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# Program and Abstract Volume

24th –26th September 2015

Earthquake Research Institute, University of Tokyo

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EARTHQUAKE RESEARCH INSTITUTE
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# Program

<u>Thursday, 24th September 2015</u>

13:00 Registration 2nd Floor, Building No. 1, Earthquake Research Institute

# Session S1: Planet

Discussion Leader: **Masaki Matsushima** (Tokyo Tech)

14:00 **Kiyoshi Kuramoto** (Hokkaido University)
Behavior of atmophile elements in the early inner solar system: Anomalous composition of Mercury and the formation of terrestrial planet atmospheres

15:00 Break

15:10 **Taku Tsuchiya** (GRC, Ehime University)
Matter in extreme condition

15:40 **Shoko Oshigami** (National Astronomical Observatory)
Mare volcanism: Reinterpretation based on Kaguya Lunar Radar Sounder data

16:10 Posters (Core Time)

16:40 General Discussion

18:00 **JSEDI Party** (ABREUVOIR)

Friday, 25th September 2015

# Session S2: Experiment

Discussion Leader: **Satoru Tanaka** (JAMSTEC)

09:00 **Kei Hirose** (ELSI, Tokyo Tech)
Phase transition and physical property of deep Earth materials revealed by ultrahigh-pressure experiments

10:00 Break

10:10 **Takatoshi Yanagisawa** (JAMSTEC)
Convection in liquid metals: basic study for the flow in the outer core

10:40 **Hiroko Watanabe** (RCNS, Tohoku University)
Geo-neutrino measurement with KamLAND

11:10 Posters (Core Time)

11:40 General Discussion

12:30 Lunch

# Session S3: Core

Discussion Leader: **Hisayoshi Shimizu** (ERI, University of Tokyo)

14:00 **George Helffrich** (ELSI, Tokyo Tech)
Frontier studies of Earth's core

15:00 Break

15:10 **Shin-ichi Takehiro** (RIMS, Kyoto University)
Penetration of mean zonal flows into an outer stable layer excited by MHD thermal convection in rotating spherical shells

15:40 **Yoichi Usui** (JAMSTEC)
Paleoarchean paleomagnetism, with special emphasis on newly discovered ca. 3.47 Ga records from the Pilbara craton, Western Australia

16:10 Poster (Core Time)

16:40 General Discussion

Saturday, 26th September 2015

# Session S4: Mantle

Discussion Leader: **Masayuki Obayashi** (JAMSTEC)

09:00 **Hisashi Utada** (ERI, University of Tokyo)
Recent progress in the study of oceanic mantle by geophysical observations

10:00 Break

10:10 **John Hernlund** (ELSI, Tokyo Tech)
Persistence of strong primitive domains in the Earth's lower mantle

10:40 **Manabu Morishige** (IGS, Kyoto University)
Along-arc variation in the thermal and flow structure around northeast Japan subduction zone

11:10 Poster (Core Time)

11:40 General Discussion

# Posters

## Session S1: Planet

S1-11

**Futoshi Takahashi** (Kyushu University)

Dynamo models of small objects: Mercury and Ganymede

## Session S2: Experiment

S2-21

**Y. Shirahata**, **K.Inoue**, **T. Mitsui**, **H. Watanabe**, **K. Ishidoshiro**, **H. Ikeda**, **T. Takai**, **S. Ishio** (RCNS, Tohoku University)

Development for anti-neutrino directional measurement

S2-22

**Daichi Takahashi**, **Ikuro Sumita** (Kanazawa University)

Experiments on the whole process of magma chamber solidification: preliminary results

S2-23

**Longjian Xie**, **Akira Yoneda**, **Eiji Ito** (ISEI, Okayama University)

Directly apply sintered boron-doped diamond cylinder as heater in the Kawaii-Cell

## Session S3: Core

S3-31

**Masaki Matsushima** (Tokyo Tech)

Thickness of a possible stratified layer at the core surface estimated from a core surface flow model

S3-32

**Ryousuke Nakashima**, **Shigeo Yoshida** (Kyushu University)

The boundary mode of the axially symmetric MAC wave in the stratified layer at the top of the Earth’s outer core

S3-33

**Toshiki Ohtaki** (GSJ/AIST), **Satoshi Kaneshima** (Kyushu University)

Sensitivity of core phase to F-layer structure

S3-34

**Youhei Sasaki** (Kyoto University), **Shin-ichi Takehiro** (RIMS, Kyoto University)

Penetration of magneto-hydrodynamic disturbances into a strongly stable outer layer caused by MHD dynamo in a rotating spherical shell

S3-35

**Koichiro Umemoto** (ELSI, Tokyo Tech), **Kei Hirose** (ELSI, Tokyo Tech; JAMSTEC)

Liquid iron alloys with hydrogen at outer core conditions by first-principles calculation

## Session S4: Mantle

S4-41

**Kouta Hamada**, **Kazunori Yoshizawa** (Hokkaido University)

Upper mantle structure of North America using inter-station phase and amplitude of surface waves

S4-42

**Christine Houser**, **John Hernlund**, **Renata Wentzcovitch**, **Maxim Ballmer** (ELSI, Tokyo Tech)

Seismic constraints on the BEAMS (Bridgmanite Enriched Ancient Mantle Structures) model for mantle evolution

S4-43

**Atsushi Nakao**, **Hikaru Iwamori** (Tokyo Tech; JAMSTEC), **Tomoeki Nakakuki** (Hiroshima University)

Effects of water and fluid transport on subduction dynamics

S4-44

**Ryo Narita**, **Kouta Hamada**, **Kzaunori Yoshizawa** (Hokkaido University)

Inter-station phase speed and amplitude measurements of surface waves toward a high-resolution upper mantle model in the Sea of Japan

S4-45

**Hisayoshi Shimizu**, **Hisashi Utada** (ERI, University of Tokyo)

Further examination of the geoelectromagnetic jerk hypothesis

S4-46

**Satoru Tanaka** (JAMSTEC), **Hitoshi Kawakatsu** (ERI, University of Tokyo)

New constraints on S-wave velocity structure near the western edge of the Pacific LLSVP

S4-47

**Kazunori Yoshizawa** (Hokkaido University)

Anisotropic layering in the continental upper mantle: Implication for the mid-lithosphere discontinuity?

# Behavior of atmophile elements in the early inner solar system: Anomalous composition of Mercury and the formation of terrestrial planet atmospheres

Kiyoshi Kuramoto

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Behavior of atmophile elements in the early inner solar system will be discussed in the light of FeO-poor and sulfur-rich chemistry of Mercury recently revealed by the MESSENGER spacecraft. The surface composition of a planet reflects the composition of planetary building stone that is controlled by cosmochemistry and the planetary differentiation that is governed by geochemistry. Sulfur is known to be a volatile element in nebula environments with the solar composition and also to behave as a siderophile element in a rocky planet. Considering that Mercury is located in the innermost hot environment proximity to the Sun and also has a large metallic core, one can have an expectation that sulfur should be significantly depleted from the surface of Mercury. Contrary to this expectation, the surface of Mercury is found to contain as much as several wt% of sulfur by the MESSENGER's X-ray and $\gamma$-ray spectroscopies.

