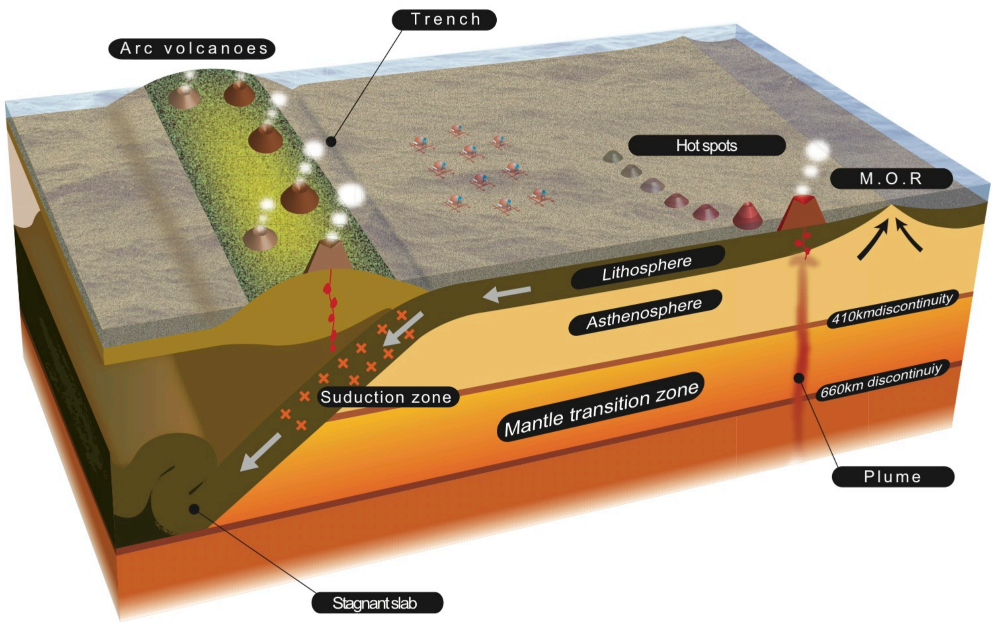
# International Workshop on
# *Normal Oceanic Mantle*




March 4-5, 2013
Earthquake Research Institute
University of Tokyo

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# International Workshop on Normal Oceanic Mantle

March 4-5, 2013

At meeting room-A, Earthquake Research Institute, University of Tokyo

## March 4

**Registration** (09:30-10:00)

**Session 1: Projects** #1 (10:00-12:15) Chair: Nozomu Takeuchi (ERI)

Utada, H. (ERI), Kawakatsu, H., Shiobara, H., Baba, K., Isse, T., Suetsugu D., and NOMan Project team

NOMan Project 1: Overview

Kawakatsu, H. (ERI)

NOMan Project 2: Toward comprehensive understanding of the lithosphere/asthenosphere system of the normal oceanic mantle *via in-situ* ocean bottom geophysical observations

(Break)

Shiobara, H. (ERI), Sugioka, H., Isse, T., Ito, A., Shinohara M., and Kanazawa, T.

NOMan Project 3: BBOBS-NX: practical observation tool for broadband seismology at the seafloor

Forsyth, D.W. (Brown), Shintaku, N., Booth, C., Takeo, A., and Weeraratne, D.

The PLATE Project in the Western Pacific

**Session 2: Projects** #2 (13:30-14:30) Chair: Hisayoshi Shimizu (ERI)

Gaherty, J.B. (Lamont), Lizarralde, D., Collins, J.A., Evans, R., and Hirth, G.

Lithospheric structure of the central Pacific: early returns from the NoMelt Experiment

Tarits, P. (UBO)

ELECTROLITH: Volatile Cycling and Electrical Conductivity in the Earth's Mantle: The Carbonatite connection

**Session3: Mantle imaging** (14:30-17:00)  Chair: Mamoru Kato (Kyoto)

Shito, A. (IFREE), Suetsugu, D., Furumura, T., and NOMan Project Team

Small-scale heterogeneities in the oceanic lithosphere inferred from guided waves

(Break)

Isse, T. (ERI), Shiobara, H., Sugioka, H., Ito, A., Suetsugu, D.

Three-dimensional shear wave structures of the upper mantle from seafloor observations in the western Pacific Ocean

Baba, K. (ERI), Tada, N., Utada, H., Shimizu, H.

Preliminary result on electrical conductivity imaging of normal oceanic mantle

Takeo, A. (ERI) and NOMan Project team

Uppermost mantle structure beneath oceanic regions from broadband array analysis of surface waves recorded by ocean bottom seismometers

**Banquette** at Hotel Edmont (19:00-21:00)

## March 5

**Session 4: Seismic anisotropy** (09:30-12:15) Chair: Kazunori Yoshizawa (Hokkaido)

Ekström, G. (Lamont)

Oceanic mantle structure from global tomography

Becker, T.W. (USC)

Seismic anisotropy below oceanic plates and large-scale mantle convection

Michibayashi, K. (Shizuoka)

Possible lateral variation of seismic anisotropies in the oceanic lithosphere due to an active mantle flow in the mid-ocean ridge: some insights from the Oman Ophiolite

(Break)

Song, TR. (IFREE) and Kawakatsu, H.

Subduction of oceanic asthenosphere: Evidence from sub-slab seismic anisotropy

Mainprice, D (Montpellier)

A database of crystal preferred orientation of olivine in upper mantle rocks – the direct mantle sample

**Poster Session (13:30-14:30)**

**Session 5: Physical properties** (14:30-16:00) Chair: Takehiko Hiraga (ERI)

Hirschmann, M. (Minnesota)

Volatile-rich partial melt at the base of the oceanic lithosphere and in the asthenosphere

Takei Y. (ERI), Karasawa F., and Suzuki A.

Experimental study on anelasticity of polycrystalline material for seismological application

Utada, H. (ERI) and Baba, K.

Estimating electrical conductivity of melt from observation

(Break)

**Session 6: Future** (16:30-17:30) Chair: Daisuke Suetsugu (IFREE)

Singh, S. (IPGP)

Imaging of Lithosphere Asthenosphere Boundary Across Atlantic Ocean: A Dream

**Discussions** (17:00-)

## Posters

Evans, R. (WHOI)

An extensive melt layer beneath the oceanic lithosphere asthenosphere boundary discovered by magnetotelluric data

Schardong, L. (ERI)

Toward a high resolution tomographic imaging of the lowermost mantle

Morishige, M. (IFREE)

Flow and thermal structure around the junction of Japan-Kurile arcs

Tada, N. (IREE)

3-D electrical conductivity structure beneath the Philippine Sea Plate

Takeuchi, N. (ERI)

Absence of the stagnant slab beneath northeast China constrained by a seismic station in Mongolia

Shimizu, H. (ERI)

Electrical voltage measured by long baseline submarine cables to probe the Earth's deep interior

Honda, S. (ERI)

Importance of hot anomaly adjacent to the subducting slab

Zhang, L. (ERI)

Three-dimensional simulation of the EM fields induced by 2011 Tohoku tsunami

Nishida, K. (ERI)

Global propagation of body waves revealed by cross-correlation analysis of seismic hum

Obayashi, M. (IFREE)

P-wave tomography using BBOBS data

# The NOMan Project: Overview

Hisashi Utada[1], Hitoshi Kawakatsu[1], Hajime Shiobara[1], Kiyoshi Baba[1], Takehi Isse[1], Daisuke Suetsugu[2], and the NOMan Project team

[1]Earthquake Research Institute, University of Tokyo, Japan,
[2]Japan Agency for Marine-Earth Science and Technology

The oceanic mantle is an important region to understand the Earth system, because more than 2/3 of the surface is covered by oceanic area. The NOMan project focuses on the 'normal oceanic mantle' in particular. Here 'the normal oceanic mantle' can be defined as the oceanic mantle without disturbance by vertical motion of mantle flow such as mid oceanic ridges, plate subductions, or hotspots (Fig. 1). We try to solve a couple of most fundamental questions concerning the normal oceanic mantle.

First question is on the cause of the asthenosphere, which is a lubricating layer below oceanic plate (lithosphere). Plate tectonics is based on a concept that a rigid lithosphere moves over a weaker asthenosphere, and thus the precise knowledge of its lubrication mechanism is fundamental to understand how our planet works.

The presence of water is one of the properties characterizing the planet Earth. Second question is the amount of water within the Earth, particularly in the mantle transition zone (MTZ). Because the MTZ minerals have very high water solubility that that of upper or lower mantle minerals, accurate estimation of water content in the MTZ is essential to understand the Earth's total water budget. The question may never be fully solved without the knowledge for the "normal oceanic mantle" that occupies the largest part of the entire mantle.

