SIT35-P01 Room:Convention Hall Time:May 26 18:15-19:30

The boundary mode of axially symmetric MAC waves can exist in the stratified layer at the top of the Earth's outer core

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Seismological observations (e.g. Helffrich & Kaneshima(2010), Kaneshima & Helffrich(2013)) and theoretical predictions show the existence of a layer stratified by the accumulation of light fluid at the top of the Earth's outer core. Helffrich(2014) suggested that its most probable origin is the vestige of primitive Earth. MAC waves, which arise from the balance among magnetic, Archimedes and Coriolis forces, can exist in the stratified layer. To explain the cause of the 60-year variations of the geomagnetic field, Braginsky(1993) examined axially symmetric approximate solutions of MAC waves theoretically. In his model, a boundary exists, where the fluid density is discontinuous between the layer and the bulk of outer core, and the buoyancy frequency is constant within the layer. (Recent seismological observations, however, indicate that the density jump is unlikely at the boundary.) The latitudinal phase velocity of the solution is equal to the Alfvén wave velocity multiplied by the buoyancy parameter ($c_{lat} = V_A \cdot B_u = V_A \cdot N / f$, 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), and the vertical structure is expressed as a superposition of sine waves. The decay rates of the wave are proportional to the magnetic diffusivity. 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's(1993) 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's(1993) solution), and spreads through magnetic diffusion. The phase propagates away from the layer boundary. The frequency of the boundary mode does not depend on the buoyancy frequency within the layer. The frequency and the vertical wavenumber depend on the magnitude of the density discontinuity, the latitudinal wavenumber, and several parameters. The wave amplitude decreases exponentially with the distance from the layer boundary. As the density jump or the latitudinal wavenumber increases, temporal and spatial decay rates increase. 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 is estimated to be about 10^{-4}. Furthermore, the boundary in contrast to the MAC wave within the layer, the spatial and temporal decay rate of the boundary mode decreases as the magnetic diffusivity increases.

Keywords: MAC waves, the top of the Earth's outer core, H layer

SIT35-P02 Room:Convention Hall Time:May 26 18:15-19:30

Effect of sulfur on the reaction between iron and water under high pressure and temperature

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It is reported that hydride phase such as FeH and FeOOH appears by a reaction between Fe and H_2O under the Earth's deep environment during the formation stage (e.g.,Okuchi,1997;Ohtani et al.,2005). In this study, we added sulfur and observed a reaction of the Fe-S-O-H system under high pressure and high temperature to investigate the effect of sulfur on Fe-O-H system.

Because hydrogen in metal hydride, which is expected to produce in the reaction, is dissipated from the sample at low pressure, we carried out the experiments at High Energy Accelerator Research Organization (KEK), Photon factory (PF-AR-NE1A), and identified phase transitions of the sample and the reaction products by in situ X-ray diffraction method.

We used a laser-heated diamond anvil cell installed at AR-NE1 to generate high pressure and high temperature. Starting materials were pelleted FeS and pure water in rhenium gasket. The pressure was measured using the equation of state of ice Ⅶ. The double-sided heating with Nd:YAG laser to heat, the reaction temperature was estimated from radiation of the high temperature portion of the sample.

In this study, the pressure was 24 and 33 GPa and the temperature was between 300 and 1200 K. As a result, FeS_2 (Pyrite), dhcp-FeH_X and ϵ-FeOOH appeared as the reaction product. It was revealed that stability field of ϵ-FeOOH is much higher puressure than that of Fe-O-H system, high temperature decomposition of ϵ-FeOOH was also constrained, FeS_2 which doesn't appear in the Fe-S-H system is observed. We will present further result of SEM-EDS analysis of the recovery sample.

