Origin of geochemical mantle components: Role of spreading ridges and thermal evolution of mantle

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We explore the element redistribution at mid-ocean ridges (MOR) using a numerical model to evaluate the role of the decompression mantle melting process in the Earth’ s geochemical cycle, particularly in the formation of the depleted mantle component. Our model uses a trace element mass balance based on an internally consistent thermodynamic-petrologic computation to explain the composition of MOR basalt (MORB) and residual peridotite. Model results for MORB-like basalts from 3.5 to 0 Ga indicate a high mantle potential temperature (T_p) of 1650–1500°C during 3.5–1.5 Ga before decreasing gradually to 1320°C today. The source mantle composition changed from primitive (PM) to depleted as T_p decreased, but this source mantle is variable with an early depleted reservoir (EDR) mantle periodically present. We examine two-stage Sr-Nd-Hf-Pb isotopic evolution of the mantle residues from melting of PM or EDR at MOR that formed ancient MORB-like basalts. Formation of depleted MORB source mantle (DMM) is also examined using modern MORBs. At high-T_p (3.5–1.5 Ga), the MOR process formed extremely depleted DMM. This coincided with formation of the majority of the continental crust, the sub-continental lithospheric mantle, and the enriched mantle components formed at subduction zones. During cooler-T_p mantle conditions (1.5–0 Ga), the MOR process formed most of the modern ocean basin DMM. Changes in the mode of mantle convection from vigorous deep mantle recharge before ˜1.5 Ga to less vigorous afterwards is suggested to explain the thermochemical mantle evolution.

Keywords: Depleted mantle, Thermal evolution, Chemical evolution

Towards constitutive equations for the deep Earth

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Currently a full treatment of both bulk- and shear properties at conditions of high pressure is only available for the Birch-Murnaghan formulation based on power series expansion of the strain energy. This representation is most suitable for extrapolation to mid-mantle conditions. Fits to experimental data for high pressures frequently favour the Vinet or Keane equations of state for bulk-modulus, but in neither case is there any connection to shear.
However, by working with invariants of the stretch tensor suitable isotropic constitutive equations can be found that add-in shear properties in a consistent way via local representations about a pre-stressed state. Such constitutive relations are particularly useful for high-pressure phases in the deep Earth, and make only slight modifications to popular representations for the bulk modulus.

Keywords: Deep Earth physical properties, Bulk modulus, Shear modulus

Rheology of $CaGeO_3$ (perovskite)±MgO: Implications for multiphase flow in the lower mantle

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With a thickness of well over 2000 km, the lower mantle is the largest rocky layer in Earth and plays a critical role in controlling dynamics of deep earth. Mineralogical mantle models suggest that the lower mantle is dominated by (Mg,Fe)SiO_3 bridgmanite (SiBr) and (Mg,Fe)O ferropariclase (Fp). In addition to rheological properties of these individual minerals, knowledge of stress/strain partitioning among the phases and texture evolution during deformation is critical in understanding dynamic processes of the deep Earth. Currently, there is a lack of experimental studies on lower mantle rheological properties, because of the difficulties in conducting quantitative experimental studies under lower mantle pressure and temperature conditions. Here we examine rheological properties of a two-phase polycrystalline assembladge consisting of $CaGeO_3$ perovskite (GePv) and MgO, deformed in the D-DIA with strain rates of ~1 - 3×10^(-5) s^(-1) at high pressures and temperatures (up to 10 GPa and 1200 K, respectively), with bulk axial strains up to ~40%. Stresses within individual phases are measured directly using in-situ monochromatic x-ray diffraction. GePv is found to have a strength 3 - 4 times that of MgO, a ratio similar to that between SiBr and Fp. Thus strain is expected to partition primarily into MgO. Elasto-ViscoPlastic Self-Consistent modeling (EVPSC) is used to reproduce experimentally measured lattice strain and texture of the two phase aggregate. Recovered samples are examined using electron back scattered diffraction (EBSD) and scanning electron microscopy (SEM), to extract final microstructural information. These results are compared with deformation of single-phase $CaGeO_3$ perovskite polycrystals. Active slip systems of the two phases, partitioning of stress and strain in the composite aggregate, and textural development will be discussed, with potential implications to the lower mantle. We find that texture development, which depends primarily on the level of shear strain, has a fundamental influence on the bulk rheology of multi-phase assemblages. A texture-induced rheological transition is likely to occur in certain regions of the lower mantle, profoundly affecting convection patterns in the Earth.

Keywords: multi-phase rheology, lower mantle, convection, mantle dynamics

First principles investigation of high pressure behavior of FeOOH

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It has been believed that water is carried into the deep Earth’s interior by hydrous minerals such as the dense hydrous magnesium silicates (DHMSs) in the descending cold plate. A numbers of researches have been conducted so far about the high pressure behaviors of DHMSs. In recent years, we found new DHMS, phase H, at lower mantle pressure condition and the solid solution between phase H and d-AlOOH has been proposed as the most important carrier of water in the deepest part of Earth’s mantle (Tsuchiya 2013, Nishi et al. 2014, Ohira et al. 2014). However, those hydrous minerals are actually not denser than surrounding (dry) mantle minerals (Tsuchiya and Mookherjee 2015) and the gravitational stability in deeper part of the Earth is questionable. Therefore, the effects of denser element such as Fe on the stability of DHMS are intimately connected to the ability of transportation of water into Earth’s deep interiors. In order to assess the effect of Fe on the phase relation of phase H and d-AlOOH, we first investigated the high pressure behavior of the end-member composition of this system, the e-FeOOH. We have found the new high pressure transformation of FeOOH in the lower mantle conditions both theoretically and experimentally. Here, I show high pressure structures and the physical properties of FeOOH polymorphs using first principles calculation and discuss the possible geophysical implications of these phases.