The NOMan project is carried out for 5 years from 2010. It aims to solve these two questions from observational approach in two target areas (A and B) in the northwestern Pacific Ocean (Fig. 2) where the mantle supposed to be normal. We plant to carry out long-term observation for one to three years at each of observation sites shown in Fig. 2, deploying state-of-the-art ocean bottom geophysical (seismic and electromagnetic) instruments installed by using ROV, as well as free-fall type instruments, which were all originally developed by our group.

In 2010, we started a 'pilot experiment' by deploying five sites in the area A. Although we originally planned to start a large array from the summer of 2011, major deployment was postponed by nearly one year due to the occurrence of the 2011 Tohoku Earthquake and Tsunami. In the fall of 2011, we have deployed only free-fall type instruments in the area B. Finally in the summer of 2012, we successfully deployed all stations in the area A for long-term observation. After replacement of several stations, all instruments will be recovered in the summer of 2012.

This presentation will give an overview of the NOMan Project, including research history of our group, motivation, progress, and perspective of the project.

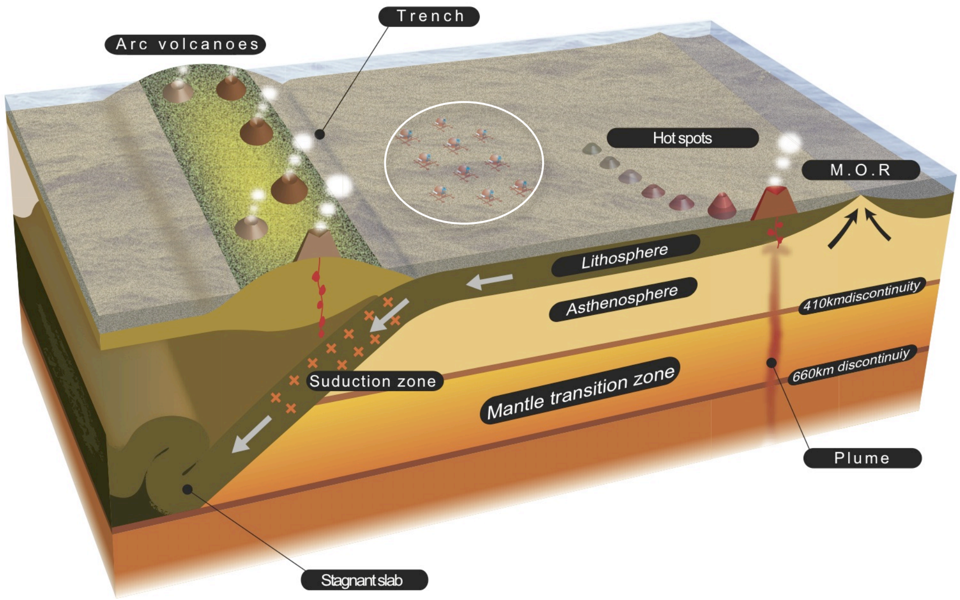



Fig. 1. The target (in the white circle) of the NOMan project, where the oceanic plate is moving horizontally. We try to have a clear image of the normal oceanic mantle from the LAB down to MTZ by long-term seafloor geophysical observation.

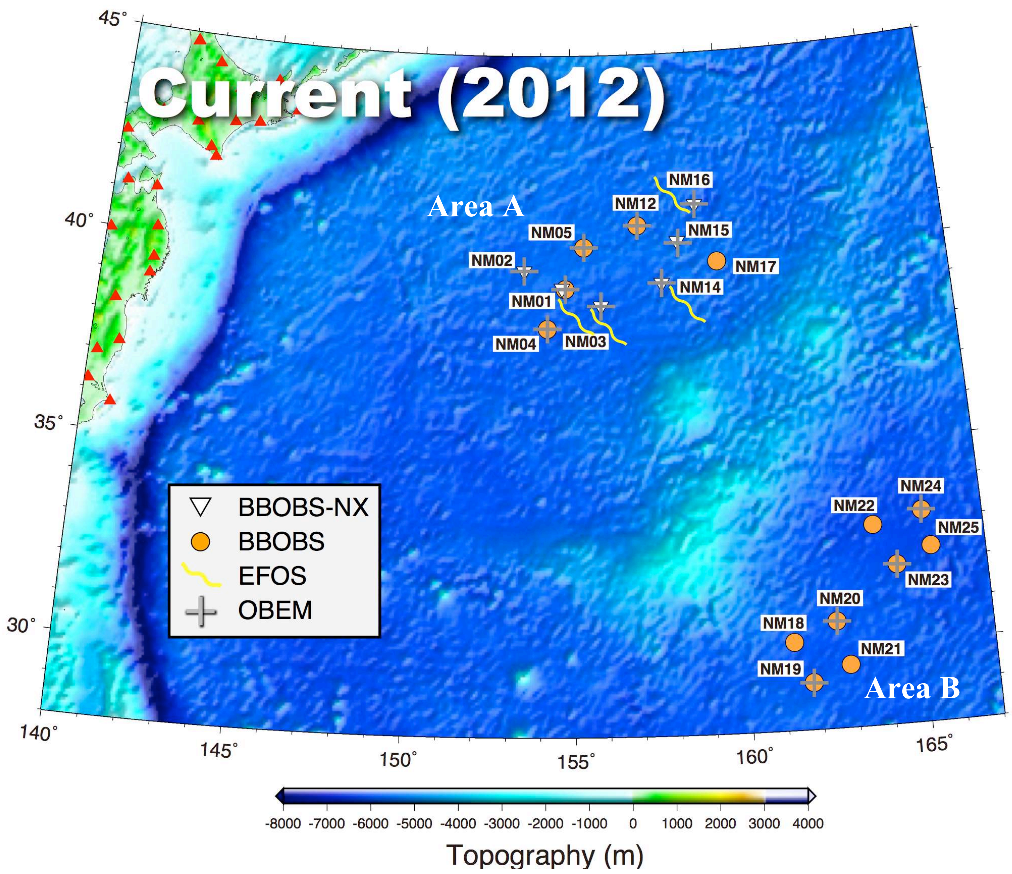



Fig. 2. Current site distribution in the NOMan study areas A and B.

# Toward comprehensive understanding of the lithosphere/asthenosphere system of the normal oceanic mantle *via in-situ* ocean bottom geophysical observations

Hitoshi Kawakatsu[1]

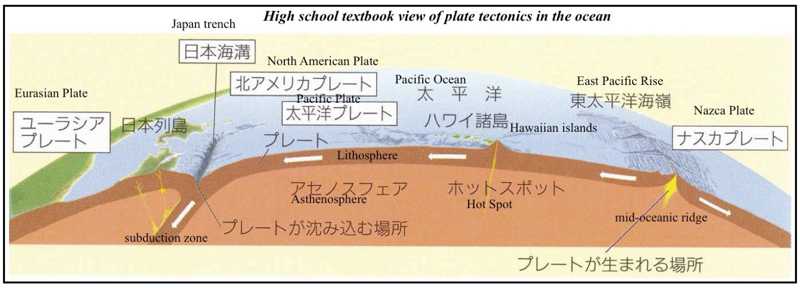
[1]Earthquake Research Institute, University of Tokyo, Japan

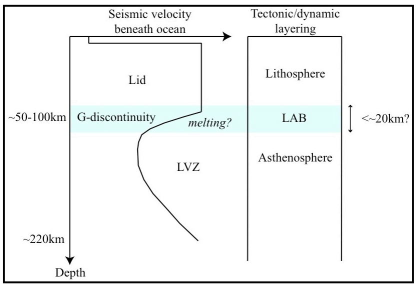
Plate tectonics started as a theory for the oceanic basin by investigating its shallowest part, leaving the deeper part of the lithosphere or lithosphere/asthenosphere system behind. Geophysical exploration in the ocean in the past several decades have focused on tectonically active areas, such as subduction zones, hot spots, mid-oceanic ridges, etc. Although these attempts have successfully elucidated the active part of the earth's processes, the importance of apparently quiet normal oceanic areas, where the structure below may offer a "textbook view" of the deep mantle, might have been underestimated. While which part of the ocean is really normal might be another interesting and difficult question to answer, a key for the breakthrough likely resides beneath there. There are few multi-disciplinary ocean bottom geophysical observations with state-of-the-art equipments have been undertaken in the "normal" Pacific ocean with which we hope to share the current knowledge and exchange ideas about future planning at this workshop.

In this summary presentation, I will review some of the recent progress made in the seismological literatures in the context of Normal Mantle Project, especially focusing on the lithosphere/asthenosphere system, and also discuss some of the issues that we hope to resolve in the project that might be also topics of the workshop.

The main issues to be discussed include:

(1) what is the nature and origin of the LID, G-discontinuity, and LVZ?
(2) what is the nature and origin of seismic anisotropy in the oceanic region?
(3) how the *in-situ* ocean bottom observation may help solving these issues?




(left) High school textbook view of plate tectonics in the ocean.
(right) Schematic diagram showing the relationship of LID, LVZ, G and LAB.

