility of anisotropic structure in electrical conductivity for the upper mantle beneath northwestern Pacific Ocean

*Kiyoshi Baba[1], Hisashi Utada[1]

1.Earthquake Research Institute, The University of Tokyo

We have estimated isotropic one-dimensional (1-D) structure in electrical conductivity beneath the northwestern Pacific through Normal Oceanic Mantle Project. However, the model did not explain observed magnetotelluric (MT) responses perfectly. The misfits should be attributed to the lateral heterogeneity and/or anisotropic structure. In this study, we examined if some possible anisotropic structures can explain the observed MT responses better or not. We consider anisotropic structures that the conductivity in the asthenospheric mantle is higher in the direction parallel to the current plate motion (~N63°W) and that the conductivity in the lithospheric mantle is higher in the direction parallel to the past plate spreading direction (~N22°W). We also consider the effect on surface heterogeneity due to ocean-land distribution and bathymetric change. We simulated MT responses in the survey area A (northwest of the Shatsky Rise) to the 3-D surface heterogeneity over 1-D anisotropic structures and compared with the MT responses observed and simulated to the isotropic model. The result showed that any models considered in this study did not improve the misfit to the data, suggesting that rather laterally heterogeneous structure is more likely.

Keywords: marine magnetotellurics, electrical conductivity, anisotropy, lithosphere, asthenosphere, Northwestern Pacific Ocean

 

# Constraints on mantle anisotropy from the NoMELT magnetotelluric data set

*Tetsuo Matsuno[1], Rob L. Evans[2], Kiyoshi Baba[1]

1.Earthquake Research Institute, The University of Tokyo, 2.Woods Hole Oceanographic Institution

The formation of lithosphere at a mid-ocean ridge and the subsequent movement of that lithosphere across the underlying convecting asthenosphere result in deformation through shearing. This deformation can result in anisotropy in measureable physical properties such as the lattice preferred orientation of olivine, with the a-axis aligned in the direction of mantle flow. Patterns of anisotropy and the depths over which anisotropy occurs can, in turn, constrain models of lithospheric formation and evolution. Seismic results from the NoMELT data at 70 Ma Pacific seafloor reveal strong anisotropy through the lithosphere, with fabric aligned parallel to the fossil spreading direction. There is a decrease in anisotropy through the lithosphere-asthenosphere boundary and almost no anisotropy in the asthenosphere (Lin et al., submitted). Despite the strong patterns of anisotropy seen in the seismic data set from the NoMELT experiment, a previous analysis of coincident magnetotelluric (MT) data showed no evidence for anisotropy in the electrical conductivity structure of either lithosphere or asthenosphere (Sarafian et al., 2015). This apparent discrepancy raises two questions: 1) Could the MT data detect the seismic anisotropy layer in the lithosphere if it existed? 2) Is such a layer compatible with observations from the NoMELT region and, if so, what are the constraints on the properties of such a layer? To answer these questions, we revisit the MT data and use 1-D anisotropic models to demonstrate the limits of acceptable anisotropy within the data. We construct 1-D anisotropic models by varying the thickness of the anisotropic layer and the degree of anisotropy in the lithosphere, based on the results of Sarafian et al. (2015), and carry out a series of forward modeling to generate a suite of MT responses. We compare the values of the calculated splits in the off-diagonal elements of the MT responses with those seen in the NoMELT data, which allows us to place some constraints on the permissible anisotropic models. We discuss several topics including consistency with the seismic anisotropy, consistency with the electrical anisotropy model by shearing (Pommier et al., 2015), and whether our result is helpful to discriminate between water and melt models of upper asthenosphere.

 

# What controls the rate of seafloor subsidence?

Tomoko Korenaga[1], *Jun Korenaga[1]

1.Department of Geology and Geophysics, Yale University

The seafloor subsides as it moves away from mid-ocean ridges, and the rate of subsidence can largely be explained by thermal isostasy. There exists, however, an important difference between theoretical predictions and the observed rate for normal seafloor, even if we restrict ourselves to relatively young seafloor with ages less than 70 Ma. Two hypotheses have been put forward to explain this discrepancy, one with the incomplete thermal contraction due to the strongly temperature-dependent viscosity of oceanic lithosphere, and the other with dynamic topography originating in radioactive heating in the convecting mantle. These two mechanisms are not mutually exclusive. As the degree of incomplete thermal contraction can be bounded by theoretical consideration, we may be able to use the observed discrepancy to infer the amount of radioactive heating in the convecting mantle. We will present a unified theoretical model that can treat these two effects simultaneously and quantify how the rate of seafloor subsidence is controlled by different processes.