This observation implies that a significant amount of sulfur is condensed into refractory solid phase in the innermost early solar system. In order to explain such chemistry, the building stones of Mercury are required to be prepared in reduced, high temperature nebula environments with C/O ratio significantly larger than that of the solar composition. Under such environments, sulfur may form solid CaS and MgS at high temperatures $\geq$ 1000 K due to the significant reduction of oxygen fugacity, which is also supported from the FeO poor composition of the Mercurian surface. The formation of the sulfur-rich Mercurian crust can be attributable to the immiscibility of those sulfide phases with iron-rich metallic liquid and their low densities.

A likely mechanism for generating such a thermo-chemical environment in the innermost solar nebula is the inward migration and partial vaporization of dust containing refractory organics. This suggests that organics have been also incorporated in the solid materials that eventually accreted to the outer terrestrial planets: Venus, Earth and Mars. Because hydrogen and carbon delivered from organics are soluble to molten metal and silicate melt produced on an accreting planet, both elements are partitioned to the proto-atmosphere with significantly fractionated proportions relatively enriched in $H_2$ and $H_2O$ while a large fraction of carbon is partitioned to the metallic iron that segregates to the core. This explains the present volatile abundance pattern observed for the silicate Earth including the hydrosphere. A hydrogen-rich wet proto-atmosphere, favorable for prebiotic chemical evolution, would then gradually become oxidized through the hydrogen escape to space.

# Matter in extreme condition

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Materials property in multi-megabar condition still remains largely unknown. Since experimental measurements are technically difficult, theoretical approach, particularly based on density functional ab initio computation, plays a substantial role. Here I will show our recently calculated results on physical properties of Earth and planetary materials under extreme pressure and temperature condition corresponding to the giant planetary interiors.

# Mare volcanism: Reinterpretation based on Kaguya Lunar Radar Sounder data

Shoko Oshigami[1], Shiho Watanabe[2], Yasushi Yamaguchi[2], Atsushi Yamaji[3], Takao Kobayashi[4], Atsushi Kumamoto[5], Ken Ishiyama[5], Takayuki Ono[5]

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The Lunar Radar Sounder (LRS) onboard Kaguya (SELENE) detected widespread horizontal reflectors under some nearside maria. Previous studies estimated that the depths of the subsurface reflectors were up to several hundreds of meters and suggested that the reflectors were interfaces between mare basalt units. The comparison between the reflectors detected in the LRS data and surface age maps indicating the formation age of each basalt unit allows us to discuss the lower limit volume of each basalt unit and its space and time variation.

We estimated volumes of basalt units in the ages of 2.7 Ga to 3.8 Ga in the nearside maria including Mare Crisium, Mare Humorum, Mare Imbrium, Mare Nectaris, Mare Serenitatis, Mare Smythii, and Oceanus Procellarum. The lower limit volumes of the geologic units estimated in this study were on the order of $10^3$ to $10^4$ km$^3$, although the resolution of our estimation was limited by the range resolution of the LRS data. This volume range is consistent with the total amount of erupted lava flows derived from numerical simulations of thermal erosion models of lunar sinuous rille formation and is also comparable to the average flow volumes of continental flood basalt units formed after the Paleozoic and calculated flow volumes of Archean komatiite flows on the Earth. The lower limits of average eruption rates estimated from the unit volumes were on the order of $10^{-5}$ to $10^{-3}$ km$^3$/yr. The estimated volumes of the geologic mare units and average eruption rate showed clear positive correlations with their ages within the same mare basin, while they vary among different maria compared within the same age range. The estimated volumes and their space and time variation potentially constrain key factors for the thermal evolution of the Moon, magma buoyancy and crustal thickness, for example.

Our results in this study depend essentially on the buried regolith model. To prove this hypothesis, in situ explorations of the buried regoliths on crater walls or holes or by drillings are desired.

# Dynamo models of small objects: Mercury and Ganymede

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Core dynamics and associated dynamo action of small objects such as Mercury and Ganymede could be very unique compared with Earth-sized and even larger objects in various aspects. Most remarkable is the peculiar core crystallization regimes due to relatively low pressure and high sulphur concentration in the core, which yields different types of convection and dynamo. Now it is a challenge for dynamo modelers to numerically model dynamos of these bodies. In this presentation, we briefly summarize such efforts and show some results obtained from our dynamo modeling.

# Phase transition and physical property of deep Earth materials revealed by ultrahigh-pressure experiments

Kei Hirose
(ELSI, Tokyo Tech)

Pressure and temperature conditions of recent laser-heated diamond-anvil cell (DAC) experiments have been largely extended, and recent experiments are being made even at conditions even beyond the center of the Earth. With such advanced techniques, phase equilibria (solid-solid phase transition, melting curve, liquidus phase relation, eutectic composition), element partitioning (solid-solid, liquid-solid), sound velocity, and transport properties (electrical and thermal conductivity) have been studied for both deep mantle and core materials. Recent topics include the compositional effects on the pressure range of post-perovskite phase transition, H-phase, CMB heat flow, the high thermal conductivity of the core, core crystallization and early dynamo, and the crystal structure of the inner core. I will review these experimental results and their implications.

# Convection in liquid metals: basic study for the flow in the outer core

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The study on the nature of thermal convection in liquid metals is important to understand the dynamics of planetary metallic cores. In laboratory experiments, it has been difficult to observe flow patterns inside liquid metals because of their opaqueness to visible light. Nowadays, velocity measurement methods utilizing Doppler shift of ultrasound realize detecting flow velocities less than 0.5 mm/s, and it can vividly illuminate the flow pattern with time fluctuations in liquid metals.

We performed laboratory experiments of Rayleigh-Benard convection of a liquid metal with and without an imposition of a uniform horizontal magnetic field, and observed the behavior of flow by the ultrasonic velocity measurement method [1]. A uniform magnetic field works, like a rotation of a system, to align the axes of convection rolls in the direction parallel to the magnetic field. If the intensity of the magnetic field is strong enough, convection pattern keeps a state of steady rolls. If the intensity is weak, the pattern is not roll-like but isotropic cellular one. For moderate intensities, the convection roll is weakly constrained by the magnetic field and repetitions of pattern transitions are observed with the change of the number of rolls. We established a regime diagram of convection patterns in relation to the Rayleigh number (Ra) and Chandrasekhar number (Q), where Q is proportional to the square of the magnetic field intensity. The identified flow regimes are classified by the value of Ra/Q, that is the ratio of buoyancy force to the Lorentz force.

We also performed MHD simulations and compared it with our laboratory experiments under various intensities of a uniform horizontal magnetic field. We successfully reproduced same flow behaviors by numerical simulations [2]. By analyzing both the laboratory experiments and numerical simulations, we clarified the process of flow pattern transitions as well as their mechanism. The process can be regarded as an interaction between aligned convection rolls and global-scale mean flow. The occurrence of global circulation bends the aligned rolls in a style of the skewed-varicose instability and induces roll number reductions. The mechanism gives an insight into the transition of flow in the outer core.

[1] Yanagisawa, T., et al., Convection patterns in a liquid metal under an imposed horizontal magnetic field, Phys. Rev. E 88 (2013) 063020.

[2] Yanagisawa, T., et al., Flow reversals in low-Prandtl-number Rayleigh-Benard convection controlled by horizontal circulations, Phys. Rev. E 92 (2015) 023018.