# BBOBS-NX: practical observation tool for broadband seismology at the seafloor

Hajime Shiobara[1], Hiroko Sugioka[2], Takehi Isse[1], Aki Ito[2],
Masanao Shinohara[1] and Toshihiko Kanazawa[1]

[1]Earthquake Research Institute, University of Tokyo, Japan
[2]IFREE, Japan Agency for Marine-Earth Science and Technology, Japan

Since 1999, we have already developed the mobile broadband ocean bottom seismometer (BBOBS, Fig. 1), and many practical observations have been conducted. But, the noise level of BBOBS's horizontal components in long periods is rather high in average and its variation in time is also large. The reason of this high noise level is assumed as the small tilt variation of the large housing sphere that contains the broadband sensor, recorder and batteries, due to the bottom current. To clear this problem, one idea of observation without the tilt variation is the use of small and low profile broadband sensor that enables to penetrate into the sediment, that is apart from the large housing. This next generation type of BBOBS (BBOBS-NX, Fig. 2) has been tested since 2008. The observation procedure of the BBOBS-NX is as following; (1) free-fall the BBOBS-NX to the seafloor aiming enough penetration of the sensor unit (CMG-3T special, 0.02–360 s) with the recording unit (ø650 Ti sphere housing) attached above it, (2) detach and move the recording unit from the sensor unit by using the ROV to start the observation, (3) pull-up the recording unit and the sensor unit connected with the umbilical rope to recover the whole BBOBS-NX by the ROV.

The averaged noise level of the BBOBS-NX is below the new high noise model (NHNM) for all three components in periods longer than 20 s, which is more than 20 dB of noise reduction in horizontal components compared to the BBOBS (Fig. 3). So, the BBOBS-NX's data is suitable for analyses using horizontal component waveforms, such as the receiver function analysis (Fig. 4). From a rough estimation, one year observation by the BBOBS-NX is long enough to get a reliable receiver function at a single station, although at least three years long observation was required for same quality by the BBOBS. This high performance in the broadband seismic observation at the seafloor is the key of this normal oceanic mantle project to research the nature of the LAB and the water content in the MTZ. Now, six BBOBS-NXs are deployed around the Shatsky Rise with other instruments.

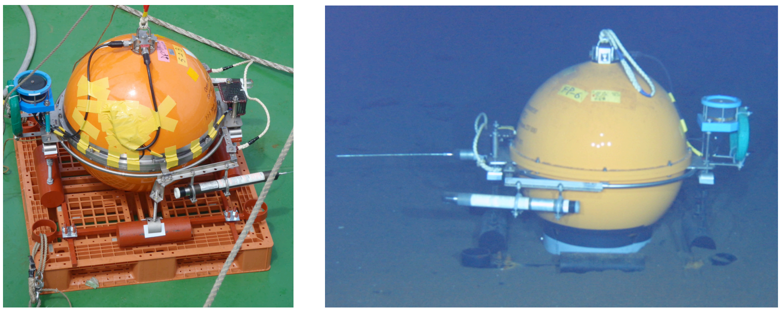


Fig. 1 The BBOBS on the deck (left) and on the seafloor (right).

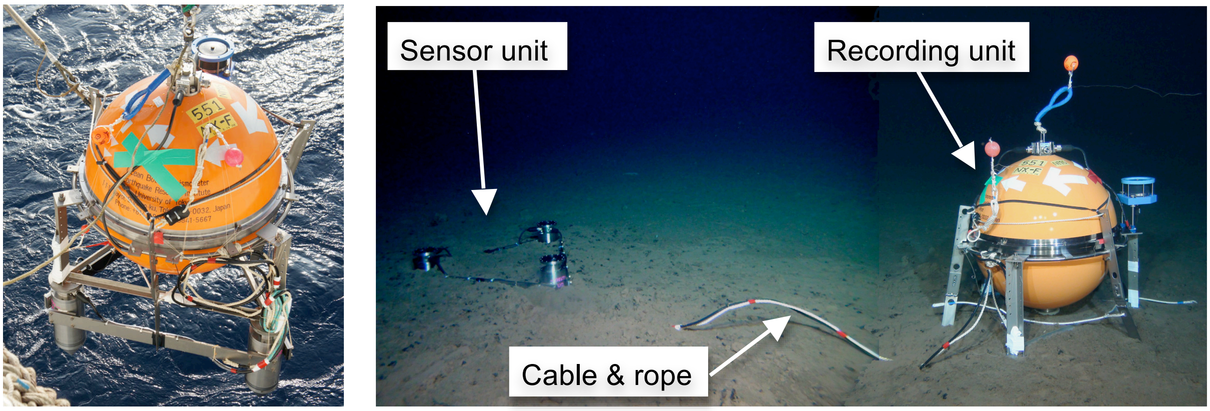



Fig. 2 The BBOBS-NX soon to be launched (left) and in observation at the seafloor (right). The ROV is required to detach from the sensor unit and move the recording unit (orange colored Ti sphere housing) and also to recover the whole BBOBS-NX.

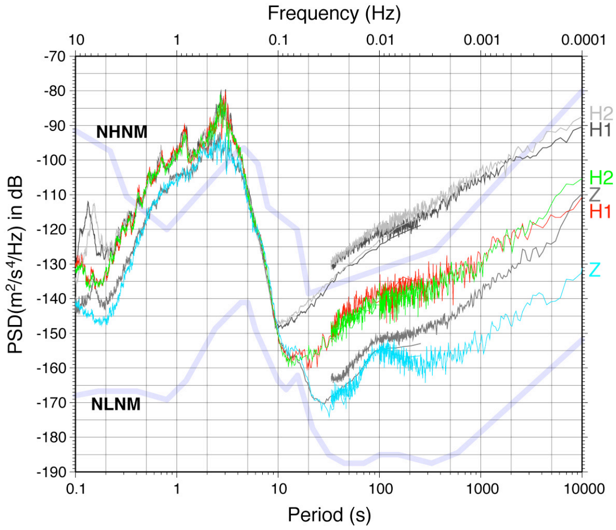



Fig. 3 The noise models of the BBOBS (1 year data, gray scale) and the BBOBS-NX (2 months data, color) at the same station in the Philippine Sea. Horizontal's noise levels (H1 and H2) of the BBOBS-NX are lower than the NHNM in the long period range (20 s –).

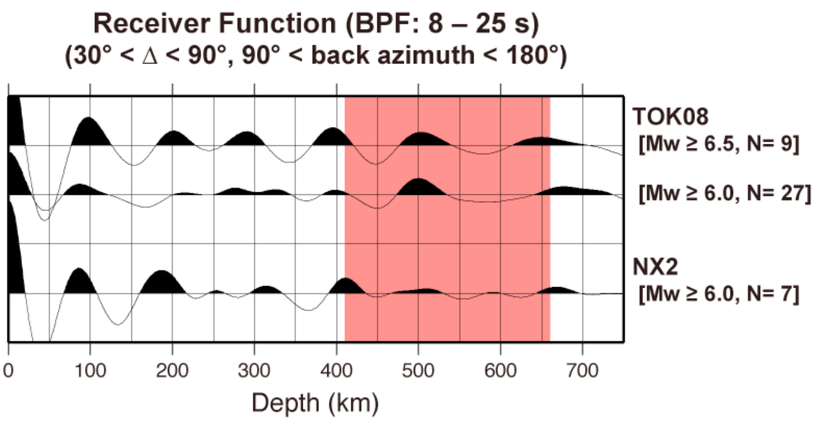



Fig. 4 Examples of receiver function analysis by using the data of the BBOBS (TOK08) and the BBOBS-NX (NX2). Only the NX2's result shows signals corresponding with the MTZ.

# The PLATE Project in the Western Pacific

Donald W. Forsyth[1], Natsumi Shintaku[1], Catherine Booth[1], Akiko Takeo[2], Dayanthie S. Weeraratne[3]

