Toward the reconciliation of seismological and petrological perspectives on oceanic lithosphere heterogeneity

*Kennett Brian[2], Takashi Furumura[1]

1.Earthquake Research Institute The University of Tokyo, 2.Research School of Earth Sciences The Australian National University

The character of the high-frequency seismic phases *Po* and *So*, observed after propagation for long distances in the oceanic lithosphere, requires the presence of scattering from complex structure in 3-D. Current models use stochastic representations of seismic structure in the oceanic lithosphere. The observations are compatible with quasi-laminate features with horizontal correlation length around 10 km and vertical correlation length 0.5 km, with a uniform level of about 2% variation through the full thickness of the lithosphere. Such structures are difficult to explain with petrological models, which would favor stronger heterogeneity at the base of the lithosphere associated with underplating from frozen melts. Petrological evidence mostly points to smaller-scale features than suggested by seismology. The models from the different fields have been derived independently, with various levels of simplification. Fortunately, it is possible to gently modify the seismological model toward stronger basal heterogeneity, but there remains a need for some quasi-laminate structure throughout the mantle component of the oceanic lithosphere. The new models help to bridge the gulf between the different viewpoints, but ambiguities remain.

Keywords: Oceanic Mantle, Heterogeneity, Scattering of seismic wave, Po/So phases

Structure and deformation of the oceanic upper mantle from surface waves

*Eric Debayle[1], Alice Adonis[1], Yanick Ricard[1], Tak Ho[2], Keith Priestley[2]

1.Univ. Lyon, Université Lyon 1, ENS de Lyon, CNRS, UMR 5276 LGL-TPE, F-69622, Villeurbanne, France, 2.Bullard Laboratories, University of Cambridge, UK

We will discuss the seismic structure of the oceanic lithosphere and asthenosphere from our recent S-wave tomographic models of the upper mantle.
We observe that on average, the deepening of fast S-wave velocities with age follows approximately the trend predicted by the square root of age cooling model. However, for ages larger than 100 Myrs, some flattening of the isotherms may be inferred, as predicted by thermal models where a constant heat flux is provided at depth.
Both radial and azimuthal anisotropies are significant in the uppermost 200-250 km of the upper mantle, and peak in the oceanic asthenosphere, between 100 and 150 km depths.
The correlation of azimuthal anisotropy with the actual plate motion in the shallow oceanic lithosphere is very weak. A better correlation is obtained with the fossil accretion velocity recorded by the gradient of local seafloor age. The transition between lithospheric and active anisotropy occurs across the typical square root of age isotherm that defines the bottom of the thermal lithosphere around 1100 C. The azimuthal anisotropy projected onto the direction of present plate motion shows a very specific relation with the plate velocity; it is very weak for plate velocities smaller than 3 cm yr^{-1}, increases significantly between 3 and 5 cm yr^{-1}, and saturates for plate velocities larger than 5 cm yr^{-1}. Plate-scale present-day deformation is remarkably well and uniformly recorded beneath the fastest-moving plates (India, Coco, Nazca, Australia, Philippine Sea and Pacific plates). Beneath slower plates, plate-motion parallel anisotropy is only observed locally, which suggests that the mantle flow below these plates is not controlled by the lithospheric motion (a minimum plate velocity of around 4 cm yr^{-1} is necessary for a plate to organize the flow in its underlying asthenosphere).
A broad region with a stronger than average S-wave attenuation is observed near 150 km depth in the middle of the Pacific ocean. This anomaly is not correlated with the age of the oceanic lithosphere. It could be explained by higher than average temperatures, possibly due to the upwelling of hot material, which would have a stronger effect on seismic attenuation than on seismic velocities.

Keywords: Oceanic lithosphere and asthenosphere, S-wave heterogeneities, azimuthal and radial anisotropy, S-wave attenuation

Constraints on composition and flow in the oceanic mantle from a high-resolution estimate of seismic velocities and electrical conductivity in the central Pacific

*James B Gaherty[1], Peiying Patty Lin[2], Joshua Russell[1], Daniel Lizarralde[3], John Collins[3], Hannah Mark[3], Rob Evans[3], Emily Sarafian[3], Greg Hirth[4]

1.Lamont Doherty Earth Observatory, 2.Taiwan Ocean Research Institute, 3.Woods Hole Oceanographic Institution, 4.Brown University