# Geo-neutrino measurement with KamLAND

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The **Kam**ioka **L**iquid-scintillator **A**nti-**N**eutrino **D**etector (KamLAND) is located in a rock cavern in the Kamioka mine, 1,000 m below the summit of Mt. Ikenoyama in Japan. The 2,700 meter water equivalent overburden reduces the cosmic ray flux by a factor of roughly $10^{-5}$ compared with the surface flux. KamLAND is marked by the ability to detect low-energy antineutrino signals at 1,000 tons of ultra pure liquid scintillator through the inverse $\beta$ reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$. We demonstrated the oscillation nature of neutrino flavor transformation by observing electron antineutrino ($\bar{\nu}_e$) from nuclear reactors and neutrino properties have been explored precisely. Since neutrinos interact with other particles only via weak interaction, they have extremely low reaction probabilities. Such elusive property of neutrinos provides us with the ability to investigate optically invisible deep interior of the astronomical objects, such as the Earth. Neutrino measurement evolved understanding of neutrino properties to utilization of neutrino as a "probe".

The detection of geo-neutrinos, $\bar{\nu}_e$'s produced in $\beta$-decays from primordial radioactivities (uranium, thorium, potassium) within the Earth's interior, brings unique and direct information about the Earth's interior and thermal dynamics. KamLAND detects geo $\bar{\nu}_e$ signals above 1.8MeV due to the reaction threshold energy of the inverse $\beta$-decay, resulting to have sensitivity to $\bar{\nu}_e$'s from the decay chains of $^{238}$U and $^{232}$Th. The KamLAND collaboration reported the results of the first study of geo $\bar{\nu}_e$ in 2005 [1]. Later the geo $\bar{\nu}_e$ signals at KamLAND were used to estimate our planet's radiogenic heat production and constrain composition models of the bulk silicate Earth [2]. Following the Fukushima nuclear accident in March 2011, the entire Japanese nuclear reactor industry, which generates >97% of the reactor $\bar{\nu}_e$ flux at KamLAND, has been subjected to a protracted shutdown. This unexpected situation allows us to improve the sensitivity for geo $\bar{\nu}_e$'s [3].

Currently, geo $\bar{\nu}_e$ observed rate is in agreement with the prediction from existing BSE composition models within $\sim 2\sigma$ C.L., but some extreme models start to be disfavored. This ability to discriminate is limited by the experimental uncertainty and crust modeling. In experimental approach, there is a good possibility that recent low-reactor data will provide new insight into geological field. Furthermore, we are planning to upgrade KamLAND detector (e.g. installation of light collector and high-output liquid scintillator) and aim to achieve better energy resolution ($6.4\%/\sqrt{\mathrm{E[MeV]}} \rightarrow 4.0\%/\sqrt{\mathrm{E[MeV]}}$). Separate measurement of $^{238}$U and $^{232}$Th geo $\bar{\nu}_e$, search for geo-reactor, study of the mantle homogeneity will be the next our targets. In this presentation, recent results and future prospects of geo $\bar{\nu}_e$ measurement with KamLAND will be presented.

[1] T. Araki et al., Nature 436, 499 (2005)
[2] A. Gando et al., Nature Geosci. 4, 647 (2011)
[3] A. Gando et al., Phye. Rev. D 88, 033001 (2013)

# Development for Anti-Neutrino Directional Measurement

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Liquid scintillator (LS) detectors have a good sensitivity to low energy anti-neutrinos. On the other hand, unlike water Cherenkov detectors, LS detectors are not sensitive to direction of anti-neutrinos. Directional sensitive LS detector has possibility that it can reveal information that cannot be seen with other methods. For example, it will contribute to the better understanding of the Earth's interior using geo-neutrino flux measurement in kton scale detector, and there is possibility of application to reactor monitoring system in small size detector.

Anti-neutrinos are detected by inverse beta decay reaction and tagged by the delayed coincidence method (prompt signal is positron and delayed signal is neutron capture event) that provides a powerful tool to suppress backgrounds. Although the emitted neutron retains the directional information of the incoming anti-neutrino, current LS cannot identify the neutron capture point before it loses the information. Li-loaded LS has the ability to shorten the neutron capture range because of large neutron capture cross section (940 barn cf. $^{1}$H 0.3 barn) of $^{6}$Li. To separate prompt and delayed points clearly, the optical discrimination of energy deposit point by high resolution imaging devices is also required. There are two types of imaging device candidates; lens array and reflection mirror.

The status of Li-loaded LS development and the design of lens array will be presented, and experimental study of proto-type reflection mirror will be also reported.

# Experiments on the whole process of magma chamber solidification: preliminary results

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How does the initially totally molten magma chamber, lava lakes and dykes cool and solidify ? Is it possible to constrain the solidification process from the resulting solidification texture ? There have been many experimental (e.g., Brandeis & Marsh, *Nature*, 1989) and theoretical (e.g., Worster et al., *EPSL*, 1990) studies focusing on how the melt solidifies when it is cooled from above and/or from below. These studies have showed a complex coupling between solidification and thermal, compositional convection. We have begun a series of solidification experiments with particular emphasis on studying the whole process until complete solidification and how the process depends on the controlling parameters. Similar process is occurring in the deep Earth (inner core growth) and early Earth (magma ocean solidification), and we hope that our experiments can provide insights into them as well.

We use a thin acrylic tank which we used previously (Shibano et al. *JGR*, 2013), having a height 80 mm, width 80 mm and a thickness of 10 mm. We fill the tank with a wax (PEG 1000) which solidifies at 37 degrees C. We heat the tank from below using a strip heater and a temperature of 70 degrees C is maintained. The wax melts and thermal convection occurs. The Prandtl number of PEG is Pr = 700 and the Rayleigh number of thermal convection is $Ra=2.4\times10^7$ . After a steady state convection is achieved, we turn off the heater. Since the tank is insulated at the bottom, the tank is cooled from the above and the sides. We record the cooling process using time-lapse photos and measure the temperature within the liquid and at the boundaries. We conducted two experiments with different temperatures at the top of the tank; one is cooled at room temperature (Case R) and the other is cooled using an ice water (Case I).

Here we report the preliminary results. We define 3 Stages during the cooling process after the heater is turned off : Stage I until the solidification starts, Stage II until the convection stops, and Stage III until the solidification is complete. We find that timing of the Stage I-II transition and the Stage II-III transition is earlier for the Case I, as expected from the lower temperature. However the timing in which the solidification ends is 150 min for Case R, and 180 min for Case I, and the differs only by a factor of 1.2. In addition we find that solidification texturing forms for both cases which records the pattern of thermal convection prior to solidification. We are formulating a 1-D numerical heat transfer model to see whether it can explain our experimental results.

