New tungsten carbide anvils potentially important for melting experiments under lower mantle conditions

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Kawai-type multianvil apparatus (KMA) is important for accurate determinations of melting relations and element partitioning to understand the processes relevant to the interaction and co-evolution of the Earth’s mantle and core. Recent developments in KMA technology with sintered diamond (SD) anvils has enabled to expand the pressure range available in this apparatus toward Mbar regime. However, the use of SD anvils has been limited only to very few laboratories due to both technological and financial reasons, as SD anvils are much expensive compared to tungsten carbide (WC) anvils and also specially designed large-volume apparatus is required to successfully pressurize the cell assemblage using SD anvils. Recently, a new class of “binderless” WC (Fujilloy TJS01) has been developed by Fuji Di. Co. Ltd., which is claimed to be harder than any other commercially available WC. We have tested this novel WC as second-stage anvils for KMA based on in situ X-ray observations at SPring-8, and found that the anvils made of this WC indeed yield pressures significantly higher than those available with other WC anvils frequently used in the KMA community. Pressures up to about 50 GPa were confirmed at room temperature with an anvil truncation (TEL) of 1.5 mm, which is about 20% higher than that achievable using the hardest known WC (Fujilloy TF05) anvils. Thus, this novel WC is potentially important for melting experiments of silicate-metal systems under simultaneous high pressure and high temperature conditions of the deep interior the early Earth (e.g. 30-50 GPa, ~3500K), which are currently difficult to be reached in KMA with either conventional WC or SD anvils

Keywords: high-pressure generation, tungsten carbide anvil, melting experiment

Problems with 1D seismic model fitting

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Tests of lower mantle composition models often compare mineral physics data bearing on the elasticity and density of lower mantle phases to the average seismic velocity profile determined by seismology, such a PREM or ak135. Here we demonstrate why such comparisons between mineralogy and seismology are an inadequate method for definitive discrimination between different scenarios. One issue is that the seismic velocity is more sensitive to temperature than composition for most lower mantle minerals. In practice, this allows one the freedom to choose the geotherm that brings the predicted seismic and density data into agreement with observations. It is commonly assumed that the temperature profile should be adiabatic, however, such a profile presupposes a particular state of the mantle and is only applicable in the absence of layering, buoyancy fluctuations, compositional segregation, and rheological complexities. The mantle temperature should depend on the composition since the latter influences the viscosity of rocks. However, the precise relation between composition, viscosity, and heat transfer would need to be specified, but unfortunately remains highly uncertain. If the mantle contains a mixture of domains with multiple bulk compositions, then the 1D seismic profile comparison is inherently non-unique. For example, while Wang et al.\cite{Wang2015} show a good match to PREM for a pyrolite model composition, they could also fit PREM just as easily by averaging domains of olivine-rich and bridgmanite rich rocks (i.e., harzburgitic and solar/chondritic, respectively). Rocks with different bulk composition likely have different isotopic abundances, and can exhibit differing degrees of internal heating and therefore distinct temperatures. Different composition domains can also exhibit variable densities, and tend to congregate at different depths in ways that also affect their thermal evolution and temperature. Therefore, we urge the deep Earth community to progress beyond fitting a 1D seismic model for evaluating lower mantle composition.

Keywords: mantle composition, mantle mineralogy, mantle seismology

Viscosity of Basaltic Melt under High Pressure: *ab initio* molecular dynamics simulations

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High-pressure behavior of basaltic aluminosilicate melt has been intensively studied due to its importance in deep Earth science related to such as early magma ocean and subsequent differentiation processes (Agee 1998; Ohtani and Maeda 2001; Suzuki, *et al.* 2005). Experimental studies reported that the viscosity of basaltic melt decreases with increasing pressure (Allwardt, *et al*. 2007; Sakamaki, *et al*. 2013). They suggested based on the results of classical molecular dynamics simulation (Nevins and Spera 1998) and ^{27}Al magic-angle spinning nuclear magnetic resonance (Allwardt, *et al*. 2007) that this anomalous behavior is related to the coordination change of Al. However, so far there exist no ab initio simulations of basaltic melt in the pressure range, where the anomaly in viscosity is observed experimentally. In this study we therefore perform ab initio molecular dynamics simulations gradually changing volume and successfully reproduce a viscosity minimum in the pressure range corresponding to the experiments. We analyze relationships between the anomalous pressure response of viscosity and variations in the atomic-scale local structure.

Reference

Agee, C. B. *Phys, Earth Planet. Inter.* 107, 63 (1998)
Ohtani, E and Maeda, M. *Earth Planet. Sci. Lett.* 193, 69 (2001)
Suzuki, A. *et al*. *Phys. Chem. Miner.* 32, 140 (2005)
Nevins D. and Spera F. *Am. Mineral.* 83 1220 (1998)
Allwardt, J. R. *et al*. *Am. Mineral.* 92, 1093 (2007)
Sakamaki, T. *at al. Nature Geoscience* 6, 1041 (2013)

Keywords: basaltic melt, viscosity, ab initio molecular dynamics

Reaction between olivine and nitrogen at high pressure and high temperature

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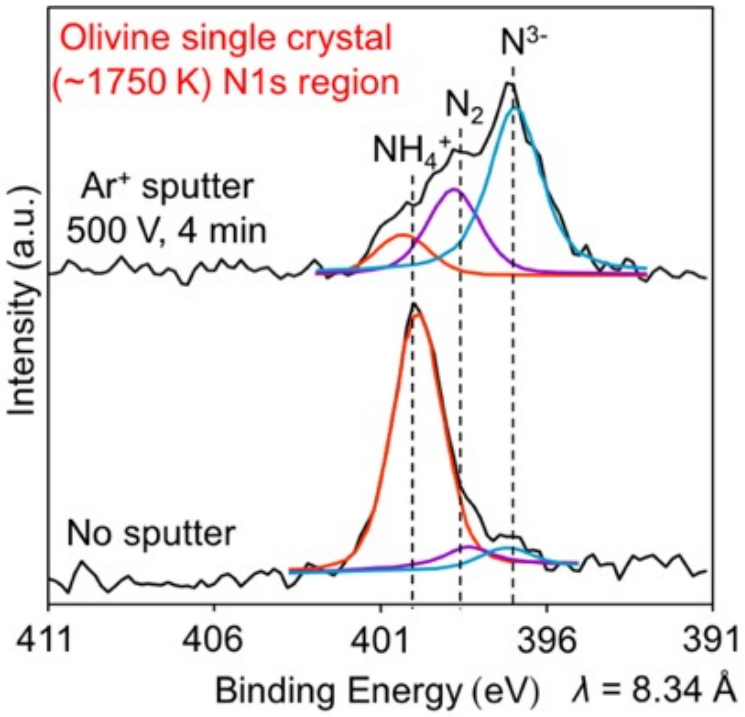
Volatiles represented by hydrogen greatly affect deep-earth dynamics. Behavior of volatiles will contribute to understandings of budget of light elements, evolution of the earth, geodynamics and so on. Among volatile components, behavior of nitrogen in the deep earth is still unclear. Nitrogen is a main constituent of atmosphere and also exists in the crust by substituting potassium ions in silicate minerals. Chondrite-normalized nitrogen concentration of the bulk earth is one order of magnitude lower than those other volatiles such as He, Ne, Ar, H_2O and so on. There could be a hidden nitrogen reservoir in the deep earth. We are going to test a possibility of a hidden nitrogen reservoir from high pressure and high temperature experiments.
San Carlos olivine or synthetic forsterite were loaded as a starting material in a diamond anvil cell with nitrogen in liquid state or compressed gas (180 MPa). After applying pressure at 5 GPa, a sample was heated using CO_2 laser or fiber laser. X-ray diffraction patterns, SEM-EDS images, XPS spectra were obtained on the recovered samples.
XRD measurements on the recovered samples revealed the formation of enstatite ($MgSiO_3$) suggesting the decomposition of Mg_2SiO_4 into $MgSiO_3$ and MgO. This reaction is contrastive to the reaction occurring in H_2 fluid (Shinozaki et al., 2013), Mg_2SiO_4 decomposed into SiO_2 and MgO. Moreover, EDS mapping observations revealed that there are some Mg-rich (Si-depleted) spots.
XPS spectra shown in Fig. 1 revealed that nitrogen was detected from an olivine sample recovered from 5 GPa and 1700 K. Before Ar-sputtering, species assignable to NH_4^+ is dominant. Presumably, the sample surface is covered with adsorbed molecules. After Ar-sputtering, a broad band attributable to intrinsic nitrogen reacted with the mineral was observed. The present results suggest the formation of nitride species (N^{3-}) in a mantle-derived silicate mineral. This study proposes nitride as a hidden nitrogen reservoir in the deep mantle.

Keywords: nitrogen, mantle, olivine



Relative Importance of Intrinsic and Scattering Attenuation in the Lower Mantle

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It is well known that the lower mantle has significant attenuation, but cause for the attenuation (i.e., relative importance of intrinsic and scattering attenuations) has not been well resolved. To address this problem, we conducted detailed analysis of seismogram envelopes.
Seismogram envelopes contain rich information to resolve intrinsic and scattering attenuations. Indeed, Lee et al. (2003, GRL) analyzed S and ScS envelopes of regional earthquakes in the Hindu Kush region and concluded the predominance of scattering attenuation in the lower mantle. They measured decay of coda envelopes for lapse time as long as 2000s and analyzed the data under the assumption of isotropic scattering. In this study, we analyze envelopes observed by a dense broadband array, F-net, and confirm that similar decay is observed in the envelopes of these modern data. We also try to better resolve the attenuation structure by analyzing envelopes for longer lapse time (7000s) without using the assumption of isotropic scattering. We apply our inversion method that systematically conducts waveform inversion of seismogram envelopes for various initial models. At the time of the presentation, we plan to show our models together with trade-offs among various unknown parameters.

Towards "Neutrino Geoscience" with Geo-neutrino Measurement

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Neutrino is an elusive particle and it can penetrate even astronomical objects. While neutrino experiments continue to explore the neutrino properties, such as the oscillation nature of neutrino flavor transformation, the mass-square differences and the mixing angles and so on, we have began to utilize neutrinos as a tool to look into the Earth. Anti-neutrinos emitted from radioactive isotopes, geo-neutrinos, bring unique and direct information about the Earth’s interior and thermal dynamics.
KamLAND, Kamioka Liquid-scintillator Anti-neutrino Detector, utilizes 1 kton liquid scintillator and reported the first experimental study of geo-neutrino in 2005. Later the geo-neutrino signals were used to estimate the Earth’s radiogenic heat production and constrain the composition models of the bulk silicate Earth. We have begun to use neutrinos as “probe” to observe the Earth’s interior.
In this talk, we will present status and future prospects of geo-neutrino measurement and possible application to geoecience.