Experimental investigation of high-pressure phase transitions in AlOOH and FeOOH

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Hydrogen is transported into deep Earth’s mantle regions as a form of hydrous minerals via subduction of oceanic plates. Recently discovered $CaCl_2$-type hydroxides such as (Mg,Si)OOH phase H, delta-AlOOH, and their solid solutions were reported to have large P–T stability fields that encompass conditions representative of the lower mantle, implying the possibility that surface water may be transported as far as the core–mantle boundary. However, although Epsilon-FeOOH has $CaCl_2$-type structure as well, the solid solution of FeOOH component in $CaCl_2$-type structure has not been studied. Since FeOOH was recently reported to decompose under the lower-mantle conditions to form FeO_2 releasing H_2, FeOOH could be a key component that strongly affect the stability of $CaCl_2$-type hydroxide. Here, we report the results of in-situ X-ray diffraction and theoretical studies on AlOOH and FeOOH using a laser-heated diamond anvil cell technique at up to ~200 GPa. In contrast to the previous work suggesting the dehydration of FeOOH in the middle of the lower mantle, we report the formation of a pyrite-type FeOOH that is significantly denser than the surrounding mantle and stable to conditions representative of its base. Furthermore, delta-AlOOH and $CaCl_2$-type (Al,Fe)OOH also transform to a pyrite-type structure at higher pressures. Based on these experimental and theoretical results, the stability of hydrous phase in the lower mantle and deep interiors of icy planets will be discussed.

Keywords: hydrous mineral, high pressure

Search for hydrogen in the Earth's core and lower mantle using neutrino oscillations

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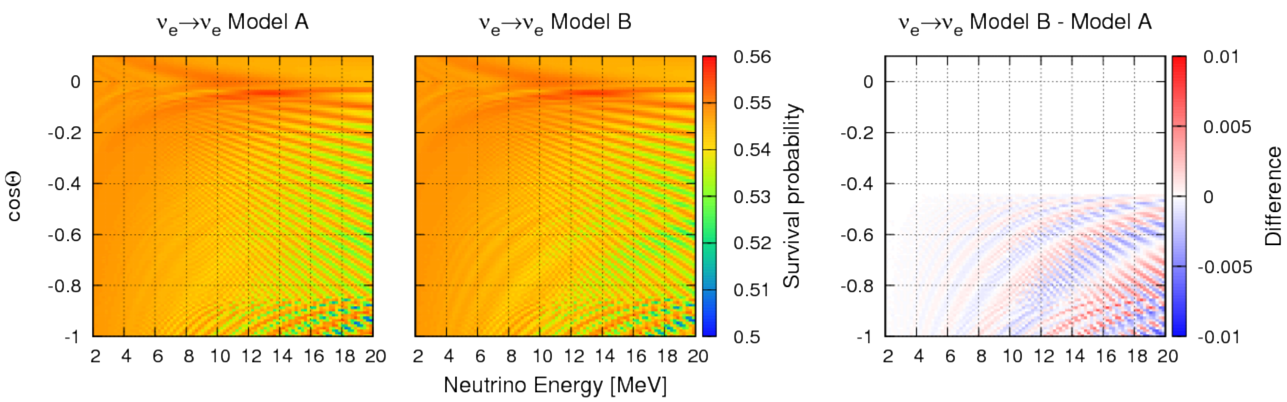
According to recent reports, lower mantle can preserve more water than previous assumption. Hydrogen is gathering attention as the light element of the outer core. But hydrogen content in the deep Earth cannot be measured directory with the present technology.
We have been studying the composition measurement of the outer core using neutrinos produced in the Earth’ s atmosphere. This method can be applied to water content measurement of the lower mantle. Also, we found the neutrino produced in the Sun can improve the sensitivity of this measurement.
Neutrinos have unique property not found in other elementary particles, called as neutrino oscillation. Neutrino oscillation refers to the phenomenon that the specie of neutrino changes to another specie of neutrino over time. For example, a neutrino produced as a muon neutrino could be detected as an electron neutrino. Probability of changing its specie depends on the mixing angle of neutrino, the masses of three species, its energy, time of flight, violation of charge conjugation parity symmetry, and the electron density of the media which is passed through by the neutrino. The other parameters than the electron density can be measured by other experiments, so neutrino oscillation can be used as the unique prove to measure the electron density of the object.
Therefore, by measuring the neutrinos, which are produced in the Earth’ s atmosphere or in the Sun and passed through the Earth, it becomes possible to measure the electron density distribution of the deep Earth. The matter density distribution is already measured by seismic wave propagation and free oscillation of the Earth. The ratio of the electron density to the matter density is equal to the ratio of the atomic number to the atomic mass (Z/A ratio), so the average chemical composition distribution of the Earth. The Z/A ratio of the standard rock is approximately 0.5, and that of iron is approximately 0.47, whereas The Z/A ratio of hydrogen is 1. So neutrino oscillation is especially sensitive to hydrogen. By using this property, hydrogen search in the deep Earth becomes possible.
We report the possibility of the hydrogen search using solar neutrino oscillations and atmospheric neutrino oscillations.

Keywords: chemical composition, lower mantle, outer core, neutrino



Waveform inversion for the 3D elastic and anelastic structure of the lowermost mantle beneath the western Pacific