# Directly apply sintered boron-doped diamond cylinder as heater in the Kawaii-Cell

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It is the first time to report synthesize of semi-conductor boron-doped diamond (BDD) cylinder in the Kawai-type multi-anvil apparatus at 15 GPa and 2100°C. The dimension of the cylinder is 2.6 mm outer diameter, 1.5 mm inner diameter and 3.35 mm length. SEM image shows that the grain size of diamond is about 1 μm. Those cylinders have been used for extremely high temperature generation in a large sample volume (~0.1mm$^3$) in the Kawai apparatus; the sample volume is ~1000 times larger than that in diamond anvil cell. The present study is the first report on pre-synthesized BDD heater in Kawai-type apparatus. The reversibility of the heater was confirmed well through three times of repeated cycles of heating and cooling. The BDD heater with 3 wt.% boron showed metallic behavior, i.e. increasing resistance with increasing temperature. This electrical characteristic is beneficial for stably generating temperature as high as 2700°C; the heating for higher temperature was failed because of failure of electrode. The X ray transparency and pressure generation efficiency by assembly using BDD heater was checked by *in-situ* X ray experiments in Spring 8. Compared with assembly using boron doped graphite heater, the pressure generation efficiency of that using BDD heater is lower at low load, but higher at high load. Being free from complicated power-temperature relationship and pressure drop associated with graphite to diamond conversion, BDD heater is more advantageous than boron doped graphite heater. High X ray transparency and potentiality of generating ultrahigh temperature make BDD the most promising heater for in-situ falling sphere viscometry. BDD heater has succeeded to melt forsterite and diopside at 10 GPa. Falling path of Rhenium sphere (~70 μm diameter) was recorded in *in-situ* experiment.

Key words: diamond synthesize, B-doped diamond heater, ultrahigh temperature, Multi-anvil apparatus

# Frontier studies of Earth's core



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Bullen's hallowed nomenclature for layering of seismic properties in the Earth encompasses the core in layers E, F and G. G is the inner core, F is the 150 km or so above the inner core, and E is the rest. All present observational and geodynamical puzzles. Wavespeeds in E and F seem to depart from homogeneous self-compression, suggesting a link with core evolution phenomena. But exactly what these physically entail - whether light element accumulation, depletion, or core-mantle reaction - is unclear. We need diagnostic tests of each physical model, and these will be summarized.

G, the inner core, at the center of a fluid whose lateral temperature variations are on the order of $10^{-4}$ K, should be a simple, uniformly crystalline object – but it isn't. This is both a curse and a blessing. Its laterally varying, quasi-hemispheric structure provides a marker with which its relative rotation or translation with respect to the mantle may be examined. G also seems to be radially inhomogeneous, with recent affirmation of the existence of an innermost inner core. The inner core's reflectivity appears to vary too, potentially providing a sensitive probe of its anisotropy beyond body wave travel times. Heterogeneities embedded in the inner core material seem to scatter body waves as well, which may find more use in studying the time variation of its properties and potentially revealing rotational or translational behavior. Greater availability of regional array data and array deployments targeting particular source-receiver geometries will help future studies.

# Penetration of mean zonal flows into an outer stable layer excited by MHD thermal convection in rotating spherical shells

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Recent seismological observations and their analyses suggest the existence of a stably stratified layer just below the core-mantle boundary of the Earth, whose thickness is O(100km). The extent of penetration of the deep convective motion into the outer stable layer is one of the important key issue for considering magnetic field generation through the dynamo process as well as the origin of the magnetic secular variation of the Earth. Takehiro and Lister (2001) theoretically derived the scaling of penetration thickness of the columnar convection into the stable layer in the case of no magnetic field, and showed that the penetration thickness is in proportion to the ratio of the angular velocity of the planet to the Brunt-Väisälä frequency of the stable layer and to the horizontal wavenumber of the disturbance. Takehiro (2015) considered the effect of magnetic field and obtained the penetration thickness when the stable stratification is sufficiently strong. The penetration thickness is proportion to the ratio of Alfvén wave speed and inverse proportion to the "arithmetic" average of viscous and magnetic diffusion coefficients and to the total wavenumber of the disturbance. However, these scalings of penetration thickness can be applied when the disturbance under the stable layer is time-dependent, such as oscillatory or propagating motions. The extent of penetration of steady fluid motions, such as mean zonal flows induced by MHD rotating convection, should be examined separately.

We reexamine the theoretical model proposed by Takehiro (2015) in the case of steady fluid motion below the bottom boundary. Steady disturbances penetrate into a density stratified MHD fluid existing in a semi-infinite region in the vertical direction. The axis of rotation of the system is tilted with respect to the vertical. The basic magnetic field is uniform and may be tilted with respect to the vertical and the rotation axis. The linear dispersion relatoin shows that the penetration distance with zero frequency depends on the amplitude of the Alfvén wave speed. When the Alfvén wave speed is small, viscous diffusion becomes dominant and the penetration distance is similar to the horizontal scale of the disturbance at the lower boundary. In contrast, when the Alfvén wave speed becomes larger, the disturbance can penetrate more deeply, and the penetration distance becomes in proportion to the Alfvén wave speed and inverse proportion to the "geometric" average of viscous and magnetic diffusion coefficients and to the total horizontal wavenumber.

In order to validate the theoretical scaling of penetration distance, we perform numerical time integration of finite amplitude MHD thermal convection in a rapidly rotating spherical shell with an upper stably stratified layer embedded in the axially uniform basic magnetic field. The numerical results show that mean zonal flows trapped below the stable layer gradually penetrate into the stable layer as the basic magnetic field is strengthened, which is qualitatively consistent with the theoretical scaling.

# Paleoarchean paleomagnetism, with special emphasis on newly discovered ca. 3.47 Ga records from the Pilbara craton, Western Australia

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Paleomagnetic field represents one of the few observable outcomes from the core and mantle evolution. In particular, the longevity of the dynamo activity (at least up to 3.44 billion years; Usui et al., 2009; Tarduno et al., 2010) implies CMB heat flow, and consequently lower mantle temperature, to be high at that time. Recently, ca. 4.2 Ga paleomagnetic records were reported from detrital zircons (Tarduno et al., 2015); however, the result is under debate (Weiss et al., 2015). The debate arises from the difficulty for detrital zircons to establish tests to distinguish primary magnetic record from later overprint. So far, >3.0 Ga paleomagnetic records are mostly from igneous rocks. Because of the sporadic nature of the igneous activity, it is difficult to evaluate the fluctuation or even persistence of the ancient geodynamo. To address these issues, there are still needs for classical paleomagnetic works in Paleoarchean and Eoarchean. We examine sedimentary chert clasts in ca 3.47 Ga conglomerate from the Pilbara craton. The pre-depositional remanence was confirmed using a conglomerate test, where random magnetic directions are interpreted to reflect the original depositional texture. In addition, common layering in each chert clast enables the reconstruction of pre-depositional inclination, with an assumption that the layering represents the bedding plane. The reconstructed “inclination” is consistent within each clast, but exhibits large scatter among clasts. Unfortunately we did not yet find the source rock for the clasts to fully recover the paleomagnetic variability, but we speculate that the directional scatter may represent large fluctuation in the dynamo activity.

References

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# Thickness of a possible stratified layer at the core surface estimated from a core surface flow model

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Recent seismic studies suggest existence of a stably stratified layer at the top of the Earth's outer core. Such a stratified layer would inhibit upwelling and downwelling flows just below the core-mantle boundary (CMB). Then only toroidal flows are likely to contribute to secular variations of the geomagnetic field observed above the Earth's surface.