Keywords: geo-neutrino, Earth's radiogenic heat

Grain boundary diffusion of siderophile elements in lower mantle phases

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Abundance of siderophile elements, especially platinum group elements, in the Earth’s mantle, is fairly higher than that expected from the distribution coefficients between Fe alloy and silicate minerals determined at low pressure. There are several explanations to solve this problem. The most popular hypothesis is late veneer. The amounts of siderophile elements would have been supplied after the core was formed by later meteorite bombardment. The other possible explanation is that before the core separation re-equilibration of Fe alloy and silicate minerals was established at the bottom of magma ocean. So far we have not paid attention to the siderophile element process after core formation. Hayden and Watson (2007) studied grain-boundary diffusion of siderophile elements through polycrystalline MgO at 2.5 GPa, and suggested that the diffusivities were high enough to allow transport of a number of siderophile elements over geologically significant length scales (tens of kilometres) over the age of the Earth. It means that grain-boundary diffusion as a potential fast pathway for chemical communication between the core and mantle. However, the dominant mantle mineral is not periclase but bridgmanite at the core-mantle boundary. In this study, grain boundary diffusion of W and Re in bridgmanite aggregates is determined.
The starting material for experiments to determine the grain boundary diffusion was mixture of San Carlos olivine or orthopyroxene with Mg#90 and 3 wt.% Al_2O_3 and Pt powder. Synthesis experiments of aggregates of postspinel or bridgmanite with tiny amount of Pt particle were conducted in a Kawai-type multianvil press at 25 GPa and 1873K. The synthesized aggregates were sliced into several disks with a few hundreds of micrometers. The disk was sandwiched by diffusion source (meta foil). This mixture was placed in an MgO cylinder. Hot-press and diffusion experiments were also performed using a Kawai-type multianvil press at 25 GPa and 1873 or 2073K. Experimental durations were more than 20 hours. The concentration of W and Re in the Pt sink was quantified using electron microprobe analyzer. The diffused siderophile element was recorded by the Pt particles behaving here as sink, which are implanted in the aggregate. A semi-infinite model for diffusion was used to calculate D from the concentration profile. The effective diffusivities of W and Re, which includes grain boundary effect were around 10^{-16} or 10^{-14} m^2 s^{-1} at 1873K for bridgmanite and postspinel. These effective diffusivities are several orders of magnitude slower than the published diffusion data for MgO aggregates. On geological scales and for coarse-grain rocks, siderofile element diffusivity in grain boundaries is not fast enough to induce chemical interaction at the core-mantle boundary. The relative large grain size of mantle rocks will ensure a very limited siderophile element transport by effective diffusion, and a good conservation of siderophile element in the Earth's core. However, to estimate more reliable grain boundary diffusivities at the core-mantle boundary, more knowledge on effect of temperature and pressure on the siderophile element diffusivities is needed.

Keywords: siderophile element, lower mantle, grain boundary diffusion

High precision analysis of Os and W for early evolution of core-mantle

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Tungsten is one of the highly siderophile and refractory elements. There are 5 stable isotopes of W as 180,182,183,184, and 186. ^{182}W is a decay product of ^{182}Hf ($t_{1/2}$=890 million year) which is extinct at present. Therefore, the amount of ^{182}W can give information on evolution of very early solar system at the timescale from tens of thousands of years to hundreds of thousands of years. Because Hf and W are highly refractory elements, ^{182}W isotope evolution process in the Earth could be same as in chondrites. W and Hf have been considered to be partitioned into metal (core) and silicate (mantle) phases, respectively, which leads to higher Hf/W ratio of mantle. Due to the decay of ^{182} Hf, the amount of ^{182}W should have increased in a planetary mantle 1 billion years after the beginning of the solar system.
In the early stage of applications of the ^{182}Hf-^{182}W isotope system has been used as a chronometer of the Earth's core formation (Lee et al., 1995) to use that iron meteorites possess lower $^{182}W/^{184}W$ isotope ratios than those of chondrites and Earth's rocks. Variation of this isotope ratio is presented as εvalue using W isotope standard solution (NIST SRM-3163).
High precision isotope analysis of W (< 0.3 ε) was difficult until 2010 even if extremely sensitive and precise mass spectrometers of N-TIMS and MC-ICP-MS were used. Recently, the mass spectrometry in MC-ICP-MS or N-TIMS and chemical separation methods were significantly improved (Touboul et al., 2011), and high precision tungsten isotope analysis of ±5 μ(=0.05ε) is possible at present. These high precision analyses lead to findings of W isotope anomaly in the early Earth's rocks such as komatiite (older than 2.8 billion years). Kostomuksha komatiite has positive anomaly (+20μ) (Touboul et al., 2012). Variation of these W isotope ratios was discussed together with PGE abundance and Os or Nd isotopes of mantle rocks. The PGE and Os isotopes could give constraints on the timing and processes of early mantle evolution such as Late Veneer, the core-mantle or mantle-silicate differentiation.
In our study, we are trying to develop the methodology of extremely high precision measurements of W, Nd and Os isotopes using N-TIMS and MC-ICP-MS and will try to reveal the core mantle coevolution on the early Earth.

Keywords: core-mantle interaction, W isotope, Os isotope, early earth chemical evolution

Metal-silicate partitioning of chlorine in a magma ocean: Implications for the origin of chlorine depletion on Earth.

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The chlorine of the Earth is highly depleted relative to other lithophile and volatile elemets [1]. There are two hypotheses for terrestrial missing chlorine; Chlorine incorporation into the core and an erosion of primordial ocean. Here we experimentally investigate the former case. More specifically, the metal-silicate partitioning of chlorine in a magma ocean is experimentally investigated.
In this study, we investigated the effect of pressure and temperature on the metal-silicate partition coefficient of chlorine in order to estimate the core-mantle partitioning of chlorine. Starting materials were a mixture of high-purity oxides (SiO_2, Al_2O_3, CaO, MgO, FeO), metallic iron, and iron sulfide. Chemical compositions in the silicate portion match those of CI- or EH-chondrites. Chlorine was added to the mixture as $FeCl_2$. The starting materials were encapsulated into either a graphite capsule or a single-crystal MgO capsule. The experiments were performed at 4 - 23 GPa and 1923 - 2673 K using multi-anvil presses at the University of Tokyo and Ehime University. The elemental compositions of recovered samples were analyzed with wavelength-dispersive electron microprobe (WDS-EPMA) and secondary ion mass spectrometry (SIMS). Our experimental results show that (1) chlorine is highly lithophile, (2) becomes more siderophile with increasing temperature, and lithophile with increasing pressure. Based on the experimental results and thermodynamic consideration, we estimated the metal-silicate partitioning coefficient of chlorine at the base of a magma ocean. The *P-T* conditions at the base of a magma ocean were estimated from the peridotite melting curve. Calculation results show that the metal-silicate partition coefficients of chlorine at the base of a magma ocean are much lower than the required value for explaining terrestrial missing chlorine. This result strongly suggests that Earth's core is unlikely to account for terrestrial missing chlorine. Given that the fluid-melt partition coefficient of chlorine is above the unity [e.g., 2], chlorine may have been partitioned into primordial ocean. If this is the case, terrestrial missing chlorine may require an extensive loss of primordial ocean during the planetary accretion phase.
[1] Sharp, Z. D. & Draper, D. S. (2013) *Earth Planet. Sci. Lett.* 369-370, 71-77.
[2] Metrich, N. et al. (2001) *Journal of Petrology* 42, 1471-1490.

Keywords: Earth, Chlorine, Magma ocean

Lattice thermal conductivity of lower mantle minerals

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Heat in the Earth's interior is transported dominantly by convection in the mantle and core, and by conduction at thermal boundary layers. The thermal conductivity of the bottom thermal boundary layer of the mantle determines the magnitude of heat flux from the core, and is intimately related to the formation of mantle plumes, the long-term thermal evolution of both mantle and core, and the driving force for generation of the geomagnetic field (Lay et al. 2008). Recent technical progress both in the experiment and the theoretical calculation enables us to reveal high-pressure and high-temperature behavior of lattice thermal conductivity of lower mantle minerals, $MgSiO_3$ perovskite (birdgmanite) and MgO periclase. However, the effect of iron incorporation into these minerals on the lattice thermal conductivity is still controversial.

We measured the lattice component of thermal conductivities both of $(Mg,Fe)(Si,Al)O_3$ bridgmanite and (Mg,Fe)O ferropericlase at the Earth's lower mantle pressures and 300 K using a pulsed light heating thermoreflectance technique in a diamond anvil cell. We found that iron incorporation into bridgmanite shows minor effect on the thermal conductivity. On the other hand, the obtained conductivity of ferropericlase was considerably lower than that of MgO periclase. The estimated lattice thermal conductivity of bridgmanite-dominant lowermost mantle is comparable to conventionally assumed value of 10 W/m/K (Stacey, 1992). However, our results imply that local existence of (Mg,Fe)O ferropericlase in the lower mantle induce strong heterogeneity of thermal conductivity.

References

Lay, T. et al.: Nature Geosci. 1, 25-32 (2008).
Stacey, F.: Physics of the Earth, 3rd ed. (1992).