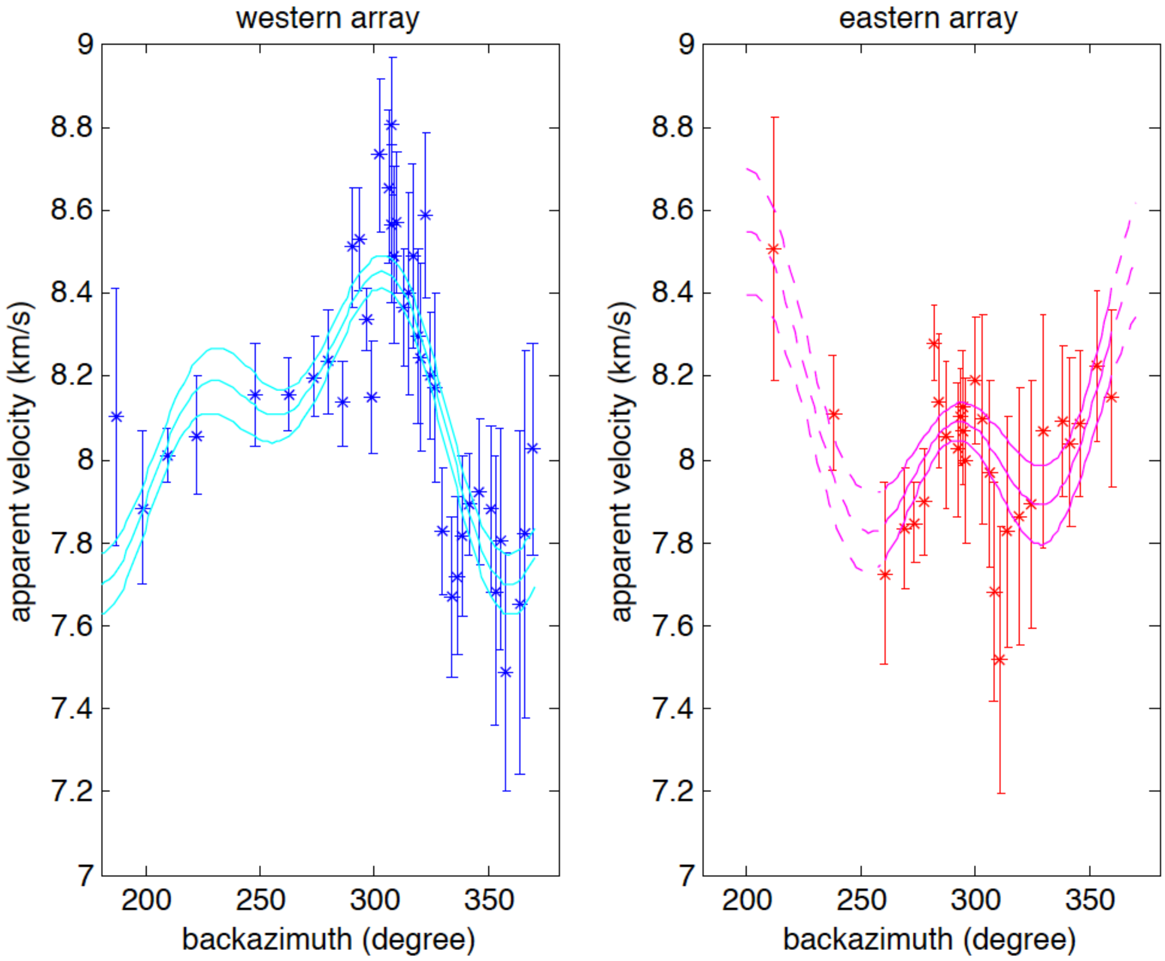
[1]Dept of Geological Sciences, Brown University, Providence, RI, USA. [2]Earthquake Research Institute, University of Tokyo, Japan, [3]Calif. St. University, Northridge, CA, USA.

The Pacific Lithosphere Anisotropy and Thickness Experiment (PLATE) is designed to address the evolution of old, normal, oceanic lithosphere and asthenosphere. On each limb of a magnetic bight south of the Shatsky Rise in the western Pacific, we deployed a small array of 8 ocean bottom seismographs for approximately one year. The magnetic bight defines a right angle bend in the magnetic anomalies formed near a ridge-ridge-ridge triple junction 150 to 160 mybp, Much of the seafloor in this area is undisturbed by subsequent volcanism, with abyssal hill topography still present. This is the oldest undisturbed seafloor in the Pacific with identifiable magnetic anomalies.

There were two primary goals: determine the structure of old lithosphere beneath undisturbed seafloor with high lateral resolution to avoid contamination with neighboring disturbed seafloor; and to detect the depth that anisotropy changes from being frozen into the lithosphere to where it is dynamically created by motion between the plate and the deeper, underlying mantle. Despite a number of instrument problems, we are making progress towards those goals with PLATE. We have measured: azimuthal anisotropy using Pn phases from earthquakes in subduction zones in the western Pacific; azimuthal anisotropy of short-period Rayleigh waves from ambient noise analysis; and P wave attenuation from deep earthquakes in the Marianas and Izu-Bonin subduction zones.

Key observations will be the dispersion and attenuation of Rayleigh waves at long periods. We are working on extending the useful period range by removing noise generated by long-period water (gravity) waves, using the coherence of vertical displacement with pressure recorded on differential pressure gauges (DPG).

Finally, a somewhat similar experiment is suggested for normal seafloor 30-40 Ma old to test a new hypothesis for the origin of the relatively sharp lithosphere-asthenosphere boundary (LAB). Key observations will be attenuation and shear wave velocity within the lithosphere and the depth of the LAB.




Pn anisotropy on the western and eastern limbs of the magnetic bight. In both cases, the fastest direction is approximately in the direction of fossil seafloor spreading.

# Lithospheric structure of the central Pacific: early returns from the NoMelt experiment

J. B. Gaherty[1], D. Lizarralde[2], J.A. Collins[2], R. Evans[2], and G. Hirth[3]

[1]Lamont-Doherty Earth Observatory of Columbia University
[2]Woods Hole Oceanographic Institution
[3]Brown University

Recent advances in laboratory measurements and theoretical models of the seismic properties of mantle rocks predict seismic velocity profiles for mature oceanic lithosphere that are fundamentally inconsistent with the best observations of seismic velocities in two ways. First, the theoretical models consistently display negative velocity gradients with depth in the lithosphere, while observed velocity profiles have positive gradients. Second, the transition from the high-velocity lithosphere to the low-velocity asthenosphere (the LAB) is too sharp, and too shallow, to be controlled entirely by temperature. These inconsistencies 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 observations of detailed lithosphere structure are limited.

In 2011-2012, 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) and short-period (SP) ocean bottom seismometers (OBS) and magnetotelluric (MT) instruments. The BB OBS array will measure anisotropic velocity and anelasticity structure based on surface waves and map the LAB based on receiver functions. The MT instruments will reveal melt and volatiles. The BB OBS and MT arrays were recovered in January 2013, and analysis is just commencing. Observations from the SP OBS array, presented here, constrain the velocity of the uppermost mantle to a depth of ~30 km below the Moho based on seismic refraction arrivals (Pn) sourced from an airgun array firing shots at 500-m intervals. We present results from the primary active-source line, which extends 600 km along the center of the segment in the flow-line direction and was instrumented with 31 SP OBS spaced 20 km apart. The instruments record Pn arrivals to distances as great as 500 km. The apparent velocity of Pn arrivals is ~8.5 km/s over most of the transect, but apparent velocities as high as 9.0 km/s are observed for Pn propagating westward over the western end of the transect. The unusually high horizontal phase velocity may indicate dipping structure within the uppermost mantle beneath a portion of the transect. Sub-Moho structure is also indicated by wide-angle reflections that approach the Pn branch near 185 km and 400 km range. A very preliminary analysis of the data suggest that these wide- angle reflections arise from discontinuities at ~12-17 and ~30 km below the seafloor. We expect that a complete analysis of this dataset will reveal uppermost lithospheric structure in unprecedented detail.

# ELECTROLITH: Volatile Cycling and Electrical Conductivity in the Earth's Mantle: The Carbonatite connection

Pascal Tarits[1,2]

[1]Institute for Marine Sciences, University of Western Brittany, France,
[2]Earthquake Research Institute, University of Tokyo, Japan,

The purpose of the ELECTROLITH project is to address the topic of fluids and volatiles in the Earth mantle. We hypothesize that volatiles are stored and transported by carbonatite melts and we study this process using a multidisciplinary approach. ELECTROLITH brings together specialists of mantle fluids with complementary methodological approaches including experimental petrology, experimental physics, theoretical physics and field geophysics. The overall aim consists in completing a relatively well established view of the geochemical role of carbonatite fluids in the deep carbon cycle by physical quantities that will allow us to evaluate the ability of carbonatite to transport other volatiles than carbon, to provide constraints on the impact of carbonatites on physical properties of mantle rocks to provide geophysical images allowing the localization of carbonatite fluids and to present a joined perspective on mantle geophysical anomalies and carbonatite transfers. To achieve these goals, we are collecting new data on physical quantities that will:

- Define the atomic structure and thermodynamic properties of multi-component carbonatite fluids using high pressure high temperature experimentation, spectroscopy and molecular dynamic simulations
- Determine the ability of carbonatites to transfer volatiles such as water and noble gases in addition to carbon.
- Characterize the effect of carbonatite fluids on the electrical conductivity and viscosity of mantle rocks by laboratory measurements
- Determine the mechanisms and velocity of carbonatite fluid transfers in the mantle and their relationships with stress distribution
- Trace carbonatite flows through the mantle using electrical conductivity as derived from deep

The first series of studies are devoted to help improve the picture of carbonatite physical properties. One task is experimental and involves high pressure high temperature synthesis and spectroscopic examination of carbonatites, to elucidate their structure and solubility laws for volatiles. The second task, strongly complementary to the first one, is numerical and involves molecular dynamic calculations on carbonatite melts. Most of the data obtained in the experimental task will be simulated by MD, but MD methods can also provide many other properties such as electrical conductivity, viscosity, and several thermodynamic parameters. Those calculations serve as theoretical guidance for the interpretation of experimental data and the consistency between both set of data will be tested. This allows us to provide an internally consistent set of data on the physical properties of those melts. Furthermore MD will be extremely useful to extrapolate some of the carbonatite properties toward pressure and temperature conditions where experimental measurements are impossible. Other studies address the physical properties of mantle rocks containing carbonatite melts, on electrical and viscous properties of carbonatite-bearing peridotite and on the transfer of carbonatite through grain boundaries. A good connection of the film together with exceptional transport properties of carbonatite melts implies that impregnation rates should be extremely fast. Then, how deformation affects impregnation is investigated. Finally, the studies are completed by investigations on geophysical sourcing of carbonatite melts in the mantle. Given the overall general picture wanted by ELECTROLITH, there is a need of large-scale probing of mantle fluids to complete and extend the above part. The purpose here is to complete the carbonatite model by performing in the EAR and exploiting in Kerguelen conductivity measurements of the mantle. Those two sites offer a view of two contrasted geodynamic settings: Continental break-up in the African rift, and a hotspot (considered by some authors as large igneous province) with a possible plume activity at Kerguelen.