Fluid motion at the core surface can be derived from the spatial distribution and secular variation of the geomagnetic field. Estimated core surface flows, which are considered to be those at the top of the main stream immediately beneath a boundary layer at the CMB, provide information on a realistic geodynamo mechanism, core-mantle coupling mechanism, and so on. If the contribution of poloidal flow to the secular variations is much less than that of toroidal flow, such an estimated core surface flow suggests that there exists a stratified layer at the CMB. It should be noted that most of core flow models are estimated on the basis of the frozen-flux hypothesis; that is, the magnetic diffusion is neglected in the induction equation. However, based on the no-slip boundary condition, the fluid velocity field should vanish at the CMB, and a significant viscous boundary layer would appear there. Furthermore, if such a viscous boundary layer exists, observed time variations of the geomagnetic field are caused only by the magnetic diffusion at the CMB, and the frozen-flux hypothesis does not necessarily hold.

A new method of estimating fluid flows near the core surface has been presented by Matsushima (2015); the magnetic diffusion inside the viscous boundary layer at the CMB is taken into account, while the magnetic diffusion below the viscous boundary layer is neglected as in the frozen-flux approximation. In the method, depth at which fluid motions are estimated below the viscous boundary layer is one of parameters. Therefore it might be possible to examine the existence of upwelling and downwelling at any depth below the CMB. In this paper, we attempt to detect a stratified layer and its thickness at the top of the core using such parameterization.

# The boundary mode of the axially symmetric MAC wave in the stratified layer at the top of the Earth's outer core

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Seismological observations (e.g. Helffrich and Kaneshima(2010), Kaneshima and Helffrich(2013) ) have shown that a stratified layer exists at the top of the outer core possibly through the accumulation of light fluid. The stratified layer can harbor the MAC wave, which arises from the balance among magnetic, Archimedes and Coriolis forces. The nature of the axially symmetric modes of the MAC wave is examined theoretically by Braginsky (1993) to explain the cause of the 60-year variations of the geomagnetic field. In his model, a sharp boundary exists between the layer and the bulk of the outer core, where the fluid density is discontinuous, and the buoyancy frequency is constant within the layer. The latitudinal phase velocity of the solution is equal to the Alfvén wave velocity multiplied by the buoyancy parameter

$$c_{lat} = V_A B_u = V_A \frac{N}{f}, \tag{1}$$

where $c_{lat}$ is the latitudinal phase velocity, $V_A$ is the Alfvén wave velocity, $B_u$ is the buoyancy parameter, $N$ is the buoyancy frequency, and $f$ is the Coriolis parameter. Since the latitudinal phase velocity is proportional to buoyancy frequency, the stratification can be estimated if the phase velocity is determined observationally. If the 60-year variation of the geomagnetic field is identified as the fundamental mode with the latitudinal wavenumber $l = 2$, the buoyancy frequency is estimated to be about twice the angular velocity of the Earth's rotation.

We have found that Braginsky(1993)'s equations also have the solutions localized at the layer boundary, which we refer to as the boundary mode. This mode has a time scale smaller than the solution within the layer (Braginsky(1993)'s solution), and spreads through magnetic diffusion. The phase propagates away from the layer boundary. The latitudinal phase velocity of the boundary mode scales as

$$c_{lat} \propto \left(\frac{V_A}{f}\right)^{4/3} \left(g\frac{\Delta\rho}{\rho}\right)^{2/3} \left(\frac{l}{\eta}\right)^{1/3}, \tag{2}$$

where $g$ is the gravity acceleration, $\Delta\rho$ is the density at the boundary, $\rho$ is the typical density, $l$ is the latitudinal wavenumber, and $\eta$ is the magnetic diffusivity. The phase velocity does not depend on the buoyancy frequency within the layer. The wave amplitude decreases exponentially with the distance from the layer boundary. Temporal and spatial decay rates increase as the density jump or the latitudinal wavenumber increases. Therefore, small density jumps and small layer thicknesses are required to find the boundary mode observationally, and waves with smaller latitudinal wavenumbers are expected to be observed more easily. If the 60-year fluctuation of the geomagnetic field is identified as the boundary mode with the latitudinal wavenumber $l = 2$, the ratio of density discontinuity $\Delta\rho/\rho$ is estimated to be about $10^{-4}$.

# Sensitivity of core phases to F-layer structure

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In this study we discuss the sensitivity of various core phases (PKIKP, PKPbc, PKPc-diff, and PKiKP) to the F-layer (lowermost outer core) structure in detail. PKIKP pierces the inner-core boundary and turns in the inner core; PKPbc turns in the lower part of the outer core; PKPc-diff diffracts on the inner-core boundary beyond the C-cusp; PKiKP reflects on the inner core boundary. In previous studies, the Vp structure of the F-layer have been investigated using absolute traveltimes of PKPbc/c-diff, differential traveltimes between PKPbc/c-diff and PKIKP, amplitude ratios between PKPbc/c-diff and PKIKP, and the position of the C-cusp. Among these observations, absolute traveltimes of PKPbc are affected by crustal and mantle structures that are strongly heterogeneous and are not precisely known, which indicates benefits of analyzing differential travels times. Differential traveltimes suppress the effects of heterogeneous structures as well as the discrepancy between a reference seismic model and the real Earth above the turning depths of rays. However, it is difficult to discriminate the Vp of the F-layer from that of the inner core using the differential traveltimes between PKPbc and PKIKP, because the inner core is more heterogeneous than the F-layer. Fine structure of the F-layer is also poorly constrained by the amplitude ratios because of the low sensitivity of the ratios to the Vp gradient and of a trade-off between the Vp profile of the F-layer and the attenuation values in the inner core. The C-cusp position can be constrained only poorly by the amplitude observations, and there exist many velocity profiles that yield the same C-cusp position. In summary, conventional observations are obviously insufficient to resolve detailed F-layer structure.

At the SEDI meeting of last year, we showed that the dispersion in PKPbc and differential traveltimes between PKiKP and PKPbc are particularly sensitive to the F-layer structure and are insensitive to the structure of the other parts of the Earth. Using these two new observations, we obtained a very well-constrained seismic profile of the F-layer (called “FVW”), which has been poorly resolved by previous seismic observations yet. Our model has P-wave velocities that lie between those of AK135 and PREM, and a velocity gradient that is slightly gentler than that of PREM. Models with a uniform P-wave velocity value within the layer are not supported by the observations.

# Penetration of magneto-hydrodynamic disturbances into a strongly stable outer layer caused by MHD dynamo in a rotating spherical shell

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Numerical experiments of magneto-hydrodynamic dynamo in a rotating spherical shell with a strongly stable outer layer are performed. Although the estimated values of penetration thickness of the disturbances into the stable layer proposed by Takehiro and Lister (2001) for non-magnetic cases are sufficiently small compared with the thickness of the stable layer, it is observed that vortical fluid motions and toroidal magnetic field disturbances deeply penetrate into the stable layer. These magneto-hydrodynamic disturbances in the stable layer can be interpreted as the Alfven waves whose fluid motions are restricted in the horizontal directions. The proposed theoretical expression of propagation distance of the Alfven waves suggests that the numerically obtained fields permit the complete propagation of the Alfven waves across the stable layer.