Keywords: lower mantle , thermal conductivity, bridgmanite, ferropericlase

Waveform inversion for 3-D shear wave velocity structure within D″ beneath the Northern Pacific and Alaska

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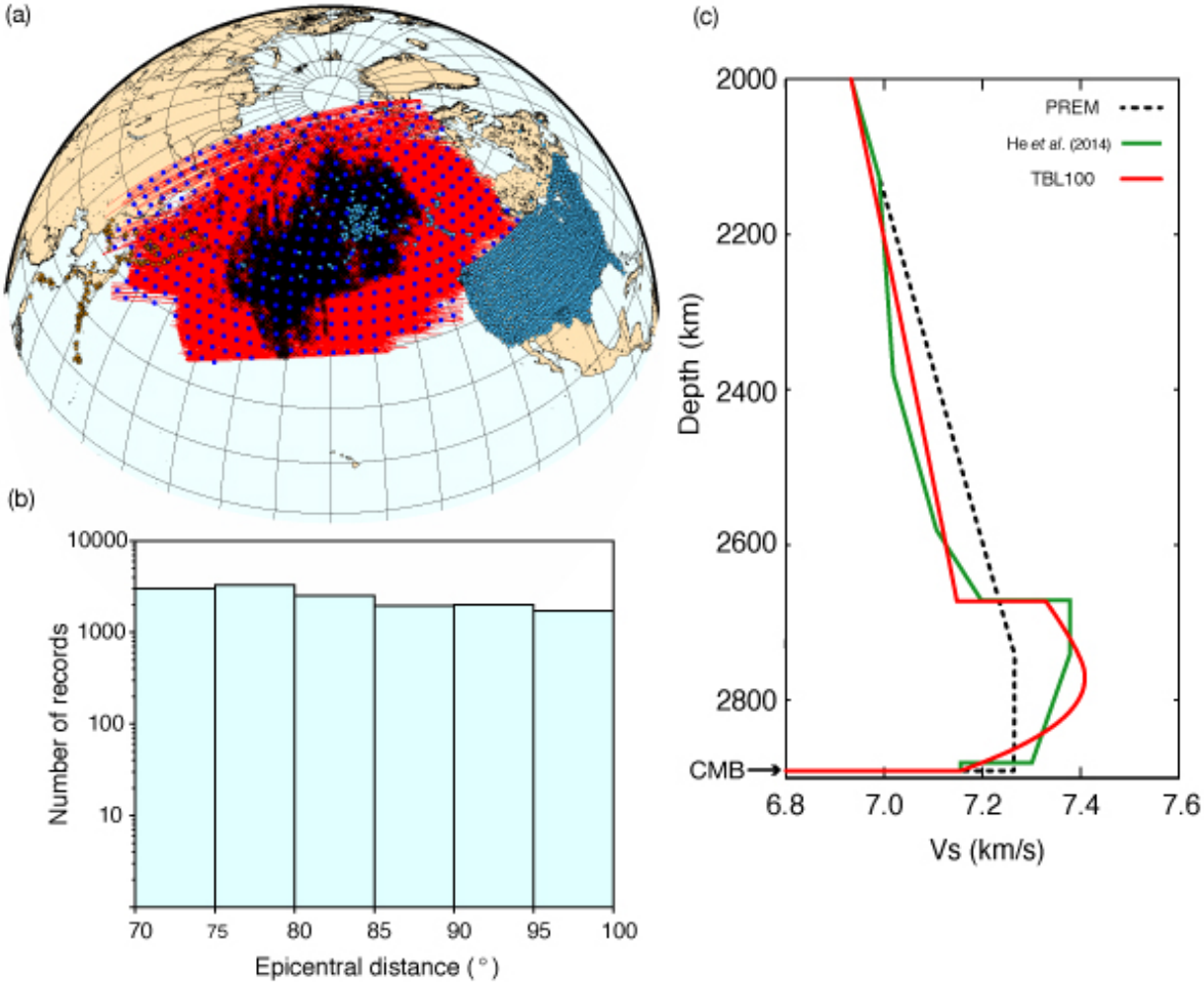
We conduct waveform inversion to infer the 3-D shear wave velocity structure within D″ beneath the Northern Pacific and Alaska (Fig. 1a). This region is suitable as the target for waveform inversion, since we are able to use data that densely sample the target region (the lowermost 400 km of the mantle beneath the Northern Pacific and Alaska). Our dataset consists of ~20,000 transverse components of broadband body-wave seismograms observed at North American stations (from dense receiver networks such as the USArray). We use 114 intermediate and deep events that are widely distributed throughout the western Pacific (Japan and Izu Bonin) region. We use *S, ScS* and other phases that arrive between them. Our dataset is homogeneous in terms of epicentral distance (Fig.1b). Resolution tests indicate that our method and data can resolve the lateral and vertical velocity profile within D″ in the target region. We use two different one dimensional shear wave velocity models (Fig. 1c) as the starting model for the inversion: PREM, and a model based on mineral physics, which includes a thermal boundary layer of 100 km effective thickness. The 3-D models obtained by our inversion show that there is a high velocity area that can be interpreted as subducted paleoslabs down to about 200 km above the core-mantle boundary (CMB), a plume like low-velocity structure, and also lateral and vertical complexity that may come from interaction between the subducted paleoslabs and development of plumes within D″.

Keywords: S-wave velocity structure, D", waveform inversion



Ultrahigh-pressure polyamorphism in GeO_2 glass: implications for structure of magma at the core-mantle boundary

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Silicate magma at the core-mantle boundary is one of the most important components in understanding nature and evolution of the Earth's deep interior. However, structure and properties of silicate magmas at the pressure condition of the core-mantle boundary remain poorly understood, because of experimental challenges. Pioneering works by Murakami and Bass (2010; 2011) showed a kink in the pressure dependence of shear-wave velocity in SiO_2 and $MgSiO_3$ glasses around 130-140 GPa, which was interpreted as evidence of ultrahigh pressure structural transition. However, no structural information is available under such high pressures. Here we show new experimental evidence of ultrahigh pressure structural transition in GeO_2 glass with Ge-O coordination number (CN) significantly greater than 6, investigated using a newly developed double-stage large volume cell combined with multi-angle energy dispersive X-ray diffraction technique for in situ amorphous structure measurement. The Ge-O coordination number (CN) is found to remain constant at ~6 between 22.6 and 37.9 GPa. At higher pressures, CN begins to increase rapidly to 6.4 at 49.4 GPa and reaches 7.4 at 91.7 GPa. The structural change to CN higher than 6 is closely associated with the change in oxygen packing fraction (OPF). This transformation begins when the OPF in GeO_2 glass is close to the maximal dense packing state (the Kepler conjecture=~0.74), which provides new insights into structural changes in network-forming glasses and liquids with CN higher than 6 at ultrahigh pressure conditions. For example, extrapolation of OPF-pressure trend in SiO_2 glass shows that OPF of SiO_2 glass reaches to 0.74 around 108 GPa, where structural change to CN higher than 6 is expected. The data imply that silicate magma at the core-mantle boundary may possess ultrahigh-pressure structure with CN higher than 6.

References

Murakami, M., & Bass, J. D. (2010). Spectroscopic evidence for ultrahigh-pressure polymorphism in SiO 2 glass. *Physical review letters*, *104*(2), 025504.

Murakami, M., & Bass, J. D. (2011). Evidence of denser MgSiO3 glass above 133 gigapascal (GPa) and implications for remnants of ultradense silicate melt from a deep magma ocean. *Proceedings of the National Academy of Sciences*, *108*(42), 17286-17289.

Keywords: high pressure, magma, core-mantle boundary

Full-waveform inversion for localized 3-D S-velocity structure in D″ beneath the Caribbean using USArray data

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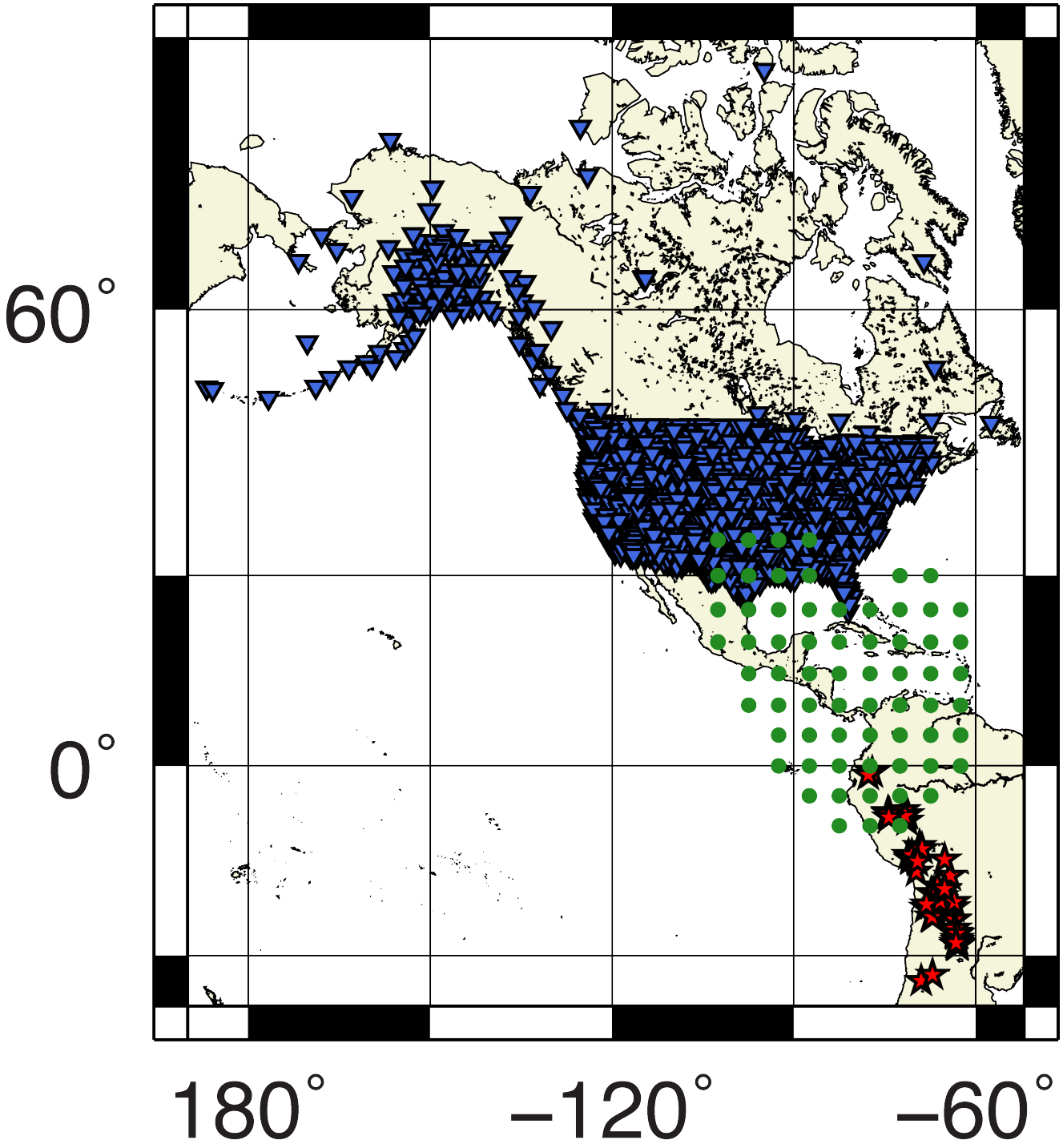
We take advantage of the dense coverage made available by USArray stations (enhanced by records from the IRIS/USGS, SCSN, PNSN, BDSN, and CNSN networks) to invert for the localized 3-D S-velocity in the lowermost 400 km of the mantle beneath the Caribbean (see in the Fig. below the distribution of stations (blue), events (red), and the location of the voxels that define the target region (green)). We use a much larger dataset than Kawai *et al.* (2014), with an improved eastward geographical coverage. We use around 13,000 S and ScS transverse component waveforms (including possible ScS precursors important to image strong velocity contrasts) down to 12.5 s for 68 intermediate and deep focus events in the period 1993–2015 beneath South America. The resulting 3-D model shows a more complex S-velocity structure than that resolved by global tomography, with vertical high velocity anomalies extending from the top of our target region down to the CMB with the strongest high-velocity perturbations 300 km and 100 km above the CMB. Our model is consistent with that of Kawai *et al.* (2014), where they overlap, and reveals another high velocity anomaly located beneath the north of South America, which is in agreement with previous works using ray tomography. Our 3-D model is consistent with the presence of cold slab material surrounded by hotter material.