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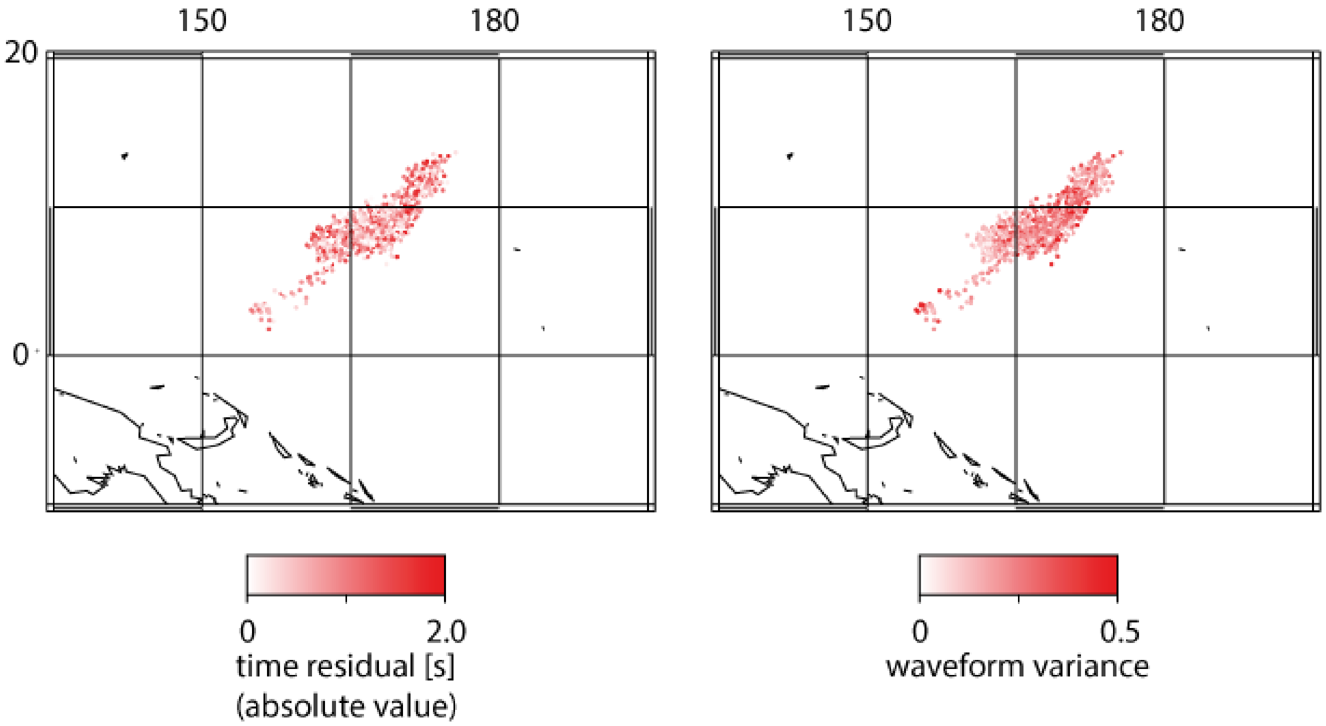
We invert seismic waveforms data for the 3D shear velocity (V_S) and attenuation (measured by the quality factor, Q) structure of the lowermost mantle beneath the western tip of the Pacific low shear velocity province (LLSVP). Our dataset consists of seismic waveforms from F-net for 31 deep earthquakes beneath Tonga and Fiji, and shows regional variations of S and ScS arrival times and amplitude ratios. Residuals between arrival times and amplitude ratios of peak-to-peak amplitude of S and ScS vary from west to east in the target region, as illustrated by inversion of our dataset for radial models of VS and Q in three subregions. The model explains lateral variations in those values. However, while the distribution of the travel time for the obtained 1D model (shown in the left) seems homogeneous, the other still shows lateral variation from west to east, that is we can see large values around 165 E. 10 N. In this study, in order to extract more information on the 3D structure from our dataset, in particular using waveform, we extend our 1D approach by dividing our region of interest in a larger number of subregions, which, when assembled together, provide a 3D elastic and anelastic model of the region. We show distribution of resolution for 3D structures and improvement of waveforms in several ways (not only peak-to-peak times and amplitudes but waveform variance, peak sharpness). We further discuss about the possibility to build models using stochastic inversion methods. Finally, we establish preliminary 3D joint models of V_S and Q for the western tip of the Pacific LLSVP.

Keywords: Waveform inversion, lowermost mantle



Correction of ScS–S travel times for 3D mantle structure to reveal shear wave azimuthal anisotropy in the lower mantle

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ScS–S differential travel times have contributed to reveal heterogeneity in the lower mantle. However, azimuthal anisotropy has not been fully considered probably due to insufficient azimuthal coverage. Recent increase of large scale seismic arrays and networks improves the coverage. Here we collected the seismograms from NECESSArray (Northeastern China), F-net (Japan), INDEPTH (Tibet), a seismic network in Thailand, whose ScS bounce points are located beneath Philippine with various azimuths.
Observed ScS–S differential travel time residuals with respect to PREM show a large scattering with a standard deviation of about 2.6 s and significant apparent azimuthal variation. When a cos 2*a* (*a* is a propagation azimuth of the seismic ray) curve is fitted by least squares, we find that the fastest azimuth is about 103° measured from the north in clockwise and the amplitude of the azimuthal variation is about ± 1.4 s. However, it is quite difficult to recognize that the azimuthal variation truly reflects the anisotropy in the lower mantle due to the large scatter of the travel time residuals.
To reduce the scattering of the data, we corrected for 3D mantle S-wave velocity structure models (e.g., S16U6L8, SB4L18, SH18CEX, S40RTS, SEMUCB-WM1). Unfortunately, the large scattering is not fully improved by using any models probably due to a poor resolution in the upper and uppermost lower mantle. However, if we use the 3D P-wave velocity model GAP-P4 (Obayashi et al., 2013) with an assumption of dlnVs/dlnVp=1.7, the scattering is significantly reduced (the standard deviation is about 1.3 s). After this mantle correction, the amplitude of the cos 2*a* function becomes ±0.4 s. However, the fastest direction is about 105°, which is almost same as in the case of the original data.