# Liquid iron alloys with hydrogen at outer core conditions by first-principles calculation

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Since the density of the outer core deduced from seismic data is about 10% lower than that of pure iron at core pressures and temperatures (*P*-*T*), it is widely believed that the outer core includes one or more light elements. Although intensive experimental and theoretical studies have been performed so far, the light element in the core has not yet been identified. Comparison of the density and sound velocity of liquid iron alloys with observations, such as the PREM, is a promising way to determine the species and quantity of light alloying component(s) in the outer core. Here we report the results of a first-principles molecular dynamics study on liquid iron alloyed with hydrogen, one of candidates of the light elements. Hydrogen had been much less studied than other candidates. However, hydrogen has been known to reduce the melting temperature of Fe-H solid [1]. Furthermore, very recently, Nomura et al. argued that the outer core may include 24 at.% H in order to be molten under relatively low temperature (< 3600 K) [2]. Since then hydrogen has attracted strong interests. We clarify the effects of hydrogen on density and sound velocity of liquid iron alloys under outer core P-T conditions. It is shown that ~1 wt% hydrogen can reproduce PREM density and sound velocity simultaneously very well. In addition, we show the presence of hydrogen rather reduces Grüneisen parameters. It indicates that, if hydrogen exists in the outer core, temperature profile of the outer core could be changed considerably from one estimated so far.

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# Recent progress in the study of oceanic mantle by geophysical observations

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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. In spite of the importance, our knowledge on the oceanic mantle directly obtained through geophysical (seismic and electromagnetic (EM)) observations is quite limited because of the observational difficulty. New development of instrumentation is indispensable for overcoming the difficulty and earlier work of such efforts can be traced back to 1960's. Now state-of-the-art seafloor instruments both for seismic and EM observations are put into practical use in recent scientific projects, providing new images of oceanic mantle. In this review talk, we would like to mainly show recent results of EM exploration of oceanic mantle, with reference to seismological results.

The most robust feature from a seafloor EM observation is the presence of highly conductive layer in the upper mantle at corresponding depths with those of seismic low velocity layers. It is also known that both depths to the low velocity and to the high conductivity layers show an apparent dependence on plate age. If the low velocity and high conductivity are both due to the common cause to that of asthenosphere lubrication, joint observation and interpretation will be a best way to solve this important scientific question. Several scientific projects are recently carried out for the particular purpose, provided clear images of the upper mantle structures but revealed the presence of more complexity.

Second we concern the amount of water within the Earth, particularly in the mantle transition zone (MTZ). Because the MTZ minerals have substantial water solubility as compared with that of upper or lower mantle minerals, accurate estimation of its water content is essential to understand the Earth’s total water budget. Some of recent results indicated that a joint interpretation of seismic and EM observations has potential to solve this problem.

The penetration depth of natural EM field variations is limited to the upper part of the lower mantle. The conductivity distributions at larger depths (at CMB for example) can be studied by analyzing short-term secular variations or geomagnetic jerks. Here we show one of the most recent results on CMB structures by analyzing data from long-term measurements of electrical voltage variations over transoceanic cables together with conventional geomagnetic observatory data.

Some of new scientific findings on oceanic mantle structures have thus been provided but only from limited areas where observations have been made. To obtain more 'global' view, we propose a feasible plan, 'the Pacific Array', in which observations will be made by a finite number (order of 10) of small seafloor arrays consisting of 10 observation sites and properly distributed in the whole Pacific region. Each array is to be deployed for 2-3 years. With an international collaboration, 2-3 arrays can be simultaneously operated so that imaging the Pacific mantle can be accomplished in 10 years or so.

# Persistence of Strong Primitive Domains in the Earth's Lower Mantle

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Geochemists and geophysicists traditionally hold widely divergent views of Earth's mantle. Geochemical data are consistent with extensive melting of the upper mantle to produce continents, leaving behind a "depleted" upper and "primitive" lower mantle. Geophysical methods, on the other hand, show that the plate tectonics cycle of lithospheric subduction extends deep into the lower mantle in some regions, and that most major seismic structures in the mantle can be explained by solid-solid phase transitions without invoking composition variations. The persistence of pristine reservoirs is seemingly at odds with the mixing that is expected to accompany whole mantle convection. Here we propose that primitive-like domains will exhibit a higher viscosity in the lower mantle owing to a higher modal abundance of the rheologically strong (Mg,Fe)SiO3-bridgmanite (Br) phase. Using mantle convection calculations that include a strong modestly dense layer in the lower mantle, we show that whole mantle thermal convection can become established without substantial mixing between depleted and primitive domains. Our models suggest that relatively weak depleted rocks circulating between the shallow and deep mantle form rheologically weak conduits between the strong primitive domains, establishing a stable planform that persists for time scales longer than the age of the Earth. This hybrid model can also explain anomalous seismic velocity variations in the mid-lower mantle, the presence of subducted lithospheric slabs that "stagnate" in or below the mantle transition zone, and the muted geoid response to deep subduction. Our model also provides a physical mechanism for proposed anchoring of deep mantle structural planforms against disruption by tectonic cycles.

# Along-arc variation in the thermal and flow structure around northeast Japan subduction zone

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It is essential to constrain the thermal and flow structure in the subduction zone to better understand not only the seismic and volcanic activities there but also the long-term material circulation between Earth's surface and its interior. Among many subduction zones, the subduction zone in Japan is one of the best place to study because of a number of observations available there. It has long been recognized that the structure in the mantle wedge shows across-arc variation, but recent observations have shown that it also changes in the along-arc direction. So far, I have mainly focused on the northeast part of Japan where cold Pacific plate is subducting beneath the overriding plate. I will show some of the results obtained by these studies in this presentation, which includes (1) the effects of trench shape for the region around the junction between Tohoku and Hokkaido, and (2) the effects of a thin, low viscosity layer just above the subducting slab for Tohoku.

The direction of Pacific plate motion is nearly normal to the trench beneath Tohoku, whereas it is oblique beneath Hokkaido. We investigated the effects of trench shape on the flow structure by using numerical model. The obtained results show that a 3D flow arises inside the mantle wedge, which is consistent with S-wave splitting observed in these regions. We also found that the 3D flow produces along-arc variation in the torque balance acting on the subducting Pacific plate, which leads to along-arc changes in the subduction angle which is consistent with the observed one. We also investigated the effects of 3D slab geometry on the thermal structure in these regions. We found that an anomaly in slab surface temperature arises around the junction between Tohoku and Hokkaido, but the magnitude is moderate.

It has been proposed that the distribution of Quaternary volcanoes form clusters whose average wavelength is $\sim$80 km in Tohoku. The obtained image of seismic wave velocity shows that the clustering of volcanoes is related to the presence of partial melting in the mantle wedge, the degree of which changes in the along-arc direction. Previous numerical studies have shown that small-scale convection of a thermal or chemical origin can produce the along-arc variation in the mantle wedge structure, which leads to the formation of volcano clustering. However, these models strongly depend on poorly constrained parameters such as the effects of water on viscosity. Therefore, I proposed an alternative explanation for the volcano clustering. I found that when a thin, low viscosity layer exists just above the slab surface, 3D flow starts to arise inside the layer and it leads to the along-arc variation in the slab surface temperature. Such a layer is needed to create a "cold corner" in the mantle wedge by decoupling the movement of the slab and mantle.

# Upper mantle structure of North America using inter-station phase and amplitude data of surface waves

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The western United States encompasses a variety of complex structural features, including regions with east-west extension, active volcanoes, and relatively stable cratonic blocks. The high-quality broadband seismic data derived from the high-density Transportable Array (USArray) have facilitated many new tomographic studies in this region. We have recently developed a new technique to measure inter-station phase velocity and amplitude ratio data for fundamental-mode surface waves based on non-linear waveform fitting between two stations of USArray (Hamada & Yoshizawa, 2015, GJI). The method has been applied to observed waveforms of USArray from 2007 to 2010, and we could collect a large-number of phase velocity and amplitude data for short inter-station distances less than 1000 km, which can be helpful in enhancing the horizontal resolution of phase velocity models in North America.