Keywords: Full-waveform Inversion, 3-D S-velocity, Central America



Thai Seismic Array (TSAR) Project

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Thailand is located in an important area for teleseismic observations to study the core-mantle boundary and the inner core. However, the number of broadband stations is limited. On the occasion of the KAKENHI project for an innovative area “Core-mantle co-evolution”, we plan to construct a mobile broadband seismic array in Thailand as a part of the project “Seismic and geo-electromagnetic observation for core and mantle”. This array will be also useful for the understanding of a local structure and seismicity in Thailand.
To date, we have conducted the site survey for 3 times (Nov.16-27, 2015; Dec.13-22, 2015; Jan. 9-16, 2015) to determine 40 possible sites. Along the western edge of Thailand to the center of Malay Peninsula, the part of TSAR will form a linear array whose approximately 15 stations run in north-south direction with a length of more than 1,000 km. In the central part of Thailand, TSAR will cover an area of about 400 km (from east to west) x 600 km (from north to south) length with station spacing of approximately 100 km. After the 3rd site survey, we have constructed two pilot stations in Suphanburi and Kanchanaburi, where we test the durability of the stations for high temperature, heavy rain, lightening and check the data quality. Since November, 2016, we plan to deploy additional 38 broadband seismic stations for a period of 2 years.

Keywords: Thailand, Mobile broadband seismic array, Site Survey

Dissolution of hydrogen into iron by the dissociation of hydrous minerals under pressure

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Although hydrogen is the most abundant element in the solar system and one of the candidates of the light element in the core, the process how the hydrogen can get into iron remains not so clear. High-pressure and high-temperature in situ neutron diffraction study on the iron-hydrous mineral system using “PLANET” at J-PARC clearly showed that when the dissociation of hydrous mineral occurred at about 4 GPa, the released water reacted with iron and formed both iron oxide and iron hydride. Iron oxide reacted with silicates and formed iron containing olivine and pyroxene. Iron hydride remained stable after further increase in temperature. This formation of iron hydride occurred below 1000K, at the temperatures no materials melted. This suggest the possibility that in the very early stage of Earth evolution, hydrogen has dissolved into iron before any other light elements have dissolved.

Keywords: hydrogen, iron, neutron

Outer core compositions by thermoelastic properties of liquid Fe alloys

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In the outer core, many light elements, such as carbon, nitrogen, oxygen, hydrogen, sulfur, and silicon, have been proposed as possible constituents. The concentrations of these elements have long been intensely debated. Here we calculate equations of state (EoS) of pure Fe and Fe-light elements alloy liquids by means of ab initio molecular dynamics at the outer core P-T conditions and evaluate P-wave velocity based on the derived EoS, which is consistent with thermodynamic properties such as Grüneisen parameter in the similar way as Ichikawa et al. 2014. Then, we search for plausible compositions which reproduce both P-wave velocities and densities of the seismological data (PREM) (Dziewonski and Anderson, 1981) under the whole outer core conditions. Finally, we analyze the plausible compositions of the outer core, which reproduce seismological values reasonably. We found several compositions with different light elements that reproduce the seismological data to the same degree. The results also show that the influence of addition of Ni with reasonable fraction is negligibly small.

Keywords: Composition of the outer core, light elements, Ab initio molecular dynamics calculation

Electrical resistivity of substitutionally disordered hcp Fe-Si and Fe-Ni alloys: Chemically-induced resistivity saturation in the Earth's core

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The thermal conductivity of the Earth's core can be estimated from its electrical resistivity via the Wiedemann-Franz law. However, previously reported resistivity values are rather scattered, mainly due to the lack of knowledge with regard to resistivity saturation (violations of the Bloch-Grüneisen law and the Matthiessen's rule). Here we conducted high-pressure experiments and first-principles calculations in order to clarify the relationship between the resistivity saturation and the impurity resistivity of substitutional silicon in hexagonal-close-packed (hcp) iron. We measured the electrical resistivity of Fe-Si alloys (iron with 1, 2, 4, 6.5, and 9 wt.% silicon) using four-terminal method in a diamond-anvil cell up to 90 GPa at 300 K. We also computed the electronic band structure of substitutionally disordered hcp Fe-Si and Fe-Ni alloy systems by means of Korringa-Kohn-Rostoker method with coherent potential approximation (KKR-CPA). The electrical resistivity was then calculated from the Kubo-Greenwood formula. These experimental and theoretical results show excellent agreement with each other, and the first principles results show the saturation behavior at high silicon concentration. We further calculated the resistivity of Fe-Ni-Si ternary alloys and found the violation of the Matthiessen's rule as a consequence of the resistivity saturation. Such resistivity saturation has important implications for core dynamics. The saturation constrains an upper limit of the resistivity, and the saturation resistivity value has almost no temperature dependence. As a consequence, the core thermal conductivity has a lower bound and exhibits a linear temperature dependence. We predict the electrical resistivity of the Earth's core to be about 1.0 $\times 10^{-6}$ Ωm, which corresponds to the thermal conductivity of 100 and 135 W/m/K at 4000 K and 5500 K, respectively. Such high thermal conductivity suggests high isentropic heat flow, leading to young inner core age (< 1 Gyr old) and high initial core temperature. It also strongly suppresses thermal convection in the core, which results in no convective motion in the inner core and possibly thermally stratified layer in the outer core.

Keywords: core, electrical resistivity, resistivity saturation, diamond-anvil cell, KKR-CPA, thermal conductivity

Spectrometry of the Earth using neutrino oscillations

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Neutrinos have favorable properties for measuring the elemental composition deep inside the earth's interior. First, they propagate a long distance almost undisturbed through the earth due to their weak interactions with matter. Secondly, neutrino oscillations in matter are sensitive to the electron density of the medium traversed by them. Therefore, neutrinos can be used for a probe to determine the average atomic mass ratio Z/A of the earth's core by comparing with the earth's nucleus density distribution that is inferred from seismic observations. There is little uncertainty in densities of the earth's core, but our knowledge of its main light element is very limited. With the advent of the new-generation megaton neutrino detectors, neutrino oscillation spectrometry will allow us to constrain directly the light elements in the earth's outer core. We report the detail of this novel technic and the sensitivity study.

Keywords: chemical composition, neutrino, Earth's outer core

Sound velocity Fe_3S at high pressure and high temperature based on inelastic X-ray scattering

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Mars, the 4th planet from the sun, has been investigated since 1960s. In spite of the investigations, the interior of Mars have not been understood well. Although the surface of Mars has been investigated by Opportunity and Curiosity in the project of NASA, the structure and seismic properties of the Martian core have not been understood well. The core of Mars have been thought to include sulfur as a light element. Sohl and Spohn (1997) proposed the seismic wave velocity and density profiles of the interior of Mars. However, there were almost no data of seismic wave velocity of the Martian core materials such as FeS and Fe_3S. Therefore, we have measured sound velocities of Fe_3S under high pressures and temperatures in order to discuss the Martian core. In addition, the InSight project of NASA will observe seismic wave velocity and probably be able to give some information of the Martian core.
There have been only a limited number of works for V_P of Fe and Fe alloys with light elements, especially Fe alloys with sulfur. Recently, sound velocities of Fe, Fe-Ni, FeS, FeS_2, FeO, Fe_3C, Fe-Ni-Si alloys have reported based on an inelastic X-ray scattering (IXS) (Fiquet et al., 2001; Antonangeli et al., 2004; Fiquet et al., 2004; Badro et al., 2007; Fiquet et al., 2009; Antonangeli et al., 2010). In the Fe-S system, V_P of FeS, the end member of the Fe-FeS system, and FeS_2, more sulfur-rich compound, have been studied but these compounds are not appropriate for the core materials of Mars because Fe-S system has a lot of intermediates such as Fe_3S_2, Fe_2S, Fe_3S under high pressures (Fei et al., 1997, 2000). In addition, Fe_3S coexists with ε-Fe as a subsolidus phase from 20 GPa to at least 200 GPa (Kamada et al., 2010, 2012). Therefore, it is essential to study the V_P of Fe_3S to understand seismic properties of the Martian core. We have measured sound velocities of Fe_3S under high temperature and pressure at BL35XU of SPring-8.
In this study, a synthesized Fe_3S was used as a starting material. A symmetric diamond anvil cell was used to generate high pressures. IXS and XRD experiments were performed at the beamline 35XU of SPring-8, Japan (Baron et al., 2000). V_P of Fe_3S were measured up to 45 GPa and 1900 K. We will discuss temperature effect on V_P of Fe_3S and the Birch's law and seismic wave velocity profile of the Martian core.