Keywords: lower mantle, anisotropy

Ab initio anharmonic lattice dynamics calculation for Fe-bearing lower mantle minerals

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Determination of lattice thermal conductivity (κ_{lat}) of lower mantle minerals is key to understanding the dynamics of the Earth's interior. Although it was impractical in the deep Earth pressure (*P*) and temperature (*T*) condition for a long time, recent experimental and computational developments have been extending the accessible *P* and *T* ranges. We recently succeeded in developing an *ab initio* technique to calculate κ_{lat} at any *P* and *T* condition based on the density-functional theory (DFT) combined with anharmonic lattice dynamics theory. The technique was then applied to major end-members of lower mantle minerals, $MgSiO_3$ bridgmanite (Dekura,Tsuchiya,Tsuchiya,2013,PRL) and MgO periclase (Dekura,Tsuchiya,2017,under review). Next we extend our technique to more realistic Fe-bearing minerals in conjunction with the internally consistent LSDA+*U* technique (Wang,Tsuchiya,Hase,2015,Nature geoscience) to deal with such strongly-correlated systems. In this presentation, we introduce the current situation of our research on κ_{lat} .

Keywords: Lower mantle minerals, Lattice thermal conductivity , Computer simulation , Phonon-phonon interaction , Density-functional theory

Constraints on lowermost mantle structure from core-mantle boundary dynamic topography

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Mantle flow induces dynamic topography at the core-mantle boundary (CMB), with distribution and amplitude that depend on details of the flow. To assess whether CMB topography can bring constraints on the deep mantle structure, we calculate the CMB dynamic topography associated with different models of mantle convection, including thermo-chemical and purely thermal models. We investigate the influence of key controlling parameters, more specifically the thermal viscosity ratio ($\delta\eta_T$) and, for thermo-chemical models, the chemical density contrast ($\delta\rho_C$) and viscosity ratio ($\delta\eta_C$) between primordial and regular materials. In purely thermal models, plume clusters induce positive topography with an amplitude that decreases with increasing $\delta\eta_T$. In thermo-chemical models with $\delta\rho_C$ around 100 kg/m^3 or more, reservoirs of dense material induce depression in CMB topography, surrounded by a ridge of positive topography. The average depression depth and ridge height increase with increasing $\delta\rho_C$ and $\delta\eta_C$, but decrease with increasing $\delta\eta_T$. We find that for purely thermal models or thermo-chemical models with low $\delta\rho_C$, 90 kg/m^3 and less, the long-wavelength (spherical harmonic degrees up to $l = 4$) dynamic topography and shear-wave velocity anomalies predicted by thermo-chemical distributions anti-correlate. By contrast, for models with $\delta\rho_C$ 100 kg/m^3 and $\delta\eta_C > 1$, long-wavelength dynamic topography and shear-wave velocity anomalies correlate well. This potentially provides a test to infer the nature, thermal or thermo-chemical, of low shear-wave velocity provinces (LLVSP) observed by global tomographic images. The presence of post-perovskite (pPv), provided that the viscosity of this phase is similar to that of bridgmanite, does not alter these conclusions. If the viscosity of pPv is lower than that of bridgmanite by 2 or 3 orders of magnitude, however, more substantial changes may arise.

Keywords: Mantle convection, Core-mantle-boundary topography, Mantle structure

Waveform inversion for whole mantle 1-D S-velocity and Q structure beneath Central America and the Caribbean

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We simultaneously infer the 1-D S-velocity and anelastic (Q) structure in the whole mantle beneath Central America using waveform inversion. Our dataset consists of ~8000 transverse components recorded at USArray broadband stations from ~40 intermediate- and deep-focus events in South America. We use waveforms in time windows cut around the minor arc arrivals which include body-wave arrivals (e.g. Sn, sSn) as well as multiple reverberations at the core-mantle boundary (ScSn, sScSn). These data provide constraints on the difference in Q structure between the upper- and lower-mantle. We use the Born approximation to compute partial derivatives for 1-D shell perturbations at depth increments of 20 km in the whole mantle. Our model is parametrized in radial splines formed by linear combination of those 20 km-increment perturbations. Synthetic tests suggest that our dataset and method can simultaneously resolve the 1-D S-velocity and Q structure in the whole mantle. Knowledge of both the S-velocity and Q structure can help to provide constraints on the origin of the S-velocity anomalies, i.e., whether they are of thermal or chemical origin.

Keywords: Waveform inversion, Earth's mantle, Anelastic structure

Mantle dynamics of the Earth through time

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Since the initial discovery of the superplume in the central Pacific Ocean in ca. 1990, the role and driving force of plumes and superplumes has been discussed in the framework of plate and plume tectonics, and more specifically whether a sufficient thermal budget is given solely from the core. Here, it is considered insufficient. Instead, the more important factor for the thermal budget is TTG enriched in radiogenic elements such as U, K and Th in the D” layer and mantle transition zone at 410-660 km depth, formed along the subduction zone through plate tectonics. In particular, primordial continents (initial solidified magma ocean at 4.53 Ga) were removed from the surface of the Earth through tectonic erosion and are now concentrated in the core mantle boundary. The distribution of these primordial rocks has been revealed in association with the mantle dynamics documented in the surface geology of the modern Earth. Accumulated primordial continent during Hadean eon raised the temperature in the D” layer to create liquid core by melting outer solid core, and resulted in the generation of strong geomagnetism.

Keywords: presence of water, hydrous plume, superplume, Hadean primordial continent

Chemical exchange between core-forming metal and magma ocean in the early differentiating Earth

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The differentiation of the Earth into its metallic core and silicate mantle and crust was among the most profound events shaping the planet in its early history, and the geochemical consequences of this event remain today, recorded in the composition of minor and trace elements in the core and mantle. Inferences can be made on the nature of the physical and chemical aspects of planetary differentiation by experimentally investigating metal-silicate partitioning of these elements under the range of thermodynamic conditions that are appropriate to the core-forming event. We report metal silicate partitioning of several key elements at high pressure, high temperature conditions. The experiments were performed using laser heated diamond anvil cells, and the samples were recovered and analyzed using focused ion beam / high resolution electron microscopy (FIB/SEM). Heat producing elements such as uranium partition into the metallic melt at high P,T conditions to a higher degree than previously observed, but still only produce <2 TW of heat in the core 4.5 Gyr ago. Partitioning of tungsten, a moderately siderophile element, places additional constraints on the range of P,T conditions that best describe the trace element composition of the modern mantle. Light lithophile elements including magnesium can dissolve into a metallic core-forming melt at sufficiently high temperature, and their exsolution can contribute to buoyant energy release as the early core cooled. These observations contribute to models of the early thermal and chemical evolution of the Earth's deep interior.