Keywords: Earth's core, light element, hydrogen, synchrotron

SIT35-P03 Room:Convention Hall Time:May 26 18:15-19:30

Measurement of thermal conductiviy of mantle minarals at pressures of the transition zone to the lower mantle

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Knowledge of thermal diffusivity or thermal conductivity of the mantle is vital for study of the dynamics of the Earth. So far we have measured thermal diffusivity and thermal conductivity of upper mantle minerals, i.e. olivine and garnet and hydrous phases, i.e. serpentine and talc. All those data were obtained by the experiments at pressures up to 10 GPa and temperatures to 1100 K. The measurements were conducted by a pulse-heating method of one-dimensional heat flow using the Kawai-type apparatus at the Institute for study of the Earth's interior, Misasa. This current method is a predominant one for study in deep Earth's materials under pressure. It has some advantages as follows:(1) comparatively small amount of samples (2) applicable to materials with anisotropy in thermal conduction (3) simple cell assembly. Moreover, this method enables to obtain specific heat capacity under pressure.

In order to expand pressure range the cell assembly is needed to advance by reducing its dimensions. A new cell-assembly similar to our previous one is designed for a sample of 2.6 mm in diameter and 0.6 mm in thickness. This smaller cell is installed in a 14 mm edged octahedral pressure medium in 7 mm trancated anvils. This cell enables to make measurements of the thermal properties at pressures exceeding 15 GPa, which will covers the condition in the mantle transition zone. The cell will be also applied to pyroxene samples of which sizes are necessarily limited. Test measurements were made using garnet samples. The results agree well with those of the previous experiments using the larger (18-11 and 14-8) cell, and the extrapolations to zero-pressure coincide to values of other methods. Thus, the pulse heating method will be applied for thermal property measurements of wadsleyite, ringwoodite and majorite. Using large anvils ($>$46 mm), the method is probable to measure the thermal conductivity of $MgSiO_3$ perovskite (bridgmanite). However, measurements at high temperature still have somewhat problems in precision. Materials of impulse heater and external furnace should be re-considered. The precision of measurements should be improved by well-controlled machining of the cell assembly and by refining the data acquisition system.

Keywords: mantle minerals, thermal diffusivity, thermal conductivity, high-pressure, Kawai-type apparatus

SIT35-P04 Room:Convention Hall Time:May 26 18:15-19:30

Lattice diffusion in MgO crystal from first principles simulation

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Rheological property is critical to understanding the mantle convection. Diffusion creep might be the dominant deformation mechanism in the Earth's lower mantle and super-Earths' mantle (e.g., Karato, 2011). Thus several experimental and theoretical studies have tried to measure lattice diffusion coefficients under pressure, which are both still technically difficult. There are two theoretical approaches to calculate self-diffusion coefficient in solids. One is based on the static lattice energy calculation and the other is based on the molecular dynamics simulation. In the former case, it is difficult to evaluate attempt frequency and in the latter case, atoms are hardly mobile in actual computation time at the Earth's lower mantle and super-Earths' mantle temperatures. These two approaches were previously applied to MgO, one of major deep mantle constituents (Ita & Cohen, 1997; Ito & Toriumi, 2007). However reported pressure dependences of the self-diffusion coefficients are contradictive with each other particularly at high pressure over 80 GPa.

In this study, we develop a new theoretical method to calculate self-diffusion coefficient in crystals with charged vacancies (Schottky pair) within the first principles framework. This method was then applied to NaCl-type MgO. We found that the calculated pressure dependences of the self-diffusion coefficients in MgO are consistent with those of Ita & Cohen (1997). Diffusion creep viscosity of MgO was then estimated using calculated diffusion coefficients. Our activation volumes are consistent with experimental values at low pressure (Van Orman et al., 2003) and decrease rapidly with increasing pressure. It suggests that super-Earths' mantle would not be quite viscous and the constant activation volume extrapolation leads to overestimation of viscosity in the deep mantle.

This method is widely applicable to other materials including bridgmanite, post-perovskite and CsCl-type MgO, which are important to analyze more realistic planetary interior dynamics.

Keywords: MgO, lattice diffusion, Earth's lower mantle, super-Earths' mantle, first principles

SIT35-P05 Room:Convention Hall Time:May 26 18:15-19:30

Are LLSVPs formed in the Earth's lowermost mantle by the subduction of oceanic crusts?