Keywords: High pressure and temperture, Inelastic X-ray Scattering, Planetary core

Pressure dependence on carbon isotope fractionation between diamond and iron carbide melt

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Stable isotope fractionation has been thought to be less affected by pressure until recently. In this study we present data on the pressure dependence of carbon isotope fractionation between diamond and iron carbide melt. Carbon, the fourth most abundant element in the solar system, is believed to be an important light element constituent in the Earth's core. The high carbon content of CI chondrites (3.2 wt.%) compared to bulk earth estimates, the presence of graphite/diamond and metal carbides in iron meteorites, the high solubility of carbon into iron melts in the Fe-C system suggests the plausible presence of carbon in the Earth's core. However, the distribution of carbon isotopes in the core is still not well understood. We carried out experimental studies in the Fe-C system and present the results on the equilibrium carbon isotope fractionation between graphite/diamond and iron carbide melt at varying pressures between 5GPa and 15 GPa and at temperature range of 1200 to 2100 ºC. Our previous results have shown that the iron carbide melt will preferentially gather 12C than 13C, which is temperature dependent (Satish-Kumar et al., 2011), consistent with the recent theoretical calculations of Horita and Polyakov (2014). The pressure dependence of this fractionation trend between iron carbide melt and graphite/diamond is examined in this study. Based on the preliminary results, we infer that pressure dependence is also important factor to consider when carbon cycle is considered in the core-mantle interface. It is anticipated that the combined pressure-temperature dependent fractionation of carbon isotopes between iron carbide melt and graphite/diamond is an effective mechanism that created a "12C enriched core" with large scale differences in the distribution of the carbon isotopes in the metallic core and bulk silicate Earth during the accretion and differentiation of early Earth. Our findings also have implications on the deep carbon cycle of the Earth, where the light carbon from the core might have transported to the mantle and crust through deep mantle plumes.
References: Horita, J. and Polyakov, V.B., 2014 PNAS doi/10.1073/pnas.1401782112; Satish-Kumar et al. 2011 Earth and Planetary Science Letters, 310, 340-348

Keywords: Carbon isotope fractionation, Diamond, Iron carbide melt

Ab initio prediction of potassium partitioning into the Earth's core

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Silicate earth is in strong depletion of K compared with chondrites [Wasserburg, 1964, Science]. The ratios of K isotope barely vary suggesting evaporation cannot be responsible for the missing of K [Humayun and Clayton, 1995, GCA]. The finding that the change in electronic structure of K from alkaline- to transition metal-like at high pressure highlighted the possibility of its incorporation into the core [Parker, 1996, Science]. If K is present, even in ~ppm, the radiogenic heat produced by ^{40}K could be an important energy source for mantle dynamics [Labrosse, 2001, EPSL]. However, previous researches didn't enclose the controversy over the K partitioning behavior between silicate and metallic system, with its partitioning coefficient range from 10^{-6} to 2.5 [Bouhifd etal., 2007, PEPI; Watanabe, 2014, PEPI], leaving the K content in the core uncertain.
In this study, ab-initio molecular dynamics simulations are performed to investigate whether and how much K can enter the metallic system. K partition coefficients are determined by Gibbs free energy changes of its exchange reactions between silicate and metallic systems. Helmholtz free energy is obtained based on "thermodynamic integration" by computing the difference between two systems with different potential energy functions.
Our preliminary results show that the K content entered into the core is limited, though it would be affected by the temperature, pressure, composition of the metallic (the type and content of light elements) and silicate system (NBO/T).

Keywords: Ab-initio simulation, Potassium, Core Mantle Boundary

High-*P*,*T* elasticity of iron and iron-carbon alloy

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Earth's inner core (329~364 GPa and 5000~6000 K) is thought to be composed of solid Fe-Ni alloy with some light elements. Thermoelasticity of iron and iron-light element alloys is therefore a key to interpreting seismological information of the inner core: density, seismic wave velocities, and their anisotropy. However, several studies reported that pure hcp iron has a shear modulus distinctly larger than that of the inner core (e.g., Mao et al., 1998; Vocadlo et al., 2009). This large Poisson ratio of the inner core is one of the remaining inexplicable features of the deep Earth, and some studies recently proposed this be explained by alloyed with carbon (e.g., Chen et al., 2014).

In this study, we perform ab initio molecular dynamics simulations of iron and iron-carbon alloy. Also computations are conducted in a wide *P*,*T* range including, but not limited to, the inner core conditions to clarify the *P*,*T* effects on their elasticity more comprehensively, and to provide an internally-consistent thermoelastic model. In addition to checking the validity of the Birch's law, the obtained Poisson ratio and aggregate anisotropy, with and without the pre-melting effect, are compared against seismological constraints to reinvestigate the viability of iron and iron-carbon alloy in the inner core.

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Keywords: Inner core, Ab initio computation, Elasticity

Preliminary result on iron self-diffusion in ε-iron

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Viscosity of the inner core is a key to understand the dynamics and structure of the core. The inner core super-rotation respect to the mantle is significantly related to the viscosity (e.g., Buffett, 1997). The seismic anisotropy observed in the inner core may be caused by the lattice preferred orientation of constituting materials (Morelli et al., 1986) formed during deformation of the inner core and hence viscosity is essential to understand the deformation rate. Recent seismic observations revealed that the seismic attenuation is heterogeneous in the inner core. The attenuation is larger in the western side of the inner core than that in the eastern side (Monnereau et al., 2010). Because the seismic attenuation can be regarded to be a function of viscosity, it is important for interpretation of the observed attenuation to estimate viscosity from the mineral physics. Diffusion is the most fundamental transportation properties and it is main controlling factor for deformation rate in any deformation mechanism. However, because of the difficulty for diffusion experiment on ε-iron, which is main constituting material of the inner core (Tateno et al., 2012), due to the limited stability of ε-iron higher than 40 GPa at >1300 k, direct measurement is not is available yet.
In this study, by using sintered diamond anvils, we conducted diffusion experiments at pressure ~50 GPa in a Kawai-type multianvil apparatus, “6-axis press”, installed at Okayama University, In the experiments, the natural isotopic iron and ^{54}Fe enriched iron was used as diffusion couple. On the recovered sample after diffusion annealing, diffusion profiles were obtained by the isotope imaging technique using SIMS1270 at Hokkaido University.
Diffusion coefficient at 1400 K was determined to be ~10^{-17} m^2/s in the present study although our result at present is preliminary one because diffusion length is small compared with the length of convolution effect and data is limited. The obtained value is 2-3 order smaller than self-diffusion coefficient in γ-iron at same temperature but ambient pressure. When homologous temperature scaling is applied, diffusion coefficient in the inner core condition is estimated to be ~10^{13} m^2/s by using T/T_m = 0.9 (where T_m is melting temperature) and melting curve of iron (Anzellini et al., 2013). The estimated diffusion coefficient suggests that Harper-Dorn creep may be the dominant deformation mechanism among dislocation creep, diffusion creep and Harper-Dorn creep. Assuming the dominant of Harper-Dorn creep, viscosity of the inner core is calculated to be 10^{12} Pas consistent with previous estimations based on mineral physics (Van Orman, 2004) and geophysics (Buffett, 1997). In the future work, effect of light element on diffusion will be investigated to understand the origin of the heterogeneity observed in seismology.

Monnereau, M., Calvet, M., Margerin, L., Souriau, A. (2010) Science, 328, 1014-1017.
Tateno, S., Hirose, K., Komabayashi, T., Ozawa, H., Ohishi, Y. (2012) Geophy. Res. Lett., 39, L12305.
Morelli, A., Dziewon´ski, A. M., Woodhouse, J. H. (1986) Geophys. Res. Lett. 13, 1545–1548.
Anzellini, S., A. Dewaele, A., Mezouar, M., Loubeyre, P., Morard, G. (2013) Science, 340, 464-466
Van Orman, J. (2004) Geophy. Res. Lett., 31, L20606.
Buffett, B.A. (1997) Nature, 388, 571-573.

Electron-phonon contribution to electrical resistivity of hcp Fe

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Determination of electron transport property of the Earth's core is a key to understanding its thermal property. Electrical resistivity (ρ) of a solid metal comprises electron-phonon and electron-electron scattering mechanisms. Two recent first-principles studies however show a significant difference in the electron-phonon contribution ($\rho_{el\text{-}ph}$) of hcp Fe (M. Pozzo, C. Davies, D. Gubbins, and D. Alfe, Nature, 485, 355, 2012; P. Zhang, R. E. Cohen, and K. Haule, Nature, 517, 605, 2015). While Pozzo *et al.* reported $\rho_{el\text{-}ph}$ smaller than the conventional estimates (e.g. F. D. Stacey and O. L. Anderson, Phys. Earth Planet Int, 124, 153, 2001), Zhang *et al.* showed approximately two times larger $\rho_{el\text{-}ph}$ than Pozzo *et al*'s and closer to the conventional values. To aim for verifying these previous studies, we develop a technique to compute electron-phonon interaction and $\rho_{el\text{-}ph}$ of metals based on the density-functional perturbation theory. In this talk, in addition to our technical advantage, preliminary results on the electrical resistivity of hcp Fe under high-P,T condition are presented.

Keywords: Earth's core, Electron transport property, First-principles calculation

Lattice diffusion in B2-type MgO

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High-pressure and high-temperature rheology is essential for understanding the dynamics in planets. Diffusion creep might be one of the dominant viscoplastic mechanisms and lattice diffusion coefficient *D* is a key property in this deformation process (e.g., Karato, 2011). Experimental measurements of *D* however still remain technically difficult under deep planetary conditions. Theoretical approaches therefore play a substantial role.
B2 (CsCl)-type MgO is a high-pressure phase of B1 (NaCl)-type MgO and expected to be one of the major constituents in super-Earths' mantle and giant planetary core (Guillot, 1999; Tsuchiya and Tsuchiya, 2011). Although diffusion creep viscosity of super Earths' mantle is usually assumed to increase with depth monotonically, a previous study (Karato, 2011) suggested that it could decrease associated with the B1-B2 transition of MgO. However, this idea is obtained based on measured plasticity of analog materials and thus *D* of actual B2-type MgO is still underdetermined.
In this study, we calculate *D* of B1- and B2-type MgO based on first principles constant-temperature molecular dynamics method combined with static lattice energy calculations. We identify distinctly larger *D* of both Mg and O in B2-type than in B1-type at the same pressure, suggesting that B2-type would be less viscous as expected. The mechanisms of increase in *D* will be presented.