Keywords: planetary differentiation, metal-silicate partitioning, experimental petrology

Light elements in the core based on elemental partitioning experiments between Fe-S melts and silicate magma

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The compositions of Earth's core are important research topics to understand the Earth's deep interior and evolution. Seismological observations provided density and sound velocity data of the Earth's interior. Comparing with experimental studies on density of Fe under the core conditions, the observed Earth's core densities are smaller than those of pure Fe. These results implied an existence of light elements in the core and the species and amount of light elements have remained still unknown.
The terrestrial magma ocean was formed in the early Earth. During the core separation from the magma ocean, elements are assumed to be partitioned between molten iron and silicates melts at the base of the magma ocean. Therefore, clarification of partitioning behavior of the Earth materials at high pressure and temperature is important for understanding characteristics of the Earth's core.
In this study, partitioning experiments between silicate (garnet) melts and metallic liquids (Fe-8wt%Sulfur) were conducted by using a diamond anvil cell combined with a fiber laser heating system. The experiments were carried out at the pressures between 52 and 76 GPa and the temperatures between 3140 and 5140 K. Recovered samples were cut and polished by FIB. Chemical analyses were performed using FE-SEM/EDS and metal/silicate partitioning coefficients (D_{Si}) and exchange partitioning coefficients (K_D) of silicon were determined.
The results demonstrated a strong oxygen fugacity dependence of D_{Si} to be negative and a positive temperature dependency of K_{DSi}. In this study, Si was less partitioned in the metal phase than previous studies of partitioning using Sulfur-free iron as a metal, suggesting less Si in the metal phase which S is included in. The present result suggests that the existence of S in the metal phase might affect the partitioning behavior of Si during the magma ocean. Assuming the values of Si content in the core and oxygen fugacity from geochemical constraints, 2.3~6.1wt% of S in the core can explain the partition between the core and mantle at 4200 K. When the estimated temperature of the bottom of the magma ocean was lower, the abundance of S would be smaller.

Keywords: Light elements, core, mantle

Reconciling Magma-Ocean Crystallization Models with the present-day Structure of the Earth’ s mantle

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Terrestrial planets are thought to experience episode(s) of large-scale melting early in their history. Studying the crystallization and fractionation of terrestrial magma oceans (MO) can provide constraints for the initial condition and thermochemical evolution of solid-state mantle convection. MO fractionation leads to unstable stratification within the cumulate layer due to progressive iron enrichment upwards, but the effects of incremental cumulate overturn that may occur during MO crystallization remain to be quantitatively explored. Here, we use geodynamic models with a moving-boundary approach to study convection and mixing within the growing cumulate layer, and thereafter within the resulting, fully-crystallized mantle. For fractional crystallization, pronounced stratification leads to incremental cumulate overturns during MO freezing and hence efficient cumulate mixing, except for the most iron-enriched final-stage cumulates, which remain unmixed and persist for billions of years near the base of the mantle. Less extreme crystallization scenarios can lead to somewhat more subtle stratification and more pervasive mixing. However, MO cooling models indicate that fractional crystallization should have been dominant at least during the slow final stages of MO freezing. The long-term preservation of strongly iron-enriched cumulates at the base of the Earth’ s mantle as predicted by MO fractional-crystallization models is inconsistent with seismic constraints. Based on scaling relationships, however, we infer that final-stage Fe-rich MO cumulates should thermally equilibrate during overturn and sinking, and hence undergo melting and reaction with the host rock. The resulting moderately iron-enriched hybrid rock assemblages should be preserved in the deep mantle through the present day. In contrast to the original strongly-enriched final-stage cumulates, moderately iron-enriched hybrid rock assemblages can much better reconcile the physical properties of the large low shear-wave velocity provinces in the present-day lower mantle. Thus, we reveal Hadean melting and rock-reaction processes by integrating simplified MO crystallization models with the present-day seismic snapshot.

Keywords: Magma Ocean, Large-Low Shear Wave Velocity Province, Lower Mantle

The sound velocity measurements of FeO at high pressure and temperature: Implications for the low velocity anomaly around the core-mantle boundary

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Wustite, $Fe_{1-x}O$, is one of the most important oxides in the Earth because it is an endmember of ferropericlase, (Mg,Fe)O, which is one of main phases in the Earth's lower mantle. In addition, it is also significant for understanding the composition of planetary cores. Seismological data reveal physical properties of the Earth's interior, such as velocities (V_P, V_S) and density. Although the seismological velocity profile of the Earth's interior can provide us an important knowledge about structure and chemical compositions, there are few experimental reports about the sound velocity of Fe-light elements system including FeO at high pressure and temperature.
Here, we report V_P of FeO up to 86 GPa and 2500 K based on a combination of the laser-heated diamond anvil cell and inelastic X-ray scattering measurements at BL35XU of SPring-8. In this experimental condition, FeO shows B1 phase and rhombohedral one, which has a distorted B1 structure. We find difference in velocity between them.
Based on our results, we could obtain the Birch's law for FeO. This relation is extrapolated to the inner core condition. Combining with Birch's law of Fe, we compared the density-velocity linear relation of Fe-FeO system to PREM. This relation is inconsistent with the seismic data of the inner core. In other words, oxygen is not suitable in the inner core as a major light element.
Seismological observations indicate a chemical heterogeneity in the deep lower mantle, and FeO can play an important role to cause the heterogeneity. Several processes have been proposed to account for formation of the enriched FeO region around the core-mantle boundary.
We can find that the velocity of FeO is smaller than that of lower mantle minerals. That is, an addition of FeO to the lower mantle can make a low velocity anomaly, such as ULVZs (ultra-low velocity zones).