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We conducted a series of numerical experiments of thermo-chemical mantle convection where a subduction is preferentially induced at a continental margin, in order to verify a hypothesis that the Large Low-Shear Velocity Provinces (LLSVPs) in the Earth's lowermost mantle are formed by subduction of oceanic crust. In this study, we adopted a model of two-dimensional rectangular box of 2900km height and aspect ratio 6 with reflective boundary condition in the horizontal direction. We placed an immobile lid as a model of surface supercontinent which covers a third of the top surface. We also put a thin layer of chemically dense materials as a model of oceanic crust, which may sink into the deep mantle along with cold descending flows from the top surface.

Our calculations showed that the subducted oceanic crusts are preferentially provided under the continent when the subduction at the margin of continent is stable. However, stable subduction caused strong convection and significantly stirred the mantle under the continent. Therefore, subducted oceanic crusts were distributed almost uniformly under the continent without accumulating on the CMB. On the other hand, the cases with unstable subduction at the margin of continent showed a long-wavelength mantle convection structure which has an ascending plume along the side wall under the continent and a descending plume at the opposite side wall. The large-scale flow gathered subducted oceanic crusts under the continent and formed large piles on the CMB.

Our results suggest that the LLSVPs are hardly formed in the presence of stable plate tectonics like the current one where a stable plate motion including subduction stirs the mantle very effectively. In other words, the formation of large thermochemical piles which are equivalent to the LLSVPs should have been completed before the plate tectonics is well established, assuming that subducted oceanic crusts are the origin of LLSVPs.

Keywords: mantle convection, numerical simulation, LLSVP, plate subduction

Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)

SIT35-P06 Room:Convention Hall Time:May 26 18:15-19:30

Experimental presentation of plate subduction using paraffin wax

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Experimental approaches using analogue materials have been widely used to understand kinematic behaviors of tectonic plates. Previously molten paraffin in a tank inside a hot water bath has been used. Although tectonic plate-like behaviors, such as inclined subduction and trench migration, have been observed, the “plate” in this case was too thin to reproduce the lithospheric strength and the heat balance through the thermal boundary layer of the Earth. In order to simulate the plate and its motion as a well-developed thermo-mechanical boundary layer on top of vigorously convecting mantle, we have developed a tank apparatus and performed preliminary experiments using paraffin wax.

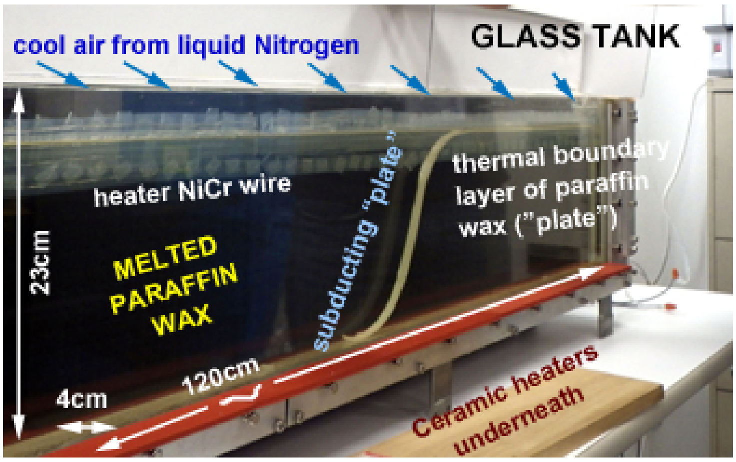
To control the complex heat and convection processes and for easy observation we constructed a glass tank with an inner size 120x23x4cm. The walls are constructed from double pane glass with panes separated by air gap to reduce heat loss, and reinforced with aluminum plates and bars. The paraffin was melted from bellow by a copper heat-sink containing 24 ceramic heating elements. To reduce heat loss to the back wall, the wall was isolated with 8cm thick foam. At the boundary layer where the paraffin wax was sticking as it cooled down we applied NiCr wire heater to the inner walls. All heating sections were controlled by variable controllers. We cooled the top layer of the wax with a cold air flow carefully controlled with thin foam plates from a vat filed with liquid Nitrogen.