Keywords: Lattice diffusion, First principles calculation, Super Earth

Microstructural development in olivine aggregates during dislocation creep under hydrous conditions

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Since hydrogen plays an important role in dynamic processes in the mantle, we conducted high-strain torsional shear experiments on aggregates of Fe-bearing olivine [$(Mg,Fe)_2SiO_4$; Fo50] under hydrous condition. Olivine with a composition of Fo50 was used because of its enhanced grain growth kinetics and low strength relative to Fo90. Two pieces of an oriented San Carlos olivine crystal were embedded in each aggregate to monitor water fugacity both before and after deformation. We deformed samples to high enough shear strain≈ 5, to achieve a steady-state microstructure.
A non-linear, least-squares fit to the stress versus strain rate data yielded a stress exponent of n ≈3.5, indicative of deformation involving dislocations. The water content determined from Fourier transform infrared (FTIR) spectroscopy analyses of the single crystals demonstrated that the samples were water saturated after deformation. Fabric analyses of the polycrystalline olivine samples, determined using electron backscatter diffraction (EBSD), indicate that the strength of the lattice preferred orientation (LPO) increases with increasing strain. Further, the LPO of olivine changes as a function of strain due to competition among three slip systems: (010)[100], (100)[001], and (001)[100]. Observed strain weakening can be attributed to geometrical softening due to LPO development, which reduces the stress by ~1/3 from its peak value in constant strain rate experiments. The evolution of fabric can be applied to investigations of upper mantle seismic anisotropy especially in a mantle wedge or in a shear zone, locations in which hydrous conditions prevail.

Keywords: olivine, high strain deformation, dislocation creep, geometrical softening due to LPO development

Differences in grain growth kinetics between MORB and pyrolitic materials under lower mantle conditions: preliminary results

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Convective mixing and persistence of chemical heterogeneities such as subducting slabs in the lower mantle largely depends on their density and viscosity contrasts. In contrast to detailed studies on the density, those on the viscosity of deep slab materials have been limited so far due to difficulties of direct quantitative deformation experiments. Previous studies suggest that both MORB and peridotite regions of deep slabs across the upper and lower mantle boundary cause significant grain-size reduction through the post-spinel and post-garnet transformations, respectively, resulting that the grain-size sensitive creep becomes dominant as the deformation mechanism (e.g., Kubo et al., PEPI2008; EPSL2009; AGU2011). Therefore, the grain growth is an important process controlling the viscosity of slab materials in the lower mantle. Here we report preliminary results on grain growth experiments of MORB and pyrolitic materials under lower mantle conditions.
Each material consists of 3-4 phases after the transformations; those are Mg-perovskite, Ca-perovskite, stishovite, and aluminous phase in MORB, and Mg-perovskite, Ca-perovskite, and ferropericlase (+majoritic garnet at the top of the lower mantle) in pyrolite. We conducted grain growth experiments in these assemblages using a Kawai-type multi-anvil apparatus at ~25-28 GPa, 1873-2373K, and for 1-600 min. SEM observations of recovered samples revealed that these assemblages exhibit relatively homogeneous equi-granular texture except for the short-duration annealing in the pyrolitic material. At the present stage, the average grain size was measured without distinction among phases in the case of MORB material, whereas the grain size in each phase was measured for the pyrolitic material. Preliminary analysis on the grain growth data indicates that the grain growth exponent is about 3.5 for both the MORB material and the major phase of Mg-perovskite in the pyrolitic material, suggesting that the grain growth kinetics in these multi-phase assemblages are controlled by an Ostwald ripening process. The grain size in the MORB material is smaller than that in the pyrolitic material, which corresponds to the difference of 100-150K in temperature. The difference in grain size evolution may lead to the viscosity contrast between MORB and pyrolitic materials in the lower mantle, however further detailed studies are needed to assess this issue.

In-situ X-ray diffraction measurement of growth kinetics of reaction rim at high pressures

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Diffusion rates of elements in minerals provide important constraints for understanding many physical and chemical processes in the Earth's interior, including mantle rheology and chemical transportation. Therefore, many researchers showed the experimental studies on the growth kinetics of reaction rims between minerals, which are often controlled by diffusion of elements. Most of the previous studies succeeded to determine the rim growth kinetics based on the direct measurement of the thickness of reaction layers of recovered samples. However, it is difficult to obtain the precise growth kinetics in this method due to the small uncertainty of temperature and water contents during each experiment.
Here we use in situ X-ray measurements in conjunction with a multi-anvil apparatus to obtain the precise kinetic data of the rim growth of $MgAl_2O_4$ spinel between MgO periclase and Al_2O_3 corundum. Time resolved X-ray diffraction patterns enable us to obtain the information with the constant temperature, pressure, and water contents.
We succeeded to obtain the time-resolved X-ray diffraction data during the rim growth of $MgAl_2O_4$ spinel. However, the obtained growth kinetics contains large uncertainty because of the grain growth of the sample minerals due to high water contents. Further experimental improvement would be required to obtain the precise growth rate of the reaction rims.

Keywords: rim growth kinetics, mantle, multi-anvil apparatus

Effect of the metallic melt on the mantle rheology

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The region around core-mantle boundary is estimated to be composed of post-perovskite phase with some fractions of outer core material. It is unclear that how these two different materials interact with each other chemically and dynamically. To understand these interactions, it is important to know the effect of a metallic melt on the viscosity of silicate rocks.
According to Hirth & Kohlstedt (2003), strain rate is an exponential function of melt fraction ($d\varepsilon/dt \propto \exp(\alpha\varphi)$) under a constant stress. With larger melt fraction, polycrystalline silicate becomes softer. Hustoft et al (2007) performed creep experiments on olivine+Fe-S and olivine+Au showing that the melt fraction factor αis approximately one-fifth relative to the value of αreported for olivine+MORB (Scott & Kohlstedt, 2006). However we don't know how the rock viscosity is affected by a relative size of metallic melt against olivine grains and by strain. To understand these effects, we performed creep experiments on olivine+Au and compared the viscosity obtained from our experiments with the viscosity reported by Hustoft et al (2007).
We synthesized Fe-free olivine polycrystals with Au particles as follows; (i) We mixed fine powders of $Mg(OH)_2$, SiO_2 and Au. (ii) We made forsterite+enstatite from calcination of $Mg(OH)_2$ and SiO_2. (iii) We sintered the formed samples under a vacuum condition. Sintered materials contain forsterite, enstatite and Au with volume fractions of 81 %, 9 %, 10 %, respectively. Grain sizes of olivine and Au are 0.7 and 0.8 μm, respectively. We performed high-temprature and uni-axial compressional creep experiments on these materials at atmospheric pressure. We changed the stress from 10 MPa to 20 MPa, 40 MPa and 80 MPa at the constant temperatures (1200℃ and 1300℃). Under each stress level, we measured a strain rate where the relationship between time and strain became linear (steady state creep). We observed microstructures of the aggregates after the experiments using scanning electron microscope (SEM).
Based on stress versus strain rate data, we obtained a relationship of $d\varepsilon/dt \propto \sigma^{1.7}$. We observed that equiaxed Au particles became flattened against compressional direction after the experiments. The samples exhibited 4~8 times softer than Au-free samples which were synthesized by the same method we used. Our samples are even 3~4 times softer relative to the aggregates used in Hustoft. In our experiments, Au particles deformed considerably, while the shape of the Au phases was not substantially changed at Hustoft's experiments. We attributed this difference to relatively larger size of Au particles to olivine grains in our study compared to that in Hustoft's sample. Substantial deformation of soft Au particles can increase the stress for olivine grains which enhanced creep rate.

Keywords: viscosity, metallic melt, olivine

Technical development and improvement for sound velocity measurements of liquid Fe-S up to 15 GPa using ultrasonic pulse-echo method

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Knowledge of the physical properties of liquid iron alloys is important for understanding the liquid core of the Earth and other terrestrial planets and satellites. Sound velocity is a key physical property to know the structure and composition of these cores because it can be directly compared with seismic observations. However, sound velocity measurements of liquid iron alloy by ultrasonic methods combined with multi anvil apparatus have been limited to below 8 GPa (Nishida et al. 2013; Jing et al. 2014; Kuwabara et al. 2016). Therefore, we have been developing and improving techniques that enable us to measure sound velocities of liquid iron alloys up to 20 GPa. Here we report newly established techniques for sound velocity measurements of liquid Fe-S up to 15 GPa. High-pressure and high-temperature experiments were conducted at the AR-NE7A beamline at the KEK PF-AR synchrotron facility. High pressure was generated by Kawai-type multi anvil apparatus (MAX-III). High temperature was generated using cylindrical resistive heater made of Al_2O_3 + TiC composite. The sample was enclosed in a flat-bottomed cylinder container made of BN with a buffer-rod and a backing plate made of sapphire single crystal. We determined the pressure and temperature simultaneously without a thermocouple from the unit-cell volumes of NaCl and MgO by employing their equations of state. Sound velocity was measured by ultrasonic pulse-echo overlap method. The sample melting was identified during the experiments using X-ray diffraction, and was confirmed afterwards from textural observations of the run products.
Preliminary results show the error in sound velocity of liquid Fe-S at 15 GPa is approximately 2.5% under good conditions. In our previous experiments, the error in sound velocity below 7 GPa was approximately 1% under the best conditions. Taking it into account, our newly techniques can provide satisfactory accuracy. Details and latest experimental results will be presented.

Keywords: core, sound velocity, liquid Fe-S, high pressure

Development for Neutrino Directional Measurement in Liquid Scintillator

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Liquid scintillator detector has a sensitivity to geo-neutrino. However, this detector can't observe direction of anti-neutrino.So we develop new-type detector that can know direction of anti-neutrino.In my poster, I talk about development of ^{6}Li loaded liquid scintillator and high vertex resolution imaging detector.