Keywords: FeO, Sound velocity, Density, Inelastic X-ray scattering, X-ray diffraction

Can the Earth's core be the source of primordial noble gases in the mantle?

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It has been suggested a number of times that the Earth's core could be the source of primordial noble gases (He, Ne, Ar, etc) observed in OIBs. The core is an attractive option for storing noble gases since it has remained mostly isolated from the convecting mantle since its formation 4.5 Ga. This view is supported by experiments show that He partitioning into Fe during core formation at elevated pressures (>10 GPa) is higher than previously thought. However, even if the core does contain primordial noble gases, there has to be a mechanism for incorportating them into OIBs. Small amounts of background degassing from the core into the mantle does not work since the noble gases will simply mix into the convecting mantle and the primordial signal will appear to be the same in both OIBs and MORBs.

We propose an alternative model whereby noble gases diffuse from the core into the base of the large low shear velocity provinces (LLSVPs), where they are stored and concentrated until sampled by plumes. To assess the viability of this model, we have determined the diffusion coefficients of He, Ne and Ar in lower mantle minerals by first-principles methods. We show that diffusion of these noble gases is sufficiently fast that they can concentrate into LLSVPs. However, diffusion is not fast enough to concentrate noble gases throughout LLSVPs and some sort of mixing within LLSVPs is needed. Assuming that LLSVPs are internally convecting, and assuming a range of reasonable mixing times for LLSVPs, we show that LLSVPs can act as a staging post for noble gases and allow them to build up in concentration over time. If LLSVPs are then periodically sampled by plumes, this provides an attractive method for sampling primordial noble gases originally residing in the core.

Keywords: Core, Mantle, Noble gases, Diffusion, Ab initio, First principles

Light element isotope fractionation processes in the deep Earth

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Partitioning of light elements and the distribution of isotopes between silicates in the mantle and metallic melts in the core during the early Earth differentiation and accretion process have governed the present day elemental and isotopic composition of the bulk silicate Earth. However, little is known till date about the factors that controll these processes in the deep Earth, especially in the core-mantle boundary, since we are unable to gather informaion from natural samples and yet to clearly reproduce the equillibrium conditions at high-pressure and high-temperature experiments. Especially, the role of light elements in the melting phase relations of mantle rocks, metal-silicate partitioning, and mass transfer between core and mantle are key in understanding the processes going on in deep Earth. Stable isotopic compositon is widely and efficiently used tool to understand the mobility of light elements in the deep Earth environments. Here I present a review of experimental determination of partitioning of light element isotopes at high-pressure and high-temperature conditions, in systems analogous to magma ocean environment where aggregation of core has happened and in the mantle conditions where recycling occurred thereafter.

A review of the previous experimental studies in the Fe-C and Mg-Si-C-O systems suggest that large carbon isotope fractionation occur between graphite/diamond and iron carbide melt. The results indicate that the iron carbide melt will preferentially gather ^{12}C than ^{13}C, and has a strong temperature dependence. Factionation is also observed between graphite/diamond and carbonate melt at temperatures and pressures corresponding to upper mantle conditions. The pressure dependence on carbon isotope fractionation is also being tested at higher pressure conditions. Preliminary results indicate that carbon isotopes also fractionate at high pressures corresponding to the deep Earth. Recent results in the sulfur, nitorgen and hydrogen sytem are consistent with the carbon-bearing system, that lighter isotopes generally fractionate to the metallic melt and heavier isotopes to the silicate melt.

In order to understand the factionation process in detail, it is essential to have accurate measurement of isotopic composition for the run products at high-pressures. The difficulty arises from the smaller volume of samples, separation of phases and confirmation of equilibration between the phases. Ongoing studies on microvolume isotope measurements using laser ablation and curie point pyrolyser gave encouraging results with good accuracy.

It is anticipated that the combined high-pressure and high-temperature dependent fractionation of light element isotopes in the deep Earth is an effective mechanism that can create a “lighter core” with large scale differences in the distribution of the isotopes between the metallic core and bulk silicate Earth during the accretion and differentiation of early Earth. Our findings also have implications on the light element cycling at the core-mantle interface.

Keywords: Isotope fractionation, Deep Earth, Metallic melt-silicate fractionation

Effects of Fe and Al incorporations on $MgSiO_3$ postperovskite phase boundary

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$MgSiO_3$ bridgmanite (Br) will undergoes a post-perovskite (PPv) phase transition[1,2,3] in the pressure (*P*) and temperature (*T*) conditions corresponding to the Earth's D" layer. Therefore, The phase change is recognized as the key for understanding the seismological observations in the D" layer. However, to date, it is still a challenging subject to determine the phase transition boundary preciously in the geophysically relevant Fe and Al-bearing compositions. Based on the first-principles methods combined with the internally consistent LSDA+*U* method and the lattice dynamics approach, the high-*P,T* thermodynamics of the $MgSiO_3$ phases are directly calculated with incorporation of 6.25 mol% of Fe^{2+}, $Fe^{3+}Fe^{3+}$, $Fe^{3+}Al^{3+}$, and $Al^{3+}Al^{3+}$ [4,5]. Using calculated free energies, we determine the PPv phase boundaries for Fe and Al-bearing compositions. Our results show that at 2500 K, incorporations of $Fe^{3+}Fe^{3+}$ and $Fe^{3+}Al^{3+}$ span coexisting domains between Br and PPv significantly with lowering the transition pressure, in contrast to the Fe^{2+} and $Al^{3+}Al^{3+}$-bearing cases.