 

# Fabrication of uni- and tri-axially oriented olivine aggregates using colloidal processing under high magnetic field

*Sanae Koizumi[1], Thoru S Suzuki[2], Yoshio Sakka[2], Takehiko Hiraga[1]

1.Earthquake Research Institute,The University of Tokyo, 2.National Institute for Material Science

Olivine is the most abundant mineral in the Earth's upper mantle and it is considered to orient crystallographically in response to the mantle flow. Physical properties of olivine such as elasticity, plasticity, thermal conductivity, thermal expansion and electron conductivity are known to be very anisotropic so that geophysical observations that show directional dependence in the mantle are often attributed to the result of crystallographic preferred orientation (CPO) of this material. To understand the CPO effects on bulk rock properties, it is ideal d to prepare a material that reproduces the rock texture and measure its properties directly.

Magnetic field (up to 12 T) was applied to fine-grained (~120 nm) equigranular Fe-free and Fe-bearing olivine particles, which were dispersed in ethanol (solvent) with expectation of alignment of certain crystallographic axis of the particles with respect to the magnetic direction due to the olivine magnetic anisotropy. To align the magnetic easy and hard axes of olivine, we used a vertical static magnetic field and horizontal magnetic field with rotating suspensions of the olivine particles, respectively. For tri-axial alignment, we used a horizontal magnetic field with changing rotation rate of the suspensions. The dispersed and aligned particles in a strong magnetic field were gradually deposited on a solid-liquid separation filter during ethanol drainage. The dried particles were then densified isostatically and sintered under vacuum condition out of magnet. With this technique, we could obtain c-, b-axes uniaxially and triaxially aligned Fe-bearing (Fe : Mg = 1 : 9) olivine aggregates with achievements of high density (≥ 99%) and fine grain size.

Keywords: olivine, crystallographic preferred orientation

 

# Doping effect on high-temperature creep of olivine aggregates

*Kosuke Yabe[1], Takehiko Hiraga[1]

1.Earthquake Research Institute, The University of Tokyo

It is very important to examine the flow properties of the upper mantle for understanding the mantle flow and the origin of asthenosphere. Previous studies on creep properties of polycrystalline olivine prepared from naturally derived olivine have shown the effects of temperature, grain size, stress, and the amount of water and melt, which help to construct an applicable flow law to the natural condition (Karato et al 1986, Hirth and Kohlstedt 1995, Mei and Kohlstedt 2000). However, Faul and Jackson (2007) showed that olivine aggregates prepared from reagents using sol-gel technique had about 2 orders of magnitude larger strength compared to the naturally derived olivine aggregates. Later Hansen et al. (2011) showed that Hirth and Kohlstedt (1995) had overestimated the grain sizes of the specimens, but even if it is considered, there remains difference in the strength by about one order of magnitude under diffusion creep regime.

The inconsistency in strength can be resulted from a small difference in chemical composition because it has been observed that a small amount of impurities such as CaO, $Al_2O_3$, $TiO_2$ were segregated at grain boundaries in naturally derived olivine aggregates (Hiraga et al. 2003), and because such impurities segregated at grain boundaries have been found to have a large effect on the strength of polycrystalline oxides such as alumina and zirconia (Yoshida et al. 1997).

In this study, we synthesized olivine aggregates by using a new technique and conducted high-temperature creep experiment on such synthesized olivine aggregates. Also we introduced small amount of impurities on such aggregates to investigate the effect of chemical composition 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, $TiO_2$ were prepared. Deformation tests on these samples showed that non-doped samples were deformed under grain boundary diffusion creep and that there was no major difference in strength between non-doped and impurity-doped samples. Further, the strength was essentially identical to the aggregates by Faul and Jackson (2007). The similar strength of synthesized olivine aggregates used in our study and Faul and Jackson (2007) strongly suggested the presence of unknown chemicals that control creep properties of polycrystalline olivine.

