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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

 