# Small-scale heterogeneities in the oceanic lithosphere inferred from guided waves

Azusa Shito[1], Daisuke Suetsugu[1], Takashi Furumura[2], and NOMan Project Team

[1]Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan

[2]Earthquake Research Institute, University of Tokyo, Tokyo, Japan

Characteristic seismic waves are observed by seismological experiment using Broad-Band Ocean Bottom Seismometers (BBOBSs) conducted in the northwestern Pacific from 2007 to 2008 and 2010 to 2011. The seismic waves have low frequency onset (< 1 Hz) followed by high frequency later phases (2.5-10 Hz). The high frequency later phases have large amplitude and long duration for both P and S waves. The seismic waves are observed commonly at the BBOBS array from events in the subducting Pacific plate. To investigate generation and propagation mechanisms of the seismic wave will help us to understand the seismic structure and the origin of the oceanic lithosphere.

We apply the method proposed by Furumura and Kennett [2005] to reproduce the seismograms recorded by the BBOBS array. We conduct 2-D numerical simulation of seismic wave propagation up to 5 Hz by using finite difference method. The 2-D model area covers 1600 km in horizontal distance and 400 km in depth with a uniform grid interval of 0.04 km. The parallel simulation is conducted by using supercomputer system at JAMSTEC. Synthetic waveforms from the earthquakes in the Pacific plate at the depths of 205 km and 15 km are computed for a variety of oceanic lithosphere models. We satisfactorily reproduce the characteristic seismograms having low frequency first arrivals and high frequency later phases. The resultant preferred model includes small-scale random heterogeneity both in subducting and horizontal part of the oceanic lithosphere. The small-scale random heterogeneity has elongated scatters described by von Karman function with correlation length of 10 km in stretcher direction and 0.5 km in thickness. The standard deviation of the seismic wave velocity fluctuation from the background model is 2 %.

# Three-dimensional shear wave structures of the upper mantle from seafloor observations in the western Pacific Ocean

Takehi Isse[1], Hajime Shiobara[1], Hiroko Sugioka[2], Aki Ito[2], Daisuke Suetsugu[2]

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

Since 1990s, seafloor observations by using newly developed long-term broadband ocean seismometers (BBOBSs) have been operated in the northwestern and center part of the Pacific Ocean. Most of them were operated in the Philippine Sea region.

The Philippine Sea, located in the northwestern part of the Pacific Ocean, consists of several small basins, ridges and troughs with various seafloor ages. The age of the seafloor in the West Philippine Basin is 35–50 Ma, whereas that in the Shikoku Basin and the Parece-Vela Basin is 15–30 Ma. Seafloor spreading within the Mariana Trough started at about 6 Ma. These ages have been explained in terms of two episodes of back-arc spreading. The older parts of the Pacific plate (seafloor ages of around 150 Ma) are subducting beneath the Philippine Sea plate along the Izu–Bonin–Mariana island arc at the eastern boundary of the Philippine Sea plate. The northern margin of the Philippine Sea plate is subducting beneath the Eurasian plate. The upper mantle structure beneath the Philippine Sea plate, which may reflect the complex evolutionary history described above, as well as lateral variations caused by modern-day subduction, has been extensively studied using surface waves and P- and S-wave travel times. However, a lack of both seismic stations and earthquakes in the central Philippine Sea has limited the spatial resolution of the upper mantle in this region in previous models, especially in the southern part of the Philippine Sea, making it difficult to reduce artifacts caused by structures located outside the Philippine Sea.

We have determined the three-dimensional shear wave speed structure of the upper mantle in the northwestern Pacific Ocean using seismograms recorded by dense land-based seismic stations and BBOBS stations [1, 2]. We used a surface wave tomography technique in which multimode phase speed of the Rayleigh wave are measured and inverted for a 3-D shear wave speed structure by incorporating the effects of finite frequency and ray bending. BBOBS data provide us with improved spatial resolution (~300 km) in the Philippine Sea region. In the upper 120km, the shear wave speed structure is well correlated with the seafloor age of the provinces. At depths greater than 160 km, fast anomalies of the subducting Pacific Plate are clearly defined. Along the Izu-Bonin-Mariana arc, we have detected three separate slow speed anomalies in the mantle wedge at depths shallower than 100 km beneath the rear arc. Each anomaly has a width of ~500 km [2].

In recent study, we analyze the azimuthal and radial anisotropic structures of the northern Philippine Sea region and show their relationships with plate motion and deformation processes using the phase velocity dispersion curves of fundamental modes of Love and Rayleigh waves [3].

We found that the fast directions of azimuthal anisotropy are parallel to the directions of ancient seafloor spreading in the lithosphere of the Shikoku and West Philippine Basins and Pacific Ocean, whereas they are parallel to the direction of the present-day absolute plate motion (APM) in the asthenosphere of the Shikoku Basin, and oblique to the direction of the APM in the Pacific Ocean (by ~30º) and in the northern part of the West Philippine Basin (by ~55º). In the subduction zones around the Philippine Sea plate, the fast direction of azimuthal anisotropy is trench-parallel in the Ryukyu arc, and oriented NW–SE in the Izu–Ogasawara island arc. The Philippine Sea plate, which is a single plate, shows very large lateral variations in azimuthal and radial anisotropies compared with the Pacific plate.

In these previous studies, we have focused on the structure around the subduction zone. In NOMan project, we have focused on the structure of the normal oceanic mantle. We started a one-year-long pilot observation by deploying five BBOBSs in 2010 and four of them were recovered. We obtained a new upper mantle seismic structure from surface wave using data of previous studies and of the pilot observation. The preliminary results suggest that pilot observation area, where the upper mantle structure supposed to be normal, is less heterogeneous compare to the surrounding area. We will show these preliminary results in this presentation.

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# Preliminary result on electrical conductivity imaging of normal oceanic mantle

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In the Normal Oceanic Mantle (NOMan) project, seafloor electromagnetic surveys have been conducted to image the electrical conductivity of the mantle beneath the two areas in the northwestern Pacific Ocean; northwest (area A) and southeast (area B) of Shatsky Rise. The observation started in June 2010 and is still going on replacing instruments. In this presentation, we introduce preliminary result for the estimation of electrical conductivity structure beneath the area A based on the data acquired in the pilot survey during June 2010 and August 2012.

The raw time series obtained by ocean bottom electromagnetometers (OBEMs) at four sites were processed to obtain magnetotelluric (MT) response at each site. We then estimated one-dimensional (1-D) conductivity structure model which explains the data of all sites averagely, correcting the topographic effect on the observed MT responses, as we applied to the previous studies for the Philippine Sea and off Bonin Trench in the Pacific Ocean (Baba et al., 2010), and the petit-spot area between Japan Trench and the area A of the NOMan project (Baba et al., in prep.).

The obtained 1-D model shows the resistive upper layer and underling conductive zone, as recognized in many studies for oceanic upper mantle, suggesting cool oceanic lithosphere and hotter asthenosphere, respectively. The thickness of the lithospheric resistive mantle is about 150 km and the conductivity value of the asthenospheric mantle is 0.03-0.1 S/m. The resistive layer is much thinner than the previous studies in the off Bonin Trench area (>200km) and in the petit-spot area (~200 km), although the seafloor age of the areas are very old (130~155 Ma) and not different very much. We expected that the conductivity structures beneath the area A and off Bonin Trench are comparable and that beneath the petit-spot is abnormally high because the petit-spot area is the field of volcanic activity. However, the actual models are thinner for the resistive layer and more conductive in the underlying layer in order of area A, the petit-spot area, and off Bonin Trench. The cause of this feature has not been clear yet.