The amplitude anomalies of surface waves are affected by not only anelastic attenuation, but also elastic focusing/defocusing, which depend on the second derivatives of phase velocity across the ray path. Thus, the amplitude data are sensitive to shorter-wavelength structure than the conventional phase data. Although the inter-station amplitude ratios of surface waves can be useful for improving the lateral resolution of phase velocity models, structural studies using the inter-station amplitude data have yet to be investigated. In this study, the measured inter-station phase velocity and amplitude ratios are inverted simultaneously for phase velocity model as well as local amplification factor at receiver locations. While our phase velocity maps derived only from phase data reflect large-scale velocity anomalies, those from both phase and amplitude data tend to exhibit better recovery of the strength of velocity perturbations, and local-scale tectonic features are more enhanced in the model; e.g., significant slow anomalies in Rio Grande Rift, Yellowstone, as well as a relatively faster anomaly in Colorado Plateau. Also, the spatial distribution of receiver amplification factor shows a clear correlation with the velocity structure, suggesting that the amplitude data also contain the elastic properties of local structures under each station. Our results indicate that inter-station amplitude data measured using a dense array can be useful for the reconstruction of shorter-wavelength elastic structures in the upper mantle.

# Seismic Constraints on the BEAMS (Bridgmanite Enriched Ancient Mantle Structures) Model for Mantle Evolution

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The BEAMS hypothesis explores the end-member scenario in which the Earth's mantle began with a uniform composition and an Mg/Si ratio close to that for the sun. Melting of the upper mantle extracted mid-ocean ridge basalt, MORB, and further melting of MORB led to the creation of continents. Continents are rich in Si compared to MORB, so are light and more viscous and thus resist erosion back into the mantle. The mantle left behind after producing MORB, the depleted MORB mantle or DMM is then depleted in Si relative to its initial composition. However, the lower mantle which was not effected by mid-ocean ridge melting would retain its Si enrichment through time, and due to the higher relative viscosity of Si rich materials, would resist erosion into the convecting mantle. Harzburgite is the olivine rich rock that makes up most of the cold subducting oceanic lithosphere or slabs that enter the mantle in subduction zones and travel through the mantle eventually reaching the core-mantle boundary, CMB. Harzburgite rheology is dominated by periclase, (Mg,Fe)O, which is at least an order of magnitude less viscous than bridgmanite. Thus, as more slab material descends into the lower mantle, it eventually forms channels that allow subducted material to flow more freely. This material is then heated by the core and its positive buoyancy leads to the formation of upwelling channels away from subduction zones. Once this plan form is in place, it is stable over geologic time.

Seismic observations that motivate the BEAMS hypothesis include: 1) The dominant pattern of heterogeneity in the upper and lower mantle are very different. Indicating a change in the dominant style of tectonics. 2) The decrease the magnitude of the fast anomaly from subducting slabs in the mid-mantle could be due to a decrease in the velocity contrast between bridgmanite and cold harzburgite. In addition, the effects of the iron spin transition will decrease the seismic signal of the slab material. 3) The strong signal from fast slabs near the CMB could be due to the absence of the bridgmanite domains. 4) The columns of slow material above the LLSVP (Large Low Shear Velocity Provinces) are consistent with warm return flow of material circulating around the bridgmanite domains.

# Effects of water and fluid transport on subduction dynamics

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A systematic study on the effects of water on subduction dynamics, e.g., plate migration rate, slab geometry, deformation of continental margin, and stress field, has been conducted using a 2-D self-consistent model for the lithosphere subduction and whole mantle convection. In the model, water transportation based on phase diagrams of hydrous rocks, and constitutive and state equations for the hydrous rocks are considered. Our model has successfully reproduced water distribution in a mantle wedge and along the slab with sufficient resolution comparable to previous models that focus on the mantle wedge structure. As a result, density reduction of hydrous areas declines subduction rates, back arc spreading, and slab stagnation on the 660-km phase boundary, while viscosity reduction of hydrous areas enhances rapid subduction, trench migration, and slab stagnation. These results suggest that hydrous buoyancy reduces the slab pull force and the accompanied tensile stress on overlying lithosphere, and that viscosity reduction due to the hydration changes mechanical coupling of the subducted slab with the wedge mantle and overriding lithosphere. Our models therefore show that hydration has important influences on plate motion and slab deformation as well as magma generation, wedge mantle flows, and erosion of the overriding lithosphere. This implies that consideration of the hydration effects are essential to gain better understanding for the whole mantle-scale dynamics of the hydrous planet with plate tectonics.

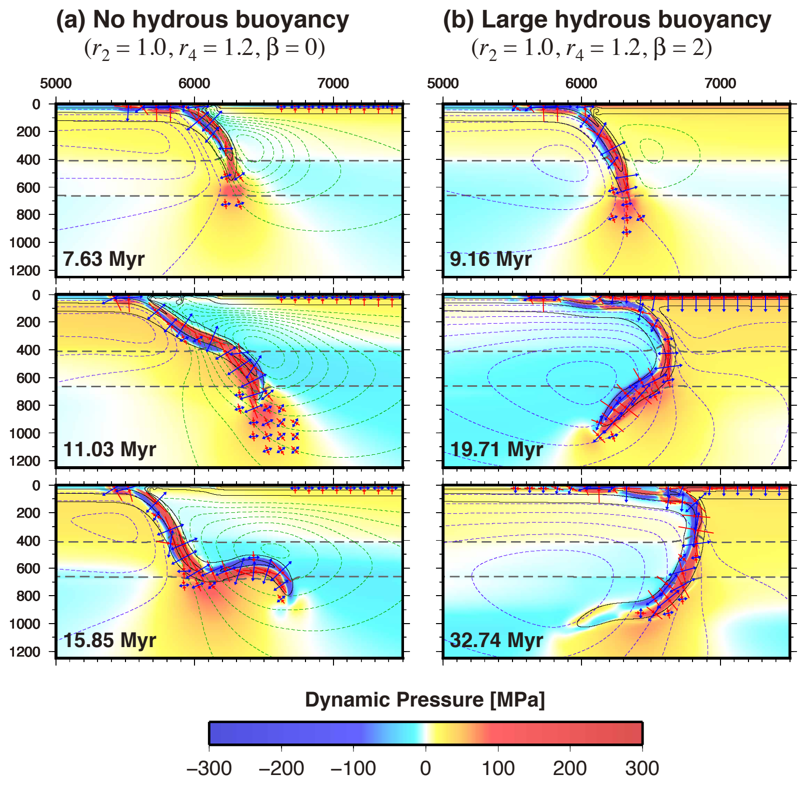


**Figure:** Comparison between evolution of two runs, where different hydrous buoyancy $\beta$ and the same viscosity reduction by hydration $r = 1.0, 1.2$ are given. Color contour shows dynamic pressure solved by a SIMPLER algorithm; red areas are compressed, and blue areas are decompressed. Solid black lines represent isotherms (400°C intervals). Purple and green doted lines are clockwise ($\psi > 0$) and counter-clockwise ($\psi < 0$) stream function ($10^{-4}$ [m$^2$/s] intervals). Red and blue allows represent magnitude and directions of maximum principal stress $\sigma_1$ and minimum principal stress $\sigma_2$, respectively. Dashed gray lines represent 410- and 660-km phase boundaries.