The biggest challenge was the “frosting” effect especially on the front uninsulated wall that prevented the “subduction” of the forming “crust” to deeper levels. External wall temperature was 65 ℃, 70 ℃ was measured at the boundary level by the wire heater, while the wax inside the tank was at 80 ℃. Some external force was necessary to initiate a start of subduction. The maintenance of balance between the various heaters, the wall temperature, the wax temperature and the cooling rate was critical for the successful completion of the experiment.

We observed continuous subduction and clear “crust” forming with subsequent “subduction” . We can say that our experiment properly reproduces the general features of plate motion of the earth. Artificially fracturing or weakening the boundary layer and applying a vertical, downward external force were required to initiate subduction in addition to collision of the plates. The thickness of the plate was the primary parameter controlling subduction behavior and plate motion. The plate showed elastic and plastic behavior depending on its thickness and temperature. A cold and thick “plate” did not subduct even after applying an external force, and formed a stagnant lid. A hot and thinner “plate” did not show continuous subduction behavior, plate motion stopped soon after subduction was initiated, possibly because the slab pull force from the thinner partially subducted slab was too weak. Our experiment results suggest that the driving force of subduction and plate motion is slab pull, not the thermal convection of the molten paraffin or ridge push. We will present photos and videos of the observed processes.

Improvements to the tank and heating elements design are necessary to provide better and easier control over the experiments.

Keywords: analogue experiment, plate subduction, paraffin wax, glass walls tank, slab pull



SIT35-P07 Room:Convention Hall Time:May 26 18:15-19:30

Numerical experiments on mantle convection of super-Earths with variable thermal conductivity and adiabatic compression

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Recently, many extra-solar planets have been discovered by improved observation technologies. Some of these planets, called super-Earths, have small masses (up to 17 times the Earth's) and high mean density (>5000 kg/m3). Numerical modeling of mantle convection of super-Earths plays an important role in studying the occurrence of plate tectonics and the surface environments on these planets. On the other hand, when considering mantle convection of super-Earths, it is also important to take into account the difference in (hydrostatic) pressure in the mantles. Since super-Earths have high inner pressure, there must exist a strong change in physical properties and the effect of adiabatic compression. While the effects of physical properties have been intensively studied so far, those of adiabatic compression have not been well studied in the previous models of mantle convection of super-Earths. Here we conduct numerical experiments of thermal convection of highly compressible fluid in a two-dimensional rectangular box whose thermal expansivity and conductivity are dependent on depth, viscosity is dependent on temperature, in order to elucidate the mantle convection on super-Earths.

Our numerical experiments showed the change in convecting flow patterns depending on the temperature-dependence in viscosity, regardless of the depth-dependence in thermal conductivity. When a viscosity is sufficiently dependent on temperature, horizontal flow becomes dominant in the mantle, with a very weak activity of hot plumes from the base of the mantle. This flow pattern is quite similar to the "stratosphere" in the field of meteorology. In addition, we found that the occurrence of "stratosphere" is enhanced for a strong depth-dependent thermal conductivity. One reason for this is that high conductivity at depth significantly reduces the difference in temperature between the basal thermal boundary layer and isothermal core. Our study therefore suggests that the depth-dependent thermal conductivity is one of the most important agents which control the mantle dynamics of super-Earths.

Keywords: suoer-Earths, mantle convection, adiabatic compression, thermal expansivity, thermal conductivity, viscosity

Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)

SIT35-P08 Room:Convention Hall Time:May 26 18:15-19:30

Implicit solution of the material transport of the core formation simulation

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In order to investigate the long time-scales of the global core formation process in a growing planet, we are developing the Stokes flow simulation code using MIC based techniques for material transport with a free-surface treatment. We are interested in the dynamical change of the internal structure after solidification of magma ponds/oceans during the core formation under a self-gravitating field, especially because it might lead to an initial heterogeneous structure in the deep mantle.

However current numerical solution method is difficult to solve the system coupled with the energy equation because the numerical system becomes stiff when the dynamical balancing time scale for the increasing/decreasing load by surface deformation is very short compared with the time scale associated with thermal convection. Any explicit time integration scheme will require very small time steps; otherwise, serious numerical oscillation (spurious solutions) will occur.