We will revise the 1-D model beneath the area A and also estimate a model for area B, by collecting further data in on-going and future observations. Interpretation of resulting models using laboratory experiments and seismic results will help to understand the status of the normal oceanic upper mantle.

# Uppermost mantle structure beneath oceanic regions from broadband array analysis of surface waves recorded by ocean bottom seismometers

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Seismic structure and seismic anisotropy in the uppermost mantle beneath oceanic regions are essential for understanding the thermal state and deformation related to plate tectonics. The structure including low velocity zone (LVZ) and high velocity lid (LID) is especially needed, as they seem to correspond to the oceanic asthenosphere and lithosphere, respectively. From 1980s, shear-wave velocity structure in the upper mantle has been estimated by global surface-wave tomography studies. As tomography studies usually analyze surface waves at periods longer than 40 s, however, the depth resolutions of their models are limited especially in the uppermost mantle. As a result, it has been difficult to discuss the detailed structure related to LID and LVZ such as the velocity gradient in the LID and the depth of transition from LID to LVZ.

The array records of ocean bottom seismometers (OBSs) enables us the broadband surface-waves analysis. At periods of about 30-100 s, phase velocities beneath the station array can be measured by the array analysis of teleseismic surface waves. At periods of about 2-30 s, phase velocities between a pair of stations can be measured by cross-correlating continuous records obtained at the stations. By combining these two methods, we can obtain phase velocities of surface waves (Rayleigh and Love waves) in a broadband period range of 2-100 s, and can estimate shear-wave velocity structure from the crust to the uppermost mantle beneath station array including radial anisotropy (azimuthally averaged anisotropy) and azimuthal anisotropy.

We obtained preliminary results by applying above array-analysis methods to records of OBSs deployed in the northwest of Shatsky Rise by the pilot observation of NOMan Project. By using similar methods, Takeo et al. (submitted) obtained results for the Shikoku Basin region, whereas Takeo et al. (2012) obtained results for the French Polynesia region and the southwest of Shatsky Rise region. We can therefore compare results from four regions (Table). The one-dimensional structures beneath each region indicate the transition from LID to LVZ at depths of about 50-70 km, and the increasing shear-wave velocity within the LVZ with seafloor age. The intensity of radial ($V_{SH}>V_{SV}$) and azimuthal anisotropy is about 3-4%. The azimuth of maximum shear-wave velocity at depths of 20-50 km seem to reflect the ancient plate motion in the French Polynesia region, the seafloor spreading in the southwest of Shatsky Rise, and the ancient seafloor spreading or the current plate motion in the northwest of Shatsky Rise, indicating various types of deformations affects the seismic anisotropy in the uppermost mantle.

**Table**. Summary of four datasets

| Project | Region | Instruments | Seafloor age |
|---|---|---|---|
| part of SSP ('05-'08) | Shikoku Basin | 7 OBSs | 15-30 Ma |
| TIARES ('09-'10) | French Polynesia | 9 OBSs | 50-70 Ma |
| PLATE ('09-'10) | SW of Shatsky Rise | 9 OBSs and 9 DPGs | 145-155 Ma |
| pilot of NOMan ('10-'11) | NW of Shatsky Rise | 4 OBSs | 125-135 Ma |

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# Oceanic Mantle Structure from Global Tomography

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Seismic tomography would be a significantly different endeavor if we could assert with some certitude (and truthfulness) that the Earth were elastically isotropic. New data and methods could confidently be used and focused on improving the 3-D resolution of just two elastic-wave velocities, Vp and Vs, and interpretations of heterogeneity could proceed with the expectation that temperature and composition were the main underlying geophysical parameters that explain the seismological observations. The Earth is not, of course, elastically isotropic, except as an approximation. In some areas this approximation may be appropriate; in others it is a convenient simplification that is likely to be inadequate. On the one hand, the seismological expressions of anisotropy offer opportunities to uncover new information on petrological fabric and strain in the Earth. Some observations, such as the geometry and magnitude of splitting of various S phases, are sought and valued for their direct sensitivity to anisotropy. On the other hand, anisotropy contributes an additional signal, often weakly resolved, to many seismological observations, confounding a straightforward interpretation of the data but demanding that the effects of anisotropy be accounted for in some manner. Possible approaches range from modeling the anisotropic structure as part of the inverse problem, to relying on geometrical averaging of wave paths to eliminate the anisotropic effects, to excluding data types that have large sensitivity to anisotropy, to ignoring the complexity. Each one of these approaches can be appropriate for a particular imaging problem, but the adequacy of the result clearly depends on the choice and its validity. These imaging challenges remain significant in global and regional tomography of the oceanic mantle. In the context of mapping the lithosphere and asthenosphere in the Pacific Basin using intermediate-period surface waves, coverage is not problem, and several hundred thousand measurements of phase speeds provide an excellent path distribution. Theoretically, isotropic velocity variations over length scales of a few hundred kilometers are resolvable without damping or regularization. However, the effects of azimuthal anisotropy are large and, depending on the inversion approach, the mapping of the signal may distort both the isotropic and anisotropic models retrieved. Experiments show that relying on azimuthal averaging provided by many criss-crossing paths does not lead to a good isotropic result. Anisotropy must be included to realize the improved resolution of the isotropic structure that is expected from the greater path coverage offered by the growing number of permanent and temporary seismic stations. Decades ago, a similar inference was made regarding the effects of radial anisotropy on retrieved profiles of shear-velocity structure in the Earth. This concern remains directly relevant today for the mapping of the oceanic asthenosphere, where strong and laterally varying radial anisotropy is evident. The necessity of addressing these tradeoffs through modeling of the complexity grows when more and better observations are brought to bear on the tomographic problem, and additional structural detail is sought.

# Seismic anisotropy below oceanic plates and large-scale mantle convection

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I review progress in our quantitative understanding of uppermost mantle, seismic anisotropy across different spatio-temporal scales of mantle convection, and what this says about the forces that govern plate motions and plate boundary evolution. Mineral physics tools constrained by laboratory experiments allow to model the formation of lattice preferred orientation (LPO) textures of olivine that is deformed over millions of years within global circulation models. This approach yields synthetic fabrics whose heterogeneity matches that seen in xenolith databases, and provides petrologically-motivated rules for new kinds of seismological inversions. When compared with surface wave models for anisotropy, LPO from mantle flow models which include the effects of thermal anomalies (inferred from isotropic seismic tomography) predict patterns of azimuthal anisotropy significantly better than plate-scale shear, or absolute plate motion (APM) models. The global average of radial anisotropy, as well as patterns of $v_{SH}$ vs. $v_{SV}$, are matched well by the global flow models overall, implying that regular, "A-type" LPOs and active asthenospheric convection, or another effect that mimics those patterns closely, are the causes of most upper mantle anisotropy underneath oceanic plates. I also discuss how high resolution global models can be used to explore regional tectonic questions, such as in the northern South America margin, self-consistently using a detailed analysis of shear wave splitting measurements and an inverse approach to geodynamic modeling. Deviations between model synthetics and observations may be used to infer the distribution of frozen-in, shallow, lithospheric anisotropy, the degree of net rotations of the lithosphere with respect to the lower mantle, the extent of partial melt, and the degree of lateral viscosity and volatile variations in asthenosphere.

# Possible lateral variation of seismic anisotropies in the oceanic lithosphere due to an active mantle flow in the mid-ocean ridge: some insights from the Oman Ophiolite

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Crystal-preferred orientation (CPO) is a common feature of peridotites and is developed during intense homogeneous plastic deformation of peridotitic minerals with a dominant slip system. Whereas an olivine CPO classification (A, B, C, D and E types) has been proposed by Karato and co-workers to illustrate the roles of stress and water content as controlling factors of olivine slip systems (e.g., Karato et al., 2008 Annu. Rev. Earth Planet. Sci.), an additional CPO type (AG) has also been proposed in recognition of its common occurrence in nature (Mainprice, 2007 Treatise on Geophysics). AG-type has been experimentally formed in sheared partially-molten samples, in which a-axes of olivine grains are aligned predominantly normal to the shear direction, rather than parallel to it (Kohlstedt & Holtzman, 2008 Annu. Rev. Earth Planet. Sci.). Thus, we can expect the development of AG-type olivine fabrics to be related to the occurrence of melt during deformation, most likely in the vicinity of mid-ocean ridges, where strong upflow is related to active mantle ascent (Nicolas et al., 2000 Marine Geophysical Researches; Michibayashi et al., 2000 MGR). Results from our analysis of peridotites from the Hilti mantle section of the Oman ophiolite show that olivine in that section is dominated more commonly by AG-Type than A-type CPO. This section preserves subhorizontal uppermost mantle lithosphere (Michibayashi & Mainprice, 2004 Jour. Petrology; Onoue & Michibayashi, 2013 JpGU abstract). Since olivine contains intrinsic elastic anisotropies, the development of CPO within peridotite during plastic deformation at mid-ocean ridges gives rise to seismic anisotropy in the upper mantle. Seismic properties of AG-type olivine fabrics reveal that whereas Vp velocity is maximum parallel to the flow direction (X) and minimum normal to the flow plane (Z), the intermediate direction (Y) has relatively higher Vp velocity than the median velocity. This feature of AG-type fabric is different from that of A-type, which occurs commonly under melt-free conditions, resulting in the different degrees of seismic anisotropies between AG-type and A-type. Thus, we propose, based on our results for the Oman ophiolite, that the intensity distribution of seismic anisotropy in the uppermost mantle could vary laterally depending on various strength of mantle ascent along a given segment of mid-ocean ridges in conjunction with various degree of melt impregnation.