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Keywords: First-principles method, internally consistent LSDA+U, MgSiO3, postperovskite

Experimental study on chemical interaction at the core-mantle boundary

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The core-mantle boundary (CMB) is the biggest physicochemical discontinuity in the Earth’s interior. Abundance of siderophile elements in the Earth’s mantle is much higher than that predicted from the partitioning study at low pressure. Chemical interaction across the CMB after core formation is one of candidates to realize the observed geochemical affinity as well as late veneer hypothesis. Hayden and Watson (2007) 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 based on grain-boundary diffusion of siderophile elements through polycrystalline MgO. On the other hand, enrichment of iron may occur at the bottom of the mantle, leading to low seismic-wave velocities and high electrical conductivity. Otsuka and Karato (2012) suggested that iron-rich melt could be transported 50 to 100 kilometres away from the core–mantle boundary by a morphological instability, providing an explanation for the iron-rich regions in the mantle. Thus there are potential fast pathways for chemical communication at the CMB. However, the dominant lower mantle mineral is not periclase but silicate minerals such as bridgmanite. In this study, validity of these processes in bridgmanite or post spinel experimentally investigated.
A study on the metal infiltration to bridgmanite, postspinel and ferropericlase was also performed using a Kawai-type multianvil press at 25 GPa and temperatures of 1600-2000 °C. Although significant penetration of metallic phase through the grain boundary was observed in only ferropericlase aggregates, iron alloy penetration to bridgmanite and postspinel was not observed. This result indicates that capillary force and morphological instability to enrichment does not contribute to the enrichment of iron and siderophile elements in the Earth’s silicate mantle.
A study on the grain boundary diffusion of siderophile elements (W and Re) in bridgmanite and postspinel was performed using a Kawai-type multianvil press at 25 GPa and above 1600 °C. The grain boundary diffusion of W in post spinel is faster than that in bridgmanite, and is only effective under highly oxidized condition. Such oxidized state at the core-mantle region is realized by accumulation of the sinking slab. Although the core-mantle interaction after the core formation can change W isotope in the mantle through the convection, it would be limited.

Keywords: core-mantle boundary, infiltration, diffusion

Thermo-chemical evolution of Earth' s core in a coupled core-mantle evolution –Stably stratification or light element precipitation

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Two possible resources for thermo-chemical convection of Earth' s core occurred in the core-mantle boundary region have been proposed, which are dissolution of light element working for the negative feedback of cooling rate and age of the inner core [O' Rourke and Stevenson, 2016; Badro et al., 2016] and diffusive processes for reactant caused by core-mantle chemical reaction [Buffett and Seagle, 2010; Gubbins and Davies, 2012]. In this investigation, we make an assessment for those two mechanisms in a coupled core-mantle evolution model based on numerical mantle convection simulations plus core energy balance model based on formulations provided from Labrosse [2015] as a function of melting temperature of iron alloy, initial CMB temperature and thermal conductivity of Earth' s core such that several constraints of evolution of Earth' s core can be satisfied (Continuous generation of magnetic field for instance). With diffusive processes caused by core-mantel chemical reactions, the initial CMB temperature should not be quite high plus high CMB heat flow because the heat transfer system is dominated by the isentropic effects. Whereas, with dissolution of light elements, the initial CMB temperature should not be quite high either but the heat flow across the CMB would be quite low. On the thermal conductivity of Earth' s core, for the best-fit parameter set found in both processes, it would not be quite high value that would not be consistent with thermal conductivity measurements based on electrical resistivity [Gomi et al., 2013; Ohta et al., 2016]. Further discussions will be done in the presentation.

Keywords: thermo-chemical evolution, core-mantle chemical coupling

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

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Silicate earth is depleted in potassium compared with chondrites [Wasserburg et al., 1964, Science]. Barely varying ratios of potassium isotope in chondrite, lunar and earth samples suggesting evaporation cannot be responsible for the missing of potassium [Humayun and Clayton, 1995, GCA]. The finding of a change in electronic structure of potassium from alkaline- to transition metal-like at high pressure highlighted the possibility of its incorporation into the core [Parker, 1996, Science]. If potassium is present, even ~ppm, the radiogenic heat produced by ^{40}K could be an important energy source for geodynamics [Labrosse, 2001, EPSL]. The potassium content in the core is determined by its partitioning behavior between silicate and metal system, which could be affected by many factors such as temperature, pressure, compositions of the metal (the type and content of light elements) and silicate systems (nbo/t: the ratio of non-bridging oxygen to tetrahedral cations) [Bouhifd etal., 2007, EPSL; Muthy etal., 2002, Nature]. However, previous experimental studies provided contradictory results of potassium incorporation into Fe-alloys, leaving its concentration in the core uncertain.
Ab-initio free energy simulations based on molecular dynamics conbined with thermodynamics integration[Taniuchi, 2014] are performed to investigate whether and how much potassium can enter the metal system. Potassium partition coefficient(D_k=$Kwt\%_{metal}/Kwt\%_{silicate}$) is determined as a function of pressure, temperature and composition by calculating the Gibbs free energy changes of its exchange reactions in different conditions. Helmholtz free energy is estimated with "thermodynamic integration" by computing the difference between two systems with different potential energy functions[Kirkwood, JCP, 1990].
Calculations performed from 3000 K to 5000 K suggest that temperature has no distinct effect in potassium incorporation into Fe-alloys. Results of D_k obtained from 20 GPa to 135 GPa at constant temperature and composition reveal that potassium partitioning behavior has a negligible pressure dependence. Besides, the potassium partial density of states (pDOS) shows its electronic structure remains to be alkaline metallic even at 135 GPa. Simulations show a limited effect of Al concentration in silicate composition to potassium solubility into metal system.
Influences of the light elements (O and S) proposed to be responsible for the density deficits of the core to potassium partitioning are also investigated in this study. Potassium solubility seems unchanged when the S content of the metal system increases. Simulations with oxygen free metal composition suggest that potassium will completely sequester into silicate system. However, with the presence of oxygen in metal, potassium will start its incorporation into metal system. Our results suggest that effects of temperature, pressure, silicate composition and S content are insignificant, while oxygen controls potassium partitioning between silicate and metal system.

Keywords: Ab initio, Potassium, Earth's core

An Introduction to Using Neutrinos for Understanding Geodynamics

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Neutrinos from radioactive decays deep in the earth reveal the location of the heating that drives most geodynamics. We will present a sketch of the physics and of the neutrino production, largely from U and Th decay, the neutrino propagation and detection. Only two experiments so far have detected these "geoneutrinos" coming out of the earth, but there are long term plans to study the distribution of the sources. We will discuss current plans and these prospects.