Recent theoretical models of the seismic properties of mantle rocks predict seismic velocity profiles for mature oceanic upper mantle that are fundamentally inconsistent with the best observations of seismic velocities in two ways. Observations of strong positive velocity gradients with depth, and a very sharp and very shallow low-velocity asthenosphere boundary (LAB), both suggest that non-thermal factors such as bulk composition, mineral fabric, grain size, and dehydration play important roles in controlling the formation of the lithosphere, and thus the underlying LAB. There is little consensus on which of these factors are dominant, in part because high-resolution observations of detailed lithosphere and asthenosphere structure are limited. To address this discrepancy, we conducted the NoMelt experiment on ~70 Ma Pacific lithosphere between the Clarion and Clipperton fracture zones. The experiment consists of a 600x400 km array of broad-band (BB) ocean bottom seismometers (OBS) and magnetotelluric (MT) instruments, and an active-source reflection/refraction experiment.

The combined results from MT, surface-wave, and P-wave refraction data suggest that the central Pacific upper mantle can be characterized by a cold, dry lithosphere overlying a damp asthenosphere, with no melt required. P-wave velocity increases rapidly in the shallow mantle, with evidence for a distinct, high-velocity reflector at mid-lithosphere depths suggestive of a possible phase change. Seismic anisotropy is extremely strong in the lithosphere with fast direction aligned with fossil spreading. Strength of the fabric increases with depth in the shallow lithosphere, before systematically decreasing with depth into the asthenosphere. Minimum azimuthal anisotropy occurs within the middle of the low-velocity zone, and then it increases with depth, achieving a secondary maximum at about 250 km depth, below the weakest portion of the asthenosphere. Fast directions rotate from fossil-spreading direction within the lithosphere, to a more east-west direction at depth. In no depth range does the direction correspond to apparent plate motion. We interpret the anisotropy as arising from the combination of two processes: shear-strain during corner flow at the ridge axis, and pressure- and/or buoyancy-driven flow within the asthenosphere, perhaps in a non-Newtonian viscous channel. Shear associated with motion of the plate over the underlying asthenosphere, if present, is weak compared to these processes.

Keywords: seismic anisotropy, electrical conductivity, lithosphere, asthenosphere, ocean-bottom seismology

Five years of the Normal Oceanic Mantle (NOMan) Project

*Hisashi Utada[1], Hitoshi Kawakatsu[1], Hajime Shiobara[1], Kiyoshi Baba[1], Takehi Isse[1], Akiko Takeo[1], Daisuke Suetsugu[2]

1.Earthquake Research Institute, University of Tokyo, 2.Institute of Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology

The Normal Oceanic Mantle (NOMan) project was carried out for 5 years from 2010, aiming to solve two fundamental questions on the ’normal’ oceanic mantle from observational approach, which are: (a) Cause of asthenosphere lubrication, and (b) Amount of water in the mantle transition zone. We selected two study areas (A and B) of similar seafloor age (about 130 and 140 Ma, respectively) in the northwestern Pacific Ocean where the mantle below is supposed to be normal. This presentation will give an overview of five years of the NOMan project, especially of its observational activities and a summary of preliminary results so far obtained.
6 scientific cruises were carried out during the five years' NOMan Project, from June 2010 to September 2014. We deployed state-of-the-art ocean bottom seismic and electromagnetic instruments (BBOBS-NXs and EFOSs) in area A that are handled by ROV for installation and recovery, as well as conventional instruments (BBOBSs and OBEMs of free-fall/self-pop-up type) both in areas A and B. The seafloor age difference between study areas A and B is only about 10 Ma, which was thought small enough for the temperature difference between two areas to be ignored at the first order approximation. So we originally expected that corresponding results in area B show close similarity to those in are A. However, a result of 1-D array analysis of the surface waves indicated certain difference in the lithosphere-asthenosphere structure between areas A and B. 1-D inversion results of multi-station seafloor magnetotelluric (MT) data also show a clear difference between these two areas. Furthermore, MT results in surrounding areas obtained by previous projects imply the presence of further large-scale lateral heterogeneity in the old oceanic mantle in the northwestern Pacific toward the subduction zone. For the moment, we are trying to invert each of NOMan geophysical dataset as accurately as possible so as to characterize the mantle structure and its lateral variation. Later we try to clarify the cause for these lateral variabilities, as it can be one of the key issues to understand the lithosphere-asthenosphere system in the old oceanic mantle.
For the key question (b), high-quality data obtained by the long-term seafloor observations are used to investigate the MTZ structure. In particular, electric field data obtained by EFOS (with 2 km electrode separation) provide longer period MT responses sensitive to the MTZ. Resulting MT and GDS (Geomagnetic Deep sounding) responses are almost consistent with the NW Pacific semi-global 1-D model (Shimizu et al., 2010). This indicates that the MTZ conductivity below the study region has weak lateral variation (well approximated by a 1-D model). Assuming geotherm in the MTZ from the receiver function analyses, this 1-D profile is consistent with the conductivity of MTZ minerals containing at most 0.1-0.5 wt.% water.