Keywords: neutrino

High-pressure *in situ* X-ray laminography using diamond anvil cell

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The diamond anvil cell (DAC) is a powerful tool to reproduce high-pressure (P) and high-temperature (T) conditions, corresponding to those of the deep Earth interior, in a laboratory. Various types of measurements such as in situ high-P–T spectroscopic measurements and ex situ chemical analysis have been conducted using DACs to understand the structure and evolution of the Earth's interior. Among these techniques, 3D visualization and textural/chemical characterization of the internal structure of samples at high-P–T is of great importance. Recently, the dihedral angle of molten iron between bridgmanite was investigated by imaging recovered DAC samples using X-ray computed tomography (CT), and the results provide important insights about the physical process of the Earth's core–mantle separation (Shi et al., 2013). In situ high-P X-ray CT has been developed by transmitting X-rays through a light metal gasket, such as Be, between diamond anvils. To date, the applications have been limited to physical purposes, such as the changes of the volume or shape of the sample with pressure (Liu et al., 2008; Wang et al., 2012).
On the other hand, Tsuchiyama et al. (2013) developed a 3D chemical imaging technique, known as analytical dual energy microtomography, in which two X-ray energies below and above the absorption energy of a key element, such as Fe, are used for CT. We applied this technique to recovered DAC samples to determine the solidus temperature of pyrolitic mantle, using incompatible Fe enrichment as a signature of melting (Nomura et al., 2014). This dual energy technique has an additional advantage that artifacts in the reconstructed images, which are a typical problem in CT, can be avoided. The next step should be to carry out in situ high-P–T dual energy X-ray imaging, which remains challenging because deep Earth is composed of light elements (e.g. Fe, O, Si, Mg) with an X-ray absorption edge far below the hard X-ray energy range, in which the light metal gasket absorbs the incident X-rays crucially.
A high-pressure in situ X-ray laminography technique was developed using a newly designed, laterally open diamond anvil cell. A low X-ray beam of 8 keV energy was used, aiming at future application to dual energy X-ray chemical imaging techniques. The effects of the inclination angle and the imaging angle range were evaluated at ambient pressure using the apparatus. Sectional images of ruby ball samples were successfully reconstructed at high pressures, up to approximately 50 GPa. The high-pressure in situ X-ray laminography technique is expected to provide new insights into the deep Earth sciences.

Keywords: High pressure, X-ray imaging, diamond anvil cell

Development of resistance-heated diamond anvil cell using boron-doped diamond heater

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Laser-heated diamond anvil cell is the most successful method for reproducing the pressures and temperatures of the Earth's deep interior entirely in a laboratory (e.g. Tateno et al., 2010 Science). However, it is well known that laser-heating results in steep temperature gradients within a sample (e.g. Rainey et al., 2013). Such steep temperature gradients cause the solid-state chemical segregation called as 'Soret diffusion'. This effect is well known in gas chemistry such that heavier elements or elements with larger ionic radii migrate from hot to cold regions, while the lighter elements move in the opposite direction (Grew and Ibbs, 1952). The Soret diffusion takes place not only in gas but also in liquid and solid. Therefore, Soret diffusion makes it difficult to perform chemical equilibrium experiments using laser-heated diamond anvil cell (Sinmyo et al., 2008 JGR).
The technique for homogeneous heating has been developed, that is internally-heated diamond anvil cell. In this method, the heater is put into a sample chamber and compressed together with the sample. Because the diamond has a high thermal conductivity, diamond anvils do not become a high temperature and the heated zone is limited to near the sample chamber. Therefore, internally-heated diamond anvil cell has a potential to generate temperature more than 2000 K because the diamond anvils do not transform to the graphite. A sample was used also as a heater in previous studies (e.g. Liu and Bassett, 1975; Boehler et al., 1986). Therefore, only electric conductor can be used as a sample for the experiment. Zha and Bassett (2003) overcame this situation by making a small hole in a Re heater and filled the hole with sample. Both metal and nonmetal can be used as the sample in this method. The study showed that temperature gradients of Re heater near sample room were gentler than that of laser-heating studies. However, its temperature gradients were still steeper than multi-anvil's temperature gradients (Canil, 1994).
On the other hand, the boron-doped semiconductor diamond heater is known to be able to have a much smaller temperature gradient than that of metallic heater (Yoneda et al., 2014). In multi-anvil experiments, Yoneda et al. (2014) successfully generate high temperature more than 3000 K, which Re and $LaCrO_3$ heaters cannot generate.
In this study, I developed the internally-heated diamond anvil cell technique using boron-doped diamond heater. The results showed that temperature gradients of boron-doped diamond heater in diamond anvil cell were smaller than that of metallic heater used in previous study (Zha and Bassett, 2003). In addition, its temperature gradients are as steep as multi-anvil's temperature gradients. In this presentation, we will show our recent progress on this study.

Keywords: Diamond anvil cell, Boron-doped diamond, Internal resistive heating

Transportation of hydrogen by iron oxide-hydroxide in the Earth's interior

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Water (hydrogen) plays important roles in dynamics in the Earth's interior. It is expected that hydrogen is transported from the surface to the interior by the subducting slab. Hydrogen is also a candidate of the light element of outer core. Therefore, the study of the hydrogen in the Earth's interior is quite important. Terasaki et al. (2012) investigated the reaction between Fe-Ni alloy and delta-AlOOH up to the pressure of core-mantle boundary. They showed that hydrogen is partitioned into Fe-Ni alloy and suggested that the core was hydrogenated by the subducting delta-AlOOH. (Dobson and Brodholt (2005) proposed that the banded iron formation subducted to the core-mantle boundary and stagnated there. The banded iron formation contains iron oxide-hydroxide. Therefore, it is important to study the stability and properties of iron oxide-hydroxide under high pressures and high temperatures to discuss the transportation of hydrogen in the Earth's interior. We carried out X-ray diffraction study and X-ray absorption measurement in the Photon Factory, Tsukuba, Japan. Goethite (alpha-FeOOH) is stable at ambient condition. However, it transformed to epsilon-FeOOH at 7.8+-0.5 GPa and 873K. Our previous study showed that epsilon-FeOOH was stable under the condition of the lower mantle. We suggest that epsilon-FeOOH can transport hydrogen to the core-mantle boundary and supply hydrogen to the outer core.

Keywords: hydrous phase, slab, mantle, banded iron formation, outer core

Possible link between East-west mantle geochemical hemispheres and Geoneutrino

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There has been an extensive debate concerning the compositional structure of the mantle: e.g., two-layered mantle model, stratified/zoned mantle model, plum-pudding mantle model, and marble-cake mantle model (e.g., Tackley, 2008; Iwamori, 2016, for review). The compositional structure is important as it reflects the flow pattern of mantle convection and differentiation processes during material cycling, yet poorly constrained at present. An geochemical end-member model argues that the mantle convection chaotically stirs geochemical heterogeneity brought by plate subduction, resulting in ubiquitously heterogeneous mantle (e.g., plum-pudding or marble-cake mantle, Zindler et al., 1984; Allègre and Turcotte, 1986). At the same time, a large-scale heterogeneity has been argued to exist, e.g., Dupal-anomaly in the southern hemisphere (Dupré and Allègre, 1983; Hart, 1984), or East-west geochemical hemispheres in terms of hydrophilic components (Iwamori and Nakamura, 2012; 2015).
Distributions and abundances of the radiogenic isotopes such as uranium (U) -238, -235 and thorium (Th) -232 in the mantle are key to constrain cooling history and mode of mantle convection of the Earth (e.g., McKenzie et al., 1974; Davies, 1999; Korenaga, 2013), because of the radiogenic heating. However, detailed information of distributions and abundances of such radiogenic elements in the Earth's interior are not well constrained. Recently, Kamioka Liquid-Scintillator Antineutrino Detector measured the geoneutrino flux from decay of U-238 and Th-232. The observations indicate that the heat from radioactive isotopes might account for about a half of Earth's total heat flux (The KamLAND Collaboration, 2011). In addition, Tanaka and Watanabe (2014) proposed Li-loaded directionally sensitive detector for possible geo-neutrinographic imaging. Based on these on-going measurements and new methods, the fundamental questions concerning the mantle compositional structures described above could be addressed.
East-west geochemical hemispheres of the mantle have been proposed based on statistical analysis (Independent Component Analysis) of the global isotopic data set of young basalts (Iwamori and Nakamura, 2012; 2015), suggesting that the eastern hemisphere is enriched in "anciently subducted fluid component". If this is the case, we expect a systematic hemispherical difference in elemental abundances and ratios, including U and Th. Although the absolute abundances of these elements in the mantle are not readily constrained by the basalt data (unless the degrees of partial melting of basalts are tightly determined), by combining the geochemical analyses and geoneutrino measurements, we might be able to constrain the distribution and abundances of crucial elements, which will lead us to evaluate Geoneutrino.

Keywords: Mantle composition, Geoneutrino

Stability field of phase Egg under high temperature and high pressure: Possibility of phase Egg as a water reservoir in mantle transition zone

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Water in the earth's interior is one of the main research topics because the water is known to affect physical properties of materials in the earth's interior such as rheology, electric conductivity, seismic velocity, density, and melting point. The sedimentary layer of the oceanic crust transfers water into the deep earth mantle via subducting slabs (Peacock, 1990). Phase Egg, $AlSiO_3(OH)$, is one of the important hydrous phases in the mantle originating from the sedimentary layer and can contain H_2O of 7.5 wt% as hydroxyl. However, two previous studies (Sano et al., 2004; Pamato et al., 2014) have reported different stability fields about phase Egg. This inconsistency leads to different earth-scientific outlooks on water cycling system via subducting slabs: whether the phase Egg can reserve water in the top of the lower mantle or not and where the superdeep diamond containing phase Egg originates (Wirth et al., 2007). Phase Egg as an inclusion in diamond might indicate a possibility that a top of the lower mantle might be wet.

Here, we conducted high-pressure experiments using Kawai-type 3000 ton multi-anvil apparatus and 1000 ton multi-anvil apparatus at Tohoku University in order to determine the stability field of phase Egg. Experiments were performed in the pressure range of approximately 17-21GPa and in the temperature range of 1000-1200℃. Starting material was a mixture of Al_2O_3, $Al(OH)_3$, and SiO_2 compounded similarly to ideal phase Egg composition, which was different from those of two previous studies (Sano et al., 2004; Pamato et al., 2014).

In this study, we found that phase Egg decomposed under the pressure corresponding to the mantle transition zone at 1000℃. This indicates that phase Egg is unstable in the top of lower mantle and can be a water reservoir in the mantle transition zone. In addition, this implies that the superdeep diamond, which Wirth et al. (2007) reported, does not originate from the lower mantle but from the wet mantle transition zone.

Keywords: water cycle in the earth's interior, phase Egg, multi-anvil apparatus, high pressure and high temperature, mantle transition zone, superdeep diamond

Viscosity of basaltic magma at high pressure

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Viscosity and density control the mobility of magma. Sakamaki et al. (2013) measured the viscosity of basaltic magma at high pressure and reported the viscosity minimum around 4 GPa. They also measured the density of magma and found a quick elevation of the density around the pressure. On the basis of the results they proposed a model of stagnation of magma around the lithosphere-asthenosphere boundary (melt pond model). However, the pressure range of their measurement was limited to 7 GPa. Reid et al. (2003) carried out viscosity measurement of diopside melt to 13 GPa and reported the viscosity maximum around 10 GPa. They suggested that the decrease in viscosity above 10 GPa was caused by the structural change of melt. Therefore, the change in viscosity is also expected in basaltic magma. Here, we report the result of viscosity measurement of basaltic magma above 10 GPa. We adopted the falling sphere method using the X-ray radiography. Experiments were carried out at the beamline BL-04B1 in SPring-8. We found the decrease in viscosity between 7 and 10 GPa. Above 10 GPa the viscosity increased to 13 GPa. On the basis of the observation of seismic wave, the existence of melt around the base of the upper mantle (e.g., Revenaugh and Sipkin, 1994). We suggest the stagnation of melt by the change in viscosity.