# Subduction of oceanic asthenosphere: Evidence from sub-slab seismic anisotropy

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The oceanic asthenosphere is characterized as a low viscosity channel down to 200-300 km depth separating the cold lithosphere from above, and it is intimately linked to a layer of low seismic velocity and prominent seismic anisotropy observed globally beneath ocean basins. While subduction of tectonic plates in convergent margins is well recognized, the fate of oceanic asthenosphere remains enigmatic. We demonstrate that subduction of the oceanic asthenosphere characterized by weak azimuthal anisotropy and strong radial anisotropy explains the essence of sub-slab shear-wave splitting patterns, where the fast splitting direction changes from predominantly trench-parallel (or sub-parallel) under relatively steep subduction zones to frequently trench-normal under shallow subduction zones. To explain the observed splitting time, the thickness of the subducted asthenosphere is estimated to be 100±50 km. The general validity of such a scenario is crucial to fundamental understandings of the development of mantle anisotropy in sub-lithosphere or/and sub-slab conditions, the nature and formation of oceanic asthenosphere as well as the flow pattern and mass transport near subduction zones.

To validate this scenario, we examine SKS splitting patterns observed across the fore-arc in central Alaska. Here the fast splitting direction varies from plate motion sub-parallel near the trench to mostly trench-parallel beyond the 100km slab-isodepth contour, while being strongly variable in between. After taking into account the rotation of anisotropy symmetry in the oceanic asthenosphere with respect to the local plate motion obliquity and down-dip variations in the slab dip, we reproduce a general 90-degree switch in fast splitting direction as well as the back azimuth dependent splitting pattern across the entire fore-arc. The current validation further augments the idea that, apart from anisotropy in the mantle wedge and the subducting slab, subduction of the oceanic asthenosphere is likely to be the dominant source of seismic anisotropy in central Alaska and potentially in many subduction zones. Furthermore, this result also provides alternative views to models of seismic anisotropy in the mantle wedge and on the length scale in which the 3D mantle flow may be important.

# A database of crystal preferred orientation of olivine in upper mantle rocks – the direct mantle sample

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Olivine is the most volumetrically abundant mineral in the Earth's upper mantle, as such it dominates the mechanical and physical properties and has a controlling influence of the geodynamics of plate tectonics. Since the pioneering work of Hess and others we know that seismic anisotropy of the shallow mantle is related to olivine and it's crystal preferred orientation (CPO). With advent of plate tectonics the understanding of the key role of peridotite rocks became a major scientific objective and the measurement CPO of olivine in upper mantle samples became an important tool for studying the kinematics of these rocks. Our group originally lead by Adolphe Nicolas introduced the systematic use of CPO measured by U-stage for field studies all over the world for over 30 years, this tradition was extended in last 15 years by the use of electron back-scattered diffraction (EBSD) to study of CPO and the associated digital microstructure. It is an appropriate time to analysis this significant database of olivine CPO of over 700 samples and 15 million measurements, which represents the work of our group, both present and former members (e.g. Prof. K. Michibayashi, Shizuoka), as well as collaborating colleagues. It is also interesting to compare the natural record as illustrated by our database in the light of recent experimental results stimulated by the extended ranges in temperature, pressure and finite strain, as well as intrinsic olivine variables such as hydrogen content.

To analysis the database, which is heterogeneous because it is constructed from the individual work of many people over a 45 year period containing U-stage data and EBSD measurements (manual indexing point per grain, automatic indexing one point per grain, automatic indexing gridded mapping data) of various formats, we need a flexible software tool that can handle large volumes of data in consistent way. We have used the state-of-art open source MTEX toolbox for quantitative texture analysis. MTEX is a scriptable MATLAB toolbox, which allows all aspects of quantitative texture analysis using the modern methods and anisotropic physical property calculations (e.g. seismic anisotropy).

# Volatile-rich partial melt at the base of the oceanic lithosphere and in the asthenosphere

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Mounting observational evidence for small amounts of partial melt beneath the oceanic lithosphere has arisen at the same time that experimental studies have demonstrated strong stabilization of volatile-rich partial melts of peridotite at appropriate temperatures and pressures. However, this fortunate coincidence does not fully resolve the question of melt in the sub-lithospheric mantle, and significant challenges remain. Chief among these are the relative roles of $H_2O$ and $CO_2$ in stabilizing melt, plausible volumes of melt derived from melting of volatile-poor mantle, and the dynamic stability of finite melt accumulations.

Several recent studies have argued that small amounts of $H_2O$ present in the upper mantle are sufficient to incite partial melting in the asthenosphere (Mierdel et al. 2007; Green et al. 2010; Other Ref?). However, experiments on the $H_2O$ storage capacity of mantle minerals (Ardia et al. 2012; Tenner et al. 2012a), together with mineral/melt partitioning of OH determinations (Aubaud et al. 2004; 2008; Tenner et al. 2009) and quantification of the influence of $H_2O$ on the extent of melting of peridotite (Tenner et al. 2012b) suggest that hydrous melting is unlikely along the geotherm beneath mature oceanic lithosphere unless bulk mantle $H_2O$ contents are elevated compared to those typically judged from MORB compositions.

In contrast, experimental evidence clearly demonstrates that the solidus of carbonated peridotite exceeds any reasonable oceanic geotherms. Previously, the data suggestd that small-degree partial melts would be carbonatitic in the coldest parts of the asthenosphere, but new experiments at low pressure (Dasgupta et al. 2013) suggest instead that they are more likely to be $CO_2$-rich silicate melts similar to $CO_2$-enriched nephelinites. Melt fractions, however, remain very small, far less than 1% for reasonable bulk C concentrations. Whether these melt fractions are dynamically stable and can account for observed geophysical anomalies remains an open question.

# Experimental study on anelasticty of polycrystalline material for seismological application.

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Due to the recent progress in seismology, we can obtain highly-resolved seismic velocity structures in the upper mantle. In order to interpret the velocity structures in terms of temperature heterogeneity, chemical heterogeneity, fluid/melt distribution, etc, it is important to assess the quantitative effects of temperature, chemical composition, and fluid/melt on Vp and Vs. Although these effects at the ultrasonic frequencies (anharmonic effect, poroelastic effect) have been measured and assessed quantitatively, these effects at the seismic frequencies are subject to large uncertainty due to the uncertainty in rock anelasticity, which additionally causes modulus relaxation at lower frequencies (anelastic effect). Rock anelasticity has been poorly understood yet, due to the difficulty of high temperature and high pressure experiments performed on the rock samples. We, therefore, developed a new experimental method by using organic polycrystalline material as a rock analogue. Previous studies have shown that anelasticity of polycrystalline materials follows the similarity rule in which frequency normalized to the Maxwell frequency, $f/f_M$, can be used as a master variable (McCarthy et al, 2012). The $Q^{-1}$ spectra obtained from olivine aggregates (e.g., Jackson et al, 2002) also collapsed onto the same master curve, when plotted as a function of $f/f_M$. The general applicability of this Maxwell frequency scaling shows that anelastic relaxation in those experiments is caused by diffusionally accommodated grain boundary sliding (GBS) (Gribb & Cooper, 1998; McCarthy et al, 2012). However, normalized frequency of the existing experimental data is usually considerably lower than the seismic frequencies normalized to the Maxwell frequency of the upper mantle ($f/f_M=10^6$-$10^{10}$). Therefore, in order to clarify the mechanism and scaling law applicable to the seismic waves, we have to measure anelasticity at higher normalized frequencies.

By improving the experimental apparatus, we measured anelasticity at higher frequencies and lower temperatures than before. We prepared one high-purity borneol sample and one impure borneol sample containing 0.83 wt% diphenylamine, so that effect of impurity on anelasticity can be investigated. Data could be obtained up to $f/f_M = 10^7$ (more than $10^2$ higher than the previous study), which is within the normalized seismic frequencies. Attenuation spectra at higher normalized frequencies did not collapse onto a single master curve, but were considerably scattered. This result demonstrates that the Maxwell frequency scaling can not fully capture the effect of temperature and impurity at higher normalized frequencies. It is revealed that $Q^{-1}$ spectra of the high purity borneol sample decrease monotonically with increasing frequencies, but on the $Q^{-1}$ spectrum of the impure borneol sample, a high and broad attenuation peak is superimposed. To clarify the underlying mechanism of this attenuation peak and to clarify the scaling law applicable to the seismic waves, further experimental studies are needed.