Keywords: Normal oceanic mantle, Lithosphere-Asthenosphere system, Ocen bottom geophysical observation

Azimuthal anisotropy and seismic discontinuity in the oceanic lithosphere revealed by active source surveys

*Takehi Isse[1], Gou Fujie[2], Hajime Shiobara[1], Hiroko Sugioka[3], Aki Ito[2], Akiko Takeo[1], Hisashi Utada[1], Shuichi Kodaira[2]

1.Earthquake Research Institute, the University of Tokyo, 2.Japan Agency for Marine-Earth Science and Technology, 3.Department of Planetology, Kobe University

We have conducted a seafloor observation called Normal Oceanic Mantle (NOMan) project to understand the physical condition for the lithosphere-asthenosphere boundary, which is not yet well determined from 2010 to 2014 in the northwestern Pacific Ocean using broadband ocean bottom seismometers (BBOBSs) and ocean bottom electromagnetometers (OBEMs).
During NOMan project, 6 extensive seismic refraction and reflection surveys by airgun sources have been conducted in the outer rise region of the northwestern Pacific region, westward of the NOMan project observation, to investigate structural changes in an incoming plate.
We observed clear seismic phases in the source-receiver distance range of 400-900 km and interpreted these phases as P-wave reflections from a depth of 50-60 km. The reflection points were located in area whose latitudes are between 36°N and 41°N and longitudes are between 149°E and 153°E, at east of the Nosappu Fracture zone.
Since we observed air-gun signals from various azimuthal directions, we can also analyze the azimuthal dependence of the propagating velocities. The obtained arrival times suggest that the peak-to-peak amplitude of azimuthal anisotropy above the reflectors are about 2 % at most. Previous studies in the northwestern Pacific Ocean show stronger anisotropy (5~10 %) in the uppermost mantle, a few kilometers beneath the Moho, by using Pn-wave. These may suggest that intensity of azimuthal anisotropy deceases with depths up to 50-60km bsf.

Keywords: oceanic lithosphere, active source survey, azimuthal anisotropy

Interpretation of the high conductive anomaly in the upper mantle beneath the Society hotspot

*Noriko Tada[1], Pascal Tarits[2], Kiyoshi Baba[3], Hisashi Utada[3], Daisuke Suetsugu[1], Takafumi Kasaya[1]

1.Japan Agency for Marine-Earth Science and Technology, 2.UMR- Domaines Océaniques, IUEM, 3.Earthquake Research Institute, The University of Tokyo

The mantle upwellings are one of the most important features for understanding the mantle dynamics. A large-scale mantle upwelling beneath the French Polynesia region in the South Pacific has been suggested from seismic studies, which is called the South Pacific superplume, and a slow velocity anomaly continues from the core mantle boundary to the upper mantle just beneath the Society hotspot (e.g., Suetsugu et al., 2009). However, the previous studies are not enough to understand the geometry, temperature, and composition of the Society hotspot. Then, we carried out the TIARES project that composed of multi-sensor stations that include broadband ocean bottom seismometers, ocean bottom electromagnetometers (OBEMs), and differential pressure gauges from 2009 to 2010 (Suetsugu et al., 2012). In this study, we will present the results of observed data obtained from OBEMs.
In order to obtain three-dimensional (3-D) image of the upwelling of the Society hotspot in terms of electrical conductivity, we newly settled eleven OBEMs. In addition to these data, the old data obtained by Nolasco et al. (1998) was reanalyzed, and we obtained magnetotelluric (MT) responses at 20 sites totally. A 3-D marine MT inversion program (Tada et al., 2012; Baba et al., 2013), which can treat topographic change distorting EM data, was applied to these MT responses to estimate 3-D electrical conductivity image beneath the seafloor.
The 3-D electrical conductivity image revealed a thumb-like high conductive anomaly beneath the Society hotspot. To clarify the cause of the high conductivity, water content, melt fraction, and H_2O and CO_2 contents in the upper mantle were estimated by adopting results of rock experiments at high temperatures and pressures. As a result, the upper mantle in the high conductive anomaly involves more water, melt, H_2O, and CO_2 rather than that in the surrounding area. Furthermore, temperature of high conductive anomaly might be higher than the surrounding area.