# Inter-station phase speed and amplitude measurements of surface waves toward a high-resolution upper mantle model in the Sea of Japan

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The upper mantle structure and dynamics beneath the Sea of Japan is important to understand its tectonic history including back-arc spreading and the subsequent formation of the Japanese islands. The seafloor topography of this marginal sea is quite variable, characterized by several basins and rises, with the Moho depths varying from 9 km beneath the Japan Basin to 22 km beneath the Yamato Rise in the center of the sea. Seismic structure in the crust and uppermost mantle beneath this region is likely to reflect the complex evolution history. The high-resolution mapping of the upper mantle structure beneath the Sea of Japan is, however, not straightforward due to the limited numbers of ray paths across the sea (e.g., Yoshizawa et al., 2010, PEPI).

A temporary broadband seismic array has recently been deployed across Northeast China (NECESSArray), which can be of great help in enhancing the ray coverage across the Sea of Japan, working with the inter-station dispersion measurements of surface waves. In combination with the Japanese permanent broadband network (F-net), global seismic network in Northeast Asia, and temporary broad-band seismic network in Far-East Russia, we are now able to collect a large number of inter-station phase speed and amplitude information across the Sea of Japan. In this study, we employ a fully non-linear waveform fitting technique to measure inter-station phase speeds and amplitude ratios (Hamada & Yoshizawa, 2015, GJI). Through the waveform analysis of the combined data sets, we could collect more than 4000 new measurements of phase speeds in the period range between 30 and 130 seconds from the seismic events with moment magnitude greater than 6.0 in 2009 and 2010. The updated preliminary phase speed maps of Rayleigh waves show fast phase speed anomalies beneath the Japan Basin in the shorter period than 60 s, while the phase speed beneath the southwestern margin including the Tsushima Basin is slower at all the period range. In the period longer than 80 s, slow anomalies are found in most areas beneath the Sea of Japan except for the Yamato Rise, implying lateral variations of lithospheric root.

# Further examination of the geoelectromagnetic jerk hypothesis

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Short time-scale geomagnetic main field variations such as a geomagnetic jerk may be influenced by electromagnetic induction and conduction in the lower mantle. Similar variations were seen in long baseline geoelectric field measurements that are in progress in the northwestern Pacific using thousand-kilometer-scale submarine cables. Geoelectric secular variation data from such measurements have potential to discuss the significance of the influence and to clarify the cause of the phenomenon if they are analyzed simultaneously with geomagnetic data. In our previous work, we found a sudden change of the geoelectric field trend at around 2006. By supposing simply that the geoelectric field variation has the same origin with the geomagnetic jerk in 2007 (geoelectromagnetic jerk hypothesis), which was evident in the south Atlantic and Africa, we made a numerical study to understand possible cause and conductivity structure in the mantle. As a result, it was found that the geoelectric and geomagnetic field variations were both explained if the variations were originated from a toroidal magnetic field at the core-mantle boundary. It was also suggested that significant electrical conduction currents existed in the D'' layer beneath the area where the geomagnetic field variation was evident. In this presentation, the validity of the geoelectromagnetic jerk hypothesis is discussed by extending the analyses adding more recent geoelectric and geomagnetic field data. Also, we estimate the amplitude of motionally induced electric field variation in the ocean by using a large-scale ocean circulation model to confirm that motional induction is not the cause of the observed geoelectric signal.

# New constraints on S-wave velocity structure near the western edge of the Pacific LLSVP

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S-wave velocity structure near the edge of the Pacific Large-Low Shear Velocity Province (LLSVP) has been examined by many researchers (e.g., He et al., 2006; He and Wen, 2009; Takeuchi et al., 2008; Idehara et al., 2013). They have mainly used the differential travel times of ScS-S observed by global or local broadband networks (e.g., IRIS GSN, F-net, CNDSN and so on). Here we add the new data of ScS–S and S–SKS travel time data obtained by NECESSArray and a temporal broadband ocean bottom seismograph network in the Philippine Sea by the Stagnant Slab Project (SSP-BBOBS) (Shiobara et al., 2005).

ScS–S anomalies observed by NECESSArray in conjunction with those by F-net, which covers the region beneath the eastern Micronesia, are roughly explained by the existing 3D S-wave models. However, S–SKS anomalies, which are affected by S-waves propagated near the base of the mantle beneath the western Micronesia and the north of New Britain Island, suddenly changes from positive in the eastern area to almost zero or slightly negative in the western, whereas all the models predict large positive anomalies without significant changes. To confirm this S-SKS observation, we further examined ScS–S anomalies observed by the SSP-BBOBS. Some data indicate nearly zero in the corresponding area although the data are scattered and still sparsely distributed. Since a low velocity anomaly beneath the New Guinea Island are confirmed by Takeuchi et al. (2008) and Idehara et al. (2013), our observation suggests that the Pacific LLSVP is separated beneath the north of New Britain Islands. The models of 3D mantle structure are possibly insufficient near the western edge of the Pacific LLSVP.

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# Anisotropic layering in the continental upper mantle: Implication for the mid-lithosphere discontinuity?

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Boundary layers in the upper mantle are the keys to better understanding of formation and evolution of tectonic plates. Seismological studies based on body wave receiver functions and surface wave tomography can be of help in detecting such boundary layers. In the continental region, thick cratonic lithosphere over 200 km depth has been mapped using surface waves (e.g., Yoshizawa, 2014, PEPI), but its base is rather ambiguous due to the lack of any clear converted signals in receiver functions from such depth (e.g., Ford et al., 2010, EPSL), implying a smooth transition from lithosphere to asthenosphere beneath cratons. Many of the receiver function studies have, however, shown the converted signals at the depth around 90 km in cratonic regions, which may indicate the existence of mid-lithosphere discontinuity (MLD) in the cratonic lithosphere, though it is not very clear in the shear wave speed profiles derived from long-period surface waves and the cause of MLD is still a controversial issue.

We have recently constructed a new radially anisotropic S wave model of the Australian upper mantle employing multi-mode phase dispersion of surface waves. The depth and thickness of the lithosphere-asthenosphere transition (LAT) underneath the Australian lithosphere are mapped using the vertical velocity gradient of the isotropic shear wave speed profiles. The new continental model of Australia shows the significant vertical and lateral variations of radial anisotropy in and under the lithospheric mantle beneath the continent. Anomalously faster SH wave speeds are found both in the shallower depth above 80 km as well as in the asthenosphere beneath LAT. The former is seen mainly in the suture zone in central Australia, which may reflect the frozen-in anisotropy due the past deformation between cratonic blocks, while the latter is likely to reflect the effects of horizontal shear beneath the fast drifting continental lithosphere beneath Australia. A striking feature is seen in the mid-lithospheric depth at around 90 km in the cratonic regions, where the strength of radial anisotropy becomes relatively weak. The depth of weakened anisotropy matched well with the estimated depths of the mid-lithosphere discontinuity estimated from body-wave receiver functions. This may imply the nature of the enigmatic MLD from the receiver functions, which may be related to the vertical change in the radial anisotropy or the anisotropic layering in the cratonic lithosphere.

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