Keywords: neutrino, Uranium, Thorium, Mantle Heating

U and Th abundances of crustal rocks in the Japan Arc: Towards better constraints on the geoneutrino flux from the mantle

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It has been widely assumed that the bulk silicate Earth (BSE) has chondritic relative abundances of refractory-lithophile elements. The validity of this long-standing paradigm can be potentially addressed using electron antineutrinos produced within the Earth, the so-called geoneutrinos. The geoneutrinos have been measured with two liquid scintillator detectors at KamLAND in Japan and Borexino in Italy. Once the crustal contribution to the measured total geoneutrino fluxes are well established by determining U and Th distributions around the detectors, the data allow us to determine the absolute U and Th abundances in the mantle with sufficient precision to evaluate the chondritic BSE model, in particular whether highly incompatible refractory-lithophile elements are significantly (~50%) depleted as inferred from an impact-erosion model. Yet, the U and Th distributions in the Japan Arc crust, in particular deep crust, are still poorly constrained.
For better understanding of U-Th distributions in the Japan Arc, we have compiled previously reported U-Th abundance data for crustal rocks in the Japan Arc and further conducted petrology and geochemistry on mafic-ultramafic xenoliths from Oki Dogo. The equilibrium temperatures of two-pyroxenes indicate their derivation from the depth of 25-35 km. By combining the compiled data and newly obtained data, we found that the relative abundances of U and Th of the Japanese deep crust are distinctive from those of the deep crust in cratonic regions. The discrepancy may reflect that the Japan Arc crust was formed under more oxidized conditions as compared to the cratonic deep crust. In the presentation, we will further discuss about a methodology for combining these rock data with seismic data to estimate the U and Th distributions within the deep crust over the wide area.

Keywords: neutrino, chondritic Earth, bulk silicate Earth

Application of nano-polycrystalline diamond to novel ultrahigh-pressure technology

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Nano-polycrystalline diamond (NPD) developed at GRC, Ehime Univ., is known to be harder than conventional sintered polycrystalline diamond (SD) and single crystal diamond, and is potentially important as anvil material for various types of high-pressure apparatus. Some successful applications of NPD to both diamond anvil cell (DAC) and Kawai-type multianvil apparatus (KMA) have been achieved, including higher pressure generation in these apparatus and some mineral physics applications in deep Earth sciences. For DAC, the following progress has been made in the last couple of years; generation of pressures exceeding 500 GPa in a double-stage DAC (Sakai, Yagi, et al.), invention of rotational DAC for rheological studies in Mbar regime (Nomura, Azuma et al.), and successful applications to large DAC for high-pressure neutron (Komatsu et al.), X-ray absorption (Ishimatsu et al.; Pascarelli et al.) and X-ray Raman (Fukui et al.) studies. Some attempts have also been made using NPD anvils for Mbar generation (Kunimoto & Irifune) in KMA, demonstrating its potential importance as the third-generation anvil material, after tungsten carbide and sintered polycrystalline diamond. The current status of applications of NPD in these techniques will be reviewed with some future perspectives.

Keywords: nano-polycrystalline diamond, high pressure technology, high pressure and high temperature experiment, mineral physics, ultrahigh-pressure generation

Newly developed internal-resistive heated diamond-anvil cell with boron-doped diamond: Toward deep lower-mantle petrology

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The development of the diamond-anvil cell (DAC) technique combined with laser heating enabled easy access to the entire lower-mantle pressure and temperature regime at laboratory. However, a number of major issues remain highly controversial, including the location of the post-perovskite phase boundary, solid–liquid iron partitioning, Fe–Mg partitioning among mantle minerals, and melting temperatures of mantle rocks. Although the discrepancies between previous experimental studies on these issues have likely arisen from multiple sources, they could more or less have originated from possible problems in the laser-heated diamond-anvil cell (LHDAC) experiment: inherited temperature gradient in the heated area and temperature fluctuation during heating.

In this study, we developed an internal-resistive heated diamond-anvil cell with a new resistance heater—boron-doped diamond (BDD)—along with an optimized design of the cell assembly, including a composite gasket. We find this heating technique to demonstrate clear advantages over the conventional LHDAC technique, such as (1) ultrahigh temperature generation (>3500 K), (2) long-term stability (>1 h at 2500 K), (3) uniform radial temperature distribution (±35 K at 2500 K across a 40-μm area), (4) chemical inertness (no boron diffusion into the silicate sample), and (5) weak X-ray diffraction intensity from the BDD heater. This newly developed IHDAC with a BDD heater can determine the phase diagrams of silicate/oxide materials with high precision and can be used in deep lower-mantle petrology.

Keywords: DAC, lower mantle

Constrains on light elements in Earth's core via sound velocity measurements of liquid Fe alloys

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The Earth's core consists mainly of iron alloying with some lighter elements. The nature of the lighter elements is the key to understand the building blocks of the bulk Earth, the core formation process, and the chemical and thermal history of the core. Seismological observations give fundamental information of the physical properties of the core. The density and sound velocity of liquid outer core based on seismological observations are about 10 % less and about 4 % faster than pure Fe under the corresponding pressure and temperature conditions (Anderson and Ahrens, 1994 JGR). The effects of possible lighter elements on those properties of liquid iron are therefore important to constrain the core composition. We have measured the sound wave velocity of liquid Fe alloying with several candidates of the light elements such as carbon (C), silicon (Si), and sulfur (S) to 50–70 GPa, using the inelastic X-ray scattering method combined with a laser-heated diamond anvil cell technique. Based on obtained sound velocity data we constructed equations of state for liquid Fe-C (Nakajima et al., 2015 Nat.Commun.), Fe-Ni-S (Kawaguchi et al., submitted), and Fe-