In this work, we propose to treat the advection as a coordinate nonlinearity, coupled to the momentum equation, thereby defining a fully implicit time integration scheme suitable for stiff problems [Furuichi and May, Compt. Phys. Commum 2015]. We utilize a Jacobian free Newton Krylov (JFNK) based Newton framework to solve the resulting nonlinear equations. We also investigate efficient solution strategies to reduce the computational cost to evaluate the nonlinearity on MIC advection.

These implicit methods are implemented within FD framework [Gerya and Yuen, 2003]. We examine the solution quality and efficiency of these methods by performing numerical experiments we have performed a series of numerical experiments which clarify the accuracy of solutions and trade-off between the computational cost associated with the nonlinear solver and time step size.

Keywords: core formation, Stokes flow, free surface, implicit time integration, JFNK

SIT35-P09 Room:Convention Hall Time:May 26 18:15-19:30

Modeling of SKS splitting parameters measured in Japan with Hi-net

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To systematically investigate the spatial variation of seismic anisotropy around Japanese islands, we measured splitting parameters (fast polarization direction ϕ, delay time δt) of teleseismic SKS phases observed by Hi-net (Ogawa et al., 2014, SSJ). The results indicated regional scale variations of splitting parameters that are apparently related to subduction systems. In order to investigate detailed anisotropic structures (fabric in mantle wedge, subducting slab, and asthenosphere), we conducted forward modeling using synthetic seismograms. We modeled the SKS phases by the ray theory. We assumed that the SKS ray is straight and that each region has homogenous anisotropy. We rigorously calculated the phase velocity in each region by solving the Christoffel matrix. The preliminary analysis indicates that the measured splitting parameters appear to be primarily affected by the A-type fabric in subducting slab (oceanic lithosphere) whose a-axis aligns in the direction of the fast axis observed at the surface by using our OBS data.

Keywords: seismic anisotropy, s-wave splitting, modeling

SIT35-P10 Room:Convention Hall Time:May 26 18:15-19:30

Constraining radial anisotropy in the upper mantle with multi-mode surface waves

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The radial anisotropy of shear waves represents the differences in the propagation speeds between vertically polarized shear waves (SV) and the horizontally polarized ones (SH), and can be a key to the understanding of the dynamic processes in the upper mantle. Seismic surface waves are the most powerful tool to determine the spatial distribution of the radial anisotropy. Some recent studies have revealed the existence of a layer with strong radial anisotropy (with SH >SV) beneath the lithosphere; e.g., under the Pacific plate (Nettles & Dziewonski, 2008, JGR) and the Australian continent (Yoshizawa, 2014, PEPI). This is, however, not always the case and there are also some studies on radial anisotropy that do not show such a clear layer with SH>SV beneath the lithosphere. These differences may be related to the differences in model parameterization.

For the inversions of multi-mode phase speeds of Rayleigh and Love waves for radial anisotropy of shear waves, we can use either set of model parameters for the representation of the anisotropic S velocity; i.e., (A) SV velocity (Vsv) and SH velocity (Vsh), or (B) SV velocity (Vsv) and radial anisotropic parameter ξ =(Vsh/Vsv)ˆ2. The choice of model parameters for inversion is arbitrary, but, through synthetic experiments, we have confirmed that this difference causes non-negligible effects on the reconstruction of radial anisotropic properties of shear waves. This is mainly caused by the differences in the sensitivity kernels of Love-wave phase speeds to Vsv, Vsh and ξ.

For the set of parameters (B) [Vsv, ξ], Love waves always have the largest sensitivity to Vsv with suppressed sensitivity to ξ, and the kernel shapes for both Vsv and ξ are nearly identical. On the other hand, for the parameterization with (A) [Vsv, Vsh], Love wave phase speeds are controlled primarily by the kernels for Vsh, which have the largest sensitivity to Love wave phase speeds with little influence from Vsv, which can be better (and independently) constrained by Rayleigh waves.

Such intrinsic differences in the sensitivities of surface waves can lead to the different results in the estimation of radial anisotropy. Our synthetic experiments suggest that the parameterization with [Vsv, Vsh] would be preferable particularly when the radial anisotropy with SH>SV is caused by anomalously slow SV velocity, which is consistent with the recent anisotropy models reported in the fast moving Pacific and Australian plates. We have also found that the strong dependence of the retrieved anisotropy on the initial model, when we use [Vsv, ξ] as model parameters.