Keywords: magma, viscosity, mantle

Thermal conductivity of lower mantle minerals from *ab initio* anharmonic lattice dynamics

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Determination of lattice thermal conductivity () of lower mantle minerals is a key to understanding the dynamics of the Earth's interior. Although determination of $\kappa$was impractical in the deep Earth *P, T* condition for a long time, recent experimental and computational developments have been extending the accessible *P* and *T* ranges (e.g. H. Dekura, T. Tsuchiya and J. Tsuchiya, Phys. Rev. Lett. 110, 025904, 2013). *Ab initio* prediction of κrequires understanding of the phonon-phonon interaction associated with the lattice anharmonicity. We recently succeeded in developing an efficient method to calculate it based on the density-functional perturbation theory combined with anharmonic lattice dynamics theory, and applying to $MgSiO_3$ perovskite in the whole lower mantle *P, T* range for the first time. Next we extend our techniques to other lower mantle minerals such as $MgSiO_3$ post-perovskite, and now calculations of more realistic Fe-bearing systems are also started. In this presentation, we introduce the current situation of our research on κ.

Keywords: Earth's lower mantle, Phonon transport property, First-principles calculation

Ab initio prediction of the incongruent melting relation in the MgO-SiO_2 system at multi-megabar

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Magnesium silicates are thought to be the major components of the mantle of terrestrial planets and the core of giant planets (Guillot, 1999; Seager *et al*., 2007). However, the thermodynamic phase equilibrium in the MgO-SiO_2 system is still not well studied at multi-megabar, including melting relations. A recent laser shock experience reported two discontinuous phase changes in $MgSiO_3$ at 300-400 GPa (Spaulding *et al*., 2012), but an *ab initio* molecular dynamics study identified no clear transition in $MgSiO_3$ liquid (Militzer, 2013). Boates and Bonev (2013), on the other hand, examined a decomposition reaction of liquid $MgSiO_3$ into solid MgO and liquid SiO_2 and reported that liquid $MgSiO_3$ is dissociated at ~300 GPa. This result implies a possible incongruent melting. However, the reaction they considered is too simple and unrealistic. The detailed phase diagram in the MgO-SiO_2 system is therefore required to be clarified at multi-megabar. In this study, we perform *ab initio* free energy calculations based on the thermodynamic integration method (Kirkwood, 1935) and determine the melting phase relation in this binary system.

Keywords: ab initio calculation, MgO-SiO2 system, incongruent melting, multi-megabar

Geoelectromagnetic jerks produced by heterogeneous electrical conductivity in the D" layer

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Geomagnetic jerks are identified at 2003, 2007 and 2011 in the Atlantic and Indian Ocean. It has been suggested by Chulliat et al. (2015) that the regional nature of the geomagnetic jerks and spatio-temporal variations of geomagnetic secular acceleration can be explained by fast equatorial magnetohydrodynamic waves propagating near the surface of the Earth's core. On the other hand, the geoelectric field observed using long baseline submarine cables in the northwestern Pacific also showed sudden change of its secular variation at 2006. In a previous study, we showed using a simplified mantle conductivity models that the geoelectric field variation and the geomagnetic jerk in 2007 can have the same origin; the variations can be generated by a sudden change of the toroidal magnetic field secular variation in the core and influence of high electrical conductivity region in the D" layer beneath the area where the geomagnetic field variation was evident. Since the geoelectric and geomagnetic field variations can have the same origin, we call the variations a geoelectromagnetic jerk. In this presentation, we show results of numerical experiment on the electromagnetic field in the mantle due to the toroidal magnetic field variation in the core employing more realistic distribution of the electrical conductivity in the D" layer based on the SH-wave velocity model obtained by Takeuchi (2012). Conductivity heterogeneity at the Earth's surface due to the conductivity contrast between the land and seawater on the electric field is also included in the numerical experiment to examine its effect on the voltages observed by submarine cables. Typical spatio-temporal variations of the observed and simulated geoelectromagnetic field are examined to consider plausibility of geoelectromagnetic jerk hypothesis.

Chulliat, A., Alken, P. and Maus, S. (2015) Fast equatorial waves propagating at the top of the Earth's core, Geophys. Res. Lett., 42, 3321-3329.
Takeuchi, N. (2012) Detection of ridge-like structures in the Pacific Large Low-Shear-Velocity Province, Earth and Planet. Sci. Lett., 319-320, 55-64.

Experimental and theoretical thermal equations of state of $MgSiO_3$ post-perovskite at multi-megabar pressures

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The $MgSiO_3$ post-perovskite phase is the most abundant silicate phase in a super-Earth's mantle, although it only exists within the Earth's lowermost mantle. We established the thermal equations of state (EoS) of the $MgSiO_3$ post-perovskite phase, which were determined by using both laser-heated diamond anvil cell (LHDAC) and density-functional theoretical techniques, within a multi-megabar pressure range, corresponding to the conditions of a super-Earth's mantle. The LHDAC experiments were performed at up to a pressure of 265 GPa at a temperature of 300 K, and 170 GPa at 2560 K. The *ab initio* calculations were performed at up to 1.2 TPa and 5000 K. The Keane and AP2 EoS models, which include parameters that limit to infinity at high pressure, were adopted for the first time to extract meaningful physical properties. The experimental volume data in a wide pressure-temperature range enabled us to determine the fully experimentally based parameters for the Mie-Grüneisen-Debye model. The Grüneisen parameter and its volume dependency were found to be consistent with their theoretically obtained values. Both the experimental and theoretical EoS are also found to be in very good agreement with one another, within 0.1% in volume at the earth's core-mantle boundary condition, and the relation is maintained within 0.8% even up to a pressure and temperature of 300 GPa and 5000 K, respectively. Our newly developed EoS should be applicable to a super-Earth's mantle, as well as the Earth's core-mantle boundary region.

Keywords: post-perovskite, equation of state, super-Earth

Sensitivity of Core Phases on F-layer

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Last year we showed that the dispersion in PKPbc and differential traveltimes between PKiKP and PKPbc are particularly sensitive to the F-layer structure (lowermost outer core) and are insensitive to the structure of the other parts of the Earth (Ohtaki and Kaneshima, 2015). 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. 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 this study we discuss the sensitivity of various core phases (PKIKP, PKPbc, PKPc-diff, and PKiKP) to the F-layer structure in detail. 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 P-wave velocity of the F-layer from that of the inner core using the differential traveltimes between PKPbc/c-diff 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.
In our previous study (Ohtaki et al., 2012), we examined the seismic structure near the inner core boundary beneath the South Pole. In that study, we investigated the velocity above the inner core boundary using the amplitude ratios between PKIKP and PKPbc/c-diff, assuming a constant velocity in the F-layer, because the ratio is not so sensitive to the velocity gradient, as mentioned above. In this study, we also examine a tolerance level of a velocity gradient there.

Keywords: Seismic velocity, Outer Core

Anomalously large PKiKP/PcP amplitude ratios at frequency of around 1 Hz observed by USArray

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Tanaka and Tkalcic (2015) observed the frequency dependent PKiKP/PcP amplitude ratios by Hi-net, of which ray paths are passing below the Western Pacific. They showed the existence of a spectral peak at approximately 2 to 3 Hz, a spectral hole at 1 and 3 Hz, and no peak and hole, suggesting lateral variations at the inner core surrface. Here I report frequency dependent PKiKP/PcP amplitude ratios observed by USArray, of which reflection points are located below the Central America. I find also a large scatter of the frequency characteristics. Interestingly, the spectral peaks in the PKiKP/PcP spectral ratios around 1-1.5 Hz are detected when the reflcetion points are located below the east of Mexico that is not observed by Hinet. The peak amplitude is about 2 times greater than that around 2 Hz. Based on the finite difference simulations by Tanaka and Tkalcic (2015), this observed peak can be explained by ICB sinusoidal topography with wavelength and height of 0.5 km, or ICB spiky topography with wavelength and height of 1.5 km. This observation suggests that the crystallization at the inner core surface or inner core growth system below the east of Mexico is different from that below the Western Pacific.

Keywords: Inner core, USArray, PKiKP/PcP

On the possible scenario of thermal evolution of Earth's core with high thermal conductivity in a coupled core-mantle evolution model

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The thermal conductivity measurement of iron alloy from high P-T physics suggested to range from 60 to 150 W/m/K under temperature and pressure condition in Earth's core [e.g. Gomi et al., 2013]. The previous study by Nakagawa and Tackley [2015] indicated that the CMB heat flow was just only 6 TW and, as a result, the magnetic evolution would be failed with high thermal conductivity and colder CMB temperature (~3500 K) caused by large adiabatic temperature gradient across the Earth's core (~1 K/km) [Labrosse, 2015]. Here we assume smaller adiabatic temperature gradient across the Earth's core (0.5 to 0.7 K/km taken from lower-bound value in Ichikara et al. [2014]) as well as high thermal conductivity of Earth's core set as 120 W/m/K. For the successful scenario of a coupled core-mantle thermal evolution matching the current size of the inner core and continuous magnetic field generation, the CMB heat flow at the present time-scale would be around 12 TW because the CMB temperature is still high (~4000 K) for finding the current size of the inner core and the age of the inner core would be 1.2 billion year, which seems to be a bit older age of inner core compared to other studies [Labrosse, 2015; Davis, 2015]. To find the successful scenario of thermal evolution of Earth's core, the adiabatic temperature gradient across the Earth's core prescribed by Grueneisen parameter and bulk modulus would be quite important in terms of high CMB heat flow than could find the continuous magnetic evolution under the high thermal conductivity. With the lastest update of core-mantle evolution, the adiabatic temperature across Earth's core would be consistent with the range found from first principle calculation rather than that used in the core evolution models approximated heat transfer across the CMB.

Keywords: Earth's core, Heat flow across the core-mantle boundary, Adiabatic temperature gradient, Thermal conductivity