Keywords: hotspot, electrical conductivity, upper mantle, melt, volatiles

Structure of suboceanic mantle below petit-spot volcanoes

*Naoto Hirano[1]

1.Center for Northeast Asian Studies, Tohoku University

Petit-spot volcanoes were first identified as eruptions on the subducting plate off the Japan Trench due to lithospheric flexure related to plate subduction (Hirano et al., 2006). Such volcanoes are likely to occur worldwide, as similar lavas have also been reported off the Chile and Java trenches (Hirano et al., 2013; Taneja et al., 2014). The magma that erupts from petit-spot volcanoes originates from the asthenosphere and ascends along the concavely flexed zone of the outer-rise prior to the zone of plate subduction. The occurrence of such volcanoes may not be limited to the zone of outer-rise warping of lithosphere prior to subduction, as they also occur in extensional basin-and-range settings (Valentine & Hirano, 2010) and lithosphere experiencing glacial rebound in the region south of Greenland (Uenzelmann-Neben et al., 2012). The geochemistry of lavas and entrained xenoliths from petit-spot volcanoes provides clues to the structure and dynamics of suboceanic mantle, which had previously been difficult to explore. Spatial variations in the geochemistry and ages of petit-spot lavas show the systematic distribution of melt pockets in the source mantle, which move with plate motion (Machida et al., 2015). Yamamoto et al. (2014) reported on areas of asthenosphere melt and its migration against plate motion. The CO_2 emissions of petit-spots are important globally and indicate a mantle source, probably asthenosphere (Hirano, 2011; Okumura & Hirano, 2013).

Monogenetic petit-spot volcanoes in the Japan Trench have erupted in clusters at 1.8, 4.2, 6.0, 6.2, and 8.5 Ma (Ar–Ar age data: Hirano et al., 2001; 2006; 2008; Machida et al., 2015). Most of the lava samples from this region do not contain phenocrysts, in spite of their differentiated compositions of 45–52 wt% SiO_2 and Mg# of 50–65 (Hirano et al., 2006); therefore, the magmas must have been differentiated in the magma chamber. Petrography and geobarometer analyses of peridotitic xenoliths show that they ascended rapidly through the upper lithosphere, as the deepest xenoliths originated from ~42 km depth, corresponding to the middle of the subducting Pacific lithosphere (Yamamoto et al., 2014). These data indicate that the magma stagnated and differentiated at depths below the middle lithosphere. The high CO_2 contents of petit-spot lavas raise the possibility that CO_2 affects the source components and their melting. Lithospheric contamination must occur during magma ascent. The lower lithosphere below clusters of petit-spot volcanoes is possibly subjected to metasomatism by carbon-rich (or highly alkaline) melt.

Lithospheric structure deduced by olivine crystal-fabrics in peridotites

*Katsuyoshi Michibayashi[1]

1.Institute of Geosciences, Shizuoka University

Crystallographic preferred orientations (CPOs) of olivine within natural peridotites are commonly depicted by pole figures for the [100], [010], and [001] axes, and they can be categorized into five well-known fabric types: A, B, C, D, and E. These fabric types can be related to olivine slip systems: A with (010)[100], B with (010)[001], C with (001)[001], D with {0kl}[100], and E with (001)[100]. In addition, an AG type is commonly found in nature, but its origin is controversial, and could involve several contributing factors such as complex slip systems, strain types, or the effects of melt during plastic flow. We present all of our olivine fabric database published previously as well as new data mostly from ocean floor, mainly for the convergent margin of the western Pacific region, and we introduce a new index named *Fabric-Index Angle* (FIA), which is related to the P-wave property of a single olivine crystal. The FIA can be used as an alternative to classifying the CPOs into the six fabric types, and it allows a set of CPOs to be expressed as a single angle in a range between -90° and 180°. The six olivine fabric types have unique values of FIA: 63° for A type, -28° for B type, 158° for C type, 90° for D type, 106° for E type, and 0° for AG type. Our results show that although our database is not yet large enough (except for trench peridotites) to define the characteristics of the five tectonic groups, the natural olivine fabrics vary in their range of FIA: 0° to 150° for the ophiolites, 40° to 80° for the ridge peridotites, -40° to 100° for the trench peridotites, 0° to 100° for the peridotite xenoliths, and -40° to 10° for the peridotites enclosed in high-pressure metamorphic rocks. We show a relationship between FIA and calculated azimuthal anisotropy. Since the direction of higher P-wave velocity is subparallel to the direction of the Plate motion, it may be likely to assume that olivine fabric types are between 0° (AG type) and 90° (D type). It shows that azimuthal anisotropy increases from 0° to 90°, indicating its direct relationship to olivine fabric types. Consequently, variation of azimuthal anisotropy in the Pacific Plate could result from variation of olivine fabric types; the region of higher azimuthal anisotropy in mantle could be dominated by A to D types, whereas the region of the lower azimuthal anisotropy in mantle could be characterized by AG-type like fabrics.