Keywords: radial anisotropy, surface waves, upper mantle, lithosphere, asthenosphere

SIT35-P11 Room:Convention Hall Time:May 26 18:15-19:30

Teleseismic P- and S-wave tomography beneath Japan Islands

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The Japan Islands are characterized by complex structure and tectonics caused by four plates which are interacting with each other. Many seismic tomography studies using local seismic data have been made to investigate the 3-D velocity structure beneath Japan. However, the study areas of the previous researches are limited to the shallow part, in the crust and shallow mantle, whereas the deep structure beneath Japan (a depth range of 200-700 km) is not well known. Investigation of the deep structure is very important for improving our understanding of the subducting slabs and mantle upwelling, as well as subduction dynamics.

In this work, we apply teleseismic tomography to relative travel-time residuals of teleseismic events to study the 3-D P- and S-wave velocity structure of the Japan subduction zone. Although there have been several studies using P-wave data so far (e.g., Zhao et al., 1994, 2012; Abdelwahed and Zhao, 2007), few studies using S-wave data have been conducted. Using both P- and S-wave data, we can determine not only the P- and S-wave velocity structures but also other physical parameters such as Poisson's ratio, which are useful for better understanding the physical property of the mantle.

Part of the P-wave relative travel-time residuals used in this work were chosen from the data collected by the previous studies (Zhao et al., 1994, 2012; Abdelwahed and Zhao, 2007). We selected 130 teleseismic events from the previous data sets based on the following criteria: (1) The epicentral distances range from 30 to 100 degrees from central Japan; (2) Each event was recorded by over 100 seismic stations on the entire Japan Islands. In addition, we newly collected data from 38 teleseismic events so that the event distribution becomes more homogeneous. Thus, our data set contains 168 teleseismic events which generated ˜60,000 P-wave arrivals. Our S-wave data set contains ˜40,000 arrivals from 56 teleseismic events.

We also selected ˜3,000 local shallow and deep earthquakes from the JMA Unified Catalog, each of which was recorded by over 100 seismic stations. We applied the tomographic method of Zhao et al. (1994, 2012) to invert the local and teleseismic data simultaneously.

Both of our P- and S-wave tomographic images show that low-velocity anomalies exist in the mantle wedge beneath the volcanic front and back-arc area, which reflect hot upwelling flow in the mantle wedge associated with slab dehydration. High-velocity anomalies are revealed, which reflect the subducting Pacific and Philippine Sea slabs where intermediate-depth and deep earthquakes are located. Beneath western Kyushu, dipping high-velocity anomalies are visible down to ˜400 km depth in both P- and S-wave tomography, suggesting that the Philippine Sea slab has subducted aseismically down to the mantle transition zone depth. In addition to the P- and S-wave tomography, we will also present images of Poisson's ratio and the R value (dlnVs/dlnVp), which provide additional information on physical properties of the Japan subduction zone.

SIT35-P12 Room:Convention Hall Time:May 26 18:15-19:30

Seismic evidence for a mantle plume beneath the Cape Verde hotspot

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The Cape Verde hotspot is located in the African plate, about 2000 km east of the nearest plate boundary. It is composed of a group of late Cenozoic oceanic islands resting on a broad bathymetric swell on mature (>110 Ma) oceanic lithosphere. This hotspot has a positive surface heat flow, high geoid anomaly, and long-term volcanism. The last known volcanic eruption occurred at Fogo volcano in 1995.

We determined P- and S-wave tomography of the upper mantle beneath the Cape Verde hotspot using arrival-time data measured precisely from three-component seismograms of 106 distant earthquakes recorded by a local seismic network. Our results show a prominent low-velocity anomaly imaged as a continuous column <100 km wide from the uppermost mantle down to about 500 km beneath Cape Verde, especially below the Fogo active volcano, which erupted in 1995. The low-velocity anomaly may reflect a hot mantle plume feeding the Cape Verde hotspot.

Keywords: Cape Verde, hotspot, mantle plume, seismic tomography, mantle transition zone