# Estimating electrical conductivity of melt from observation

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The presence of upper mantle high conductivity layer has been recognized and called as the 'electrical asthenosphere' since the very beginning of seafloor magnetotelluric study. Effect of water (proton) is considered as a promising cause of the high conductivity, and has been adopted to interpret obtained conductivity profiles (Baba et al., 2010).

If CO2 content in the upper mantle exceeds 5 ppm wt., conductivity profile may be interpreted by partial melting model because of the extremely high conductivity of carbonatite melt (Gaillard et al., 2009). Under such a situation, electrical conductivity profile will constrain the product of melt conductivity and volume fraction. If melt volume fraction is constrained by independent information (by model or seismology, for example), we can estimate the conductivity of melt (carbonatite and/or silicate).

Here we try to interpret three recent results (1-Dimensional conductivity profiles ) of ocean bottom magnetotelluric study made by our group. Two profiles are obtained by the Stagnant Slab Project (SSP) in the Philippine Sea and the Western Pacific Ocean (Baba et al., 2010), which are called SSP-PS and SSP-WP, respectively. Another is obtained in the Northwestern Pacific Ocean by the NOMan project. As for distribution of melt fraction, we refer to the calculation by Hirschmann (2009), assuming mean seafloor age for SSP-PS to be 30 ma and for SSP-WP and NOMan to be 100 ma. Although actual seafloor age of the latter is much older, we use this value assuming the age dependence is weak after 100 ma. Melt conductivity profiles were estimated from three conductivity profiles by using Hashin-Strickman upper bound model.

We found the results of SSP-PS and NOMan are compatible with the present framework. Relatively low conductivity below the LAB close to that of wet silicate melt was estimated for the SSP-PS result. From the NOMan profile higher conductivity between those for silicate and carbonatite melts was indicated. However, if we assume large melt fraction at the shallowest part of the asthenosphere just below the LAB for the NOMan profile as suggested by Kawakatsu et al. (2010) at WP2, resulting conductivity value becomes lower and closer to that of silicate melt. If acceptable model of partially molten asthenosphere is obtained in this way, the volatile (carbon) content in the upper mantle will be estimated from resulting melt conductivity values with a systematic laboratory measurement of melt conductivity with accurate control of volatile contents. On the other hand, the profile from SSP-WP cannot consistently be explained by the present approach. Difference between SSP-WP and NOMan results is so large that it should be interpreted by other effects.

The solution (cause of asthenosphere) may not be unique, but stronger constraints will be obtained by seeking for consistency among multi-parameters from seismology, EM, and mineral physics.

## Imaging of Lithosphere Asthenosphere Boundary Across Atlantic Ocean: A Dream

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The base of the lithosphere, *Lithosphere Asthenosphere Boundary* (LAB), is the lower boundary of the plate. Although the lithosphere is a basic building block of the plate tectonics theory, its nature, its thickness, its boundary with the asthenosphere (LAB) is still matter of heated debates. For example, some studies suggest that the LAB could be a sharp boundary, but the others propose a thick transition. Some people argue that the thickness of the lithosphere increases with the age of the lithosphere and others argue that it lies at a constant depth at 70 km. In order to address these fundamental questions we propose to image the LAB and internal structure of the lithosphere in a systematic manner across the Atlantic Ocean for a lithosphere of 0-100 Ma age using a combination of different geophysical methods. Along with using seismological and magnetotelluric methods, we propose to use a technology newly developed for the oil and gas exploration that is capable of providing a seismic reflection image down to 120 km depth with a few hundred metres resolution. Subject to funding, we propose first to acquire a short seismic reflection profile (800 km) across Mid-Atlantic Ridge covering 0-15 Ma of the lithosphere and then crossing three fracture zones of 28 Ma, 40 Ma and 12 Ma age contrasts, covering a lithosphere of 0-75 Ma. In the second stage, we propose to acquire coincident seismic reflection, refraction, broadband OBS and MT data along a 2200 km long profile covering the oceanic lithosphere of 0-100 Ma of age. These new seismic data should also provide images of melt lenses in the mantle beneath the spreading centre axis, if present, or frozen melt lenses in old lithosphere which will help us to build a new model of melt generation and migration from the mantle. We should also be able to image deep penetrating faults that might have been generated due to the cooling of the lithosphere as it moved away from the spreading centre, allowing the development of a new model of hydration of the oceanic lithosphere.

In this talk, I will discuss the design of the survey. I will show some results that have already been obtained using deep seismic profiling of the Indian ocean lithosphere where we have imaged the 2012 Mw=8.6 earthquake rupture zone down to 50 km depth. We have also imaged a band of reflectivity at 10-15 km below the oceanic Moho, which could be due to either a phase change from plagioclase to spinel or the presence of gabbroic melt lenses, or a combination of the above two. These images were possible because I was able to persuade seismic industry to provide their best technology, very long streamers (12-15 km long) and low frequency energy source capable of penetrating deep.

Poster

# Flow and thermal structure around the junction of Japan-Kurile arcs

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The junction of the Japan-Kurile arc is the best studied junction in the world and we can see several characteristic features in this region. These include trench-normal fast polarization direction of S-wave splitting in the mantle wedge and along-arc variation of the angle of subduction. In this presentation, I show the dynamic effects of the junction using a numerical model of mantle convection with a realistic curved shape of the trench. I obtain 3D flow in the mantle wedge which is consistent with the observation of seismic anisotropy. The fast polarization direction of S-wave anisotropy beneath the slab is nearly parallel to that of plate motion at least in the shallow part. I also find that the subduction angle varies along-strike, which agrees with the observations. This variation can be explained by a torque balance acting on subducting slabs in the case of oblique subduction.

The results obtained using numerical model with higher resolution show that the temperature of slab surface also changes along the strike of the trench, although the magnitude is not so large (~70K). This might affect intermediate seismicity in this region.

# Importance of hot anomaly adjacent to the subducting slab

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The origin and past evolution of seismically detected hot material in the sub-slab mantle under the subducting Pacific plate are studied. Forward modeling studies show that its origin is likely to be originated from the hot material next to the cold sinking material typically observed in the internally heated convection. Backward modeling of thermal structure under Japan and its surrounding show the common source of present hot materials in the sub-slab mantle and the mantle wedge. The results also suggest the leakage of hot material from the sub-slab to the back-arc regions which is also observed in the forward modeling studies. Thus, this thermal anomaly plays potentially important role in controlling the dynamics of subduction zone and back-arc mantle.

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Poster

# Three-dimensional simulation of the EM fields induced by 2011 Tohoku tsunami

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The motion of seawater induces electromotive force of significant intensity (Sanford, 1971) due to Faraday's law, and resulting electromagnetic (EM) field can be recorded by instruments installed on land or at ocean bottom (Tyler, 2005; Toh et al. 2011). However, few studies were successfully simulating Tsunami induced EM fields by an exact and accurate application of Maxwell equations that is essential for a quantitative interpretation to get geophysical information from observations of tsunami-related EM signals.

There are a number of observations of such EM fields that were caused by the devastating Tohoku tsunami of 2011 not only on land observatories but also at some seafloor sites (e.g. Utada et al., 2011; Ichihara et al., 2012). Here we present a 3-D modeling scheme to simulate these observed fields. We apply a 3-D EM induction code in Cartesian coordinate system with the heterogeneous source term, which is based on the modified iterative dissipative method (MIDM) (Zhang et al. 2012). The source current distribution is predicted by the flow data calculated by a tsunami simulation (Maeda and Furumura, 2011) based on the linear long-wave theory. The flow data provided in the time domain are transformed to the frequency domain, and the induced current distribution was calculated by applying Faraday's law. The frequency domain solutions of Maxwell's equations with heterogeneous distribution of the source current in the sea are then transformed back to the time domain to compare with observations. Here we show examples of comparison for one land observatory in Tohoku district, one island observatory in the Izu-Bonin arc, and one seafloor station installed by the NOMan Project.

The water motion generates source current in the sea both of poloidal (without vertical currents) and toroidal modes (with vertical currents). Lateral heterogeneities would convert the toroidal to poloidal mode but the amplitude of converted mode is generally much smaller than that of original poloidal mode. Therefore the source of the toroidal mode can be ignored in case of modeling observations on land. Our numerical simulation shows that the toroidal mode can be effective for seafloor observations, but only when the seafloor (sedimentary layer) is very conducting. In such a case, the effect of toroidal mode would bias the estimation of the wave propagation direction (the wave number vector) by seafloor electromagnetic data. We also examined how the tsunami-induced EM field observations constrain the conductivity of the shallower part of the seabed, which is difficult to be resolved by using ordinary seafloor magnetotelluric signals. We also defined the motional impedance just as the case of ordinary magnetotellurics, and showed that both model and observed impedances indicate the phase velocity of the long wave as predicted by a simple theory.