Keywords: Mantle, Peridotite, Olivine fabric

Mantle superplasticity and anisotropy

*Takehiko Hiraga[1], Genta Maruyama[1], Kosuke Yabe[1], Kenta Sueyoshi[1], Tadashi Nakakoji[1], Sanae Koizumi[1]

1.Earthquake Research Institute, University of Tokyo

Recently, we have experimentally shown that a significant crystallographic preferred orientation (CPO) of forsterite develops during Newtonian flow of the forsterite aggregate (Miyazaki et al., 2013). The aggregate also exhibits (i) superplasticity (>>100 % tensile strain) (Hiraga et al. 2010), (ii) same phase aggregation at the direction of compression (Hiraga et al. 2013) and (iii) essentially, no change in grain shape before and after the deformation. Thus, we concluded that grain boundary sliding (GBS) should have accommodated a majority of the sample strain. We found that the preexisting grain shape, which is controlled by crystallography of forsterite, controls the CPO development and its pattern. Based on these results, we estimated that the preferential GBS at the boundary parallel to the specific crystallographic plane (i.e., low-index plane grain boundary) resulted in CPO. To examine this hypothesis, we imposed line markers to the lateral surface of samples which were subsequently deformed. Absence of intragranular deformation, significant GBS and grain rotation were identified after the sample deformation. We found that the grain rotation was well reproduced by resolved shear stress applied to the low-index plane grain boundary (GB). Based on analysis of rate of grain rotation, we estimated that the low-index GB is 3~4 times less viscous relative to general (normal) GB resulting in an alignment of low-index GB with respect to deformation geometry. Appearance and type of such boundaries change with temperature and presence of melt indicating that GBS-induced CPO change with geological conditions. We apply our prediction to the asthenosphere beneath the Pacific basin, where the horizontal flow of the mantle starting from beneath the East Pacific Rise is well resolved by seismic tomography. We show that strong radial anisotropy is anticipated at temperatures corresponding to depths where melting initiates to depths where strongly anisotropic and low seismic velocities are detected. Conversely, weak anisotropy is anticipated at temperatures corresponding to depths where almost isotropic mantle is found. We propose superplastic (diffusion) creep to be the primary means of mantle flow.

Keywords: mantle, superplasticity, anisotropy

Generation and recycling of proto-oceanic lithosphere in Archean plume-lid tectonics

*Taras Gerya[1], Elena Sizova[2], Ria Fischer[1], Robert Stern[3]

1.Institute of Geophysics, ETH-Zurich, Switzerland, 2.Department of Earth Science, University of Graz, Austria, 3.Geosciences Department, University of Texas at Dallas, USA

Modern geodynamics and oceanic lithosphere growth are critically driven by subduction and plate tectonics, however how this tectonic regime started and what geodynamic regime was before remains controversial. Stability of modern-style single-sided subduction requires strong oceanic lithospheric plates with free surface and hydrated upper crust, but how such plates could have formed before plate tectonics remains enigmatic. Based on 2D and 3D magmatic-thermo-mechanical numerical experiments we suggest that a distinct Venus-like plume-lid tectonics regime operated on Earth before plate tectonics, which was associated with widespread tectono-magmatic heat and mass exchange between the crust and the mantle. This regime was characterized by the presence of weak internally deformable highly heterogeneous lithosphere with low topography, massive juvenile crust production from mantle derived melts, mantle-flows-driven crustal deformation, magma-assisted crustal convection and widespread development of lithospheric delamination and eclogitic drips. Both proto-continental and proto- oceanic domains were formed in this regime by a combination of eclogitic drips and ultra-slow proto-oceanic spreading. Proto-oceanic lithospheric mantle was colder, more depleted and poorer in eclogite inclusions compared to its proto-continental counterpart, due to higher degree of decompression melting within proto-oceanic spreading centers localized atop hot mantle upwellings. Numerical models show feasibility of short-lived deep subduction of ultra-depleted eclogite-poor proto-oceanic lithosphere. Subsequent rising and accretion of these chemically buoyant ultra-depleted mantle rocks to the bottom of unrelated heterogeneous crustal terrains may offer a feasible way for Archean cratonization and sub-continental lithospheric mantle (SCLM) formation. Numerical models also suggest that plume-induced subduction may likely played a crucial role for making transition from global plume-lid tectonics to global plate tectonics.

Keywords: Archean geodynamics, oceanic spreading, plate tectonics, numerical modeling

Macroscopic strength of oceanic lithosphere revealed by ubiquitous fracture-zone instabilities

*Cécilia Cadio[1], Jun Korenaga[2]

1.Géosciences Montpellier, Université Montpellier II and CNRS UMR 5243, 2.Department of Geology and Geophysics, Yale University

The origin of plate tectonics is one of the most fundamental issues in earth and planetary sciences. Laboratory experiments indicate that the viscosity of silicate rocks is so strongly temperature-dependent that the entire surface of the Earth should be one immobile rigid plate. The rheology of oceanic lithosphere is, however, still poorly understood, and there exist few constraints on the temperature dependency of viscosity on the field scale. Here we report a new kind of observational constraint based on the geoid along oceanic fracture zones. We identify a large number of conspicuous small-scale geoid anomalies, which cannot be explained by the standard evolution model of oceanic lithosphere, and estimate their source density perturbations using a new Bayesian inversion method. Our results suggest that they are caused most likely by small-scale convection involving temperature perturbations of ~300 K ±100 K. Such thermal contrast requires the activation energy of mantle viscosity to be as low as 100±50 kJ mol^{-1}, substantially reducing the thickness of the stiffest part of oceanic lithosphere. Oceanic lithosphere may thus be broken and bent much more easily than previously thought, facilitating the operation of plate tectonics.

Keywords: Plate tectonics, upper mantle rheology, convective instabilities, geoid anomalies

Rheological weakening via hydration reactions in a mantle shear zone: Implications for the initiation of oceanic plate subduction

*Ken-ichi Hirauchi[1], Kumi Fukushima[2], Masanori Kido[3], Jun Muto[3], Atsushi Okamoto[4]

1.Department of Geosciences, Faculty of Science, Shizuoka University, 2.Department of Science, Graduate School of Integrated Science and Technology, Shizuoka University, 3.Department of Earth Science, Graduate School of Science, Tohoku University, 4.Graduate School of Environmental Studies, Tohoku University

Plate tectonics on Earth is essential for mantle geochemistry and planetary habitability; however, its initiation remains controversial and previous geodynamic models require a preexisting zone of weakness (average stress less than 30 MPa) in the oceanic lithosphere. Although the operation of grain-sensitive creep (e.g., diffusion creep) causes a reduction in stress, fault strength near the brittle–ductile transition (BDT) remains remarkably high (1500 MPa), even when assuming olivine diffusion creep with an anomalously small grain size (1 μm) and a slow strain rate (10^{-15} s^{-1}). Although the oceanic lithosphere is considered to be dry, infiltration of seawater into a preexisting fault zone (e.g., fracture zones) will lead to the formation of hydrous phyllosilicates (e.g., amphibole, serpentine, and talc). To investigate hydration-induced rheological weakening effects on preexisting faults in intra-oceanic settings, we conducted high-pressure friction experiments on peridotite gouge under hydrothermal conditions. We find that increasing strain and reactions lead to the development of localized talc-rich shear zones, which induce an order-of-magnitude reduction in stress. The rate of reaction is strongly dependent on the degree of cataclastic deformation, rather than time.

Our laboratory experiments demonstrate that the operation of frictional–viscous flow, controlled by pressure-solution-accommodated frictional sliding on weak hydrous phyllosilicates, leads to a drastic reduction (down to 40 MPa) in the high stresses near the BDT within the oceanic lithosphere. Our results also suggest that the existence of oceans is a prerequisite for the initiation of plate tectonics on terrestrial planets (e.g., Earth); otherwise, stagnant lid convection operates in the mantle (e.g., Venus).

Keywords: oceanic mantle, subduction initiation, rheological weakening, brittle–plastic transition, frictional–viscous flow, talc

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, η_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 η_k is about twice as large as that of the conventional η, indicating that η_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 η_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:

$V_{Po} = 8.25 + 0.20 \cos2(x - 153)$,

$V_{So} = 4.71 + 0.04 \cos2(x - 159)$.

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 α= 69. This value is considerably larger than the value (α = 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