Keywords: olivine aggregates, rheology, doping effect

 

# Effects of chemical composition and melting on viscosity and electrical conductivity of synthesized lherzolite.

*Kenta Sueyoshi[1], Takehiko Hiraga[1]

1.Earthquake Research Institute, The University of Tokyo

Viscosity and electrical conductivity of the mantle are considered to be sharply changed at around solidus temperature during ascend of the mantle. In order to evaluate the melting effects on such physical properties of ascending mantle (ex. beneath mid-ocean ridge), we monitored the viscosity and electrical conductivity of synthesized lherzolite aggregates during raising temperature from well below solidus temperature under atmospheric pressure.
We synthesized Fe-free lherzolite aggregates composed of forsterite (fo), enstatite (en), diopside (di) and anorthite (an) from $Mg(OH)_2$, $SiO_2$, $CaCO_3$ powders with particle size of <50 nm and spinel powders with particle size of ~200nm. By changing the amount of spinel, we controlled fraction (φ) of incipient melt ranging from 0.005 to 0.06. Samples were sintered at temperature below solidus (~ 1230°C ) to prepare melt-free aggregates before experiments.
We found two types of chemical effects on subsolidus condition. The spinel-added samples exhibited about an order of magnitude lower viscosity compared to spinel-free samples. Fo + en + di and fo + en samples (Tasaka et al., 2013) exhibited the similar viscosity. Further, fo + en + spinel samples and fo + en + di + an samples exhibited the similar viscosity indicating that small amount of Al at grain boundaries or grain interior increases creep rate of the aggregates. Electrical conductivities of all diopside-bearing samples were higher than the conductivity of fo + en sample. No dependency of electron conductivity on grain size was detected for diopside-bearing samples indicating that Ca at grain interior of forsterite enhanced the electrical conductivity. During crossing solidus temperature, the samples with the lowest incipient melt fraction (φ = 0.005) showed a gradual decrease in viscosity and gradual increase in electrical conductivity whereas larger incipient melt fraction (φ = 0.04) samples showed step-wise decrease and increase in viscosity and electrical conductivity, respectively. The melt effect on viscosity could be expressed in empirical expression of $\eta \propto \exp(\alpha\varphi)$ where $\alpha$= 69. This value is considerably larger than the value ($\alpha$ = 21) previously proposed from creep experiment of synthesized lherzolite aggregates using natural minerals, (Zimmerman and Kohlstedt, 2004).

Keywords: viscosity, electrical conductivity, melt

 

# Dependency of creep mechanism on stress and temperature for two phase system of forsterite + enstatite

*Tadashi Nakakoji[1], Takehiko Hiraga[1]

1.Earthquake Research Institute, The Univeristy of Tokyo

Flow mechanism of the earth’s upper mantle is estimated based on observation of microstructure of natural rocks, geophysical observation and experimental results obtained in laboratory. The experimental results are extrapolated to the mantle condition by using flow law. Therefore, obtaining precise flow-law parameters are key to understand the mechanism. However it is difficult to determine their values with small error range because of their strong dependency on stress, grain size and temperature. Tasaka et al. (2013) developed a viscosity model which includes a fraction of second phase for forsterite + enstatite system. They showed that a combination of flow laws for each mineral phase is applicable to polymineralic system with incorporating the fraction of mineral phases. However, their proposed activation energy of creep have a large error of ±50 kJ/mol, and obtained stress exponent, $n$, varies from 1.0 to 1.5 so that application of their results to nature is not precise yet.

We conducted two different types of creep experiments with synthetic sample of forsterite + 10vol% enstatite under high temperature ranging from 1150°C to 1370°C with application of various constant loads of 3 to 320 MPa. One was aimed for evaluating activation energy of creep and the other was for obtaining a precise stress exponent. We obtained stress-dependent activation energy and temperature-dependent stress exponent. At lower stress condition, apparent activation energy is ~ 600 kJ/mol. In contrast, at stress range of 60~120 MPa, the lower energy of ~ 370 kJ/mol was obtained. At 1370°C, the apparent stress exponent of ~ 1.2 was obtained whereas a larger value of ~ 1.5 was obtained at 1150°C. These results indicate that two types of deformation mechanisms were operated during our experiments.

In two-phase system, Burton (1973) proposed that the second phase particle on grain boundaries of the primary phase inhibits diffusion creep, because the second phase limits grain boundary to act as a perfect sink or source of vacancy. When density or mobility of defects at grain boundary is small, deformation will be rate-controlled by defect formation at interfaces. In this case, strain rate is proportional to ~ $s^2/d$ (Ashby and Verrall 1973) where $s$ is applied stress and $d$ is grain size. Since such interface reaction-control creep and diffusion creep both are rate-limiting processes for bulk deformation, reciprocal bulk strain rate can be expressed by a sum of reciprocal strain rate of interface-controlled diffusion and normal diffusion creep. Based on our obtained flow-law parameters, interface–reaction controlled diffusion creep dominated at lower temperature and lower stress conditions, and Coble-type diffusion creep dominated at higher temperature and higher stress conditions.

Keywords: creep mechanism, forsterite, interface reaction, two-phase system, rate-controlling process, activation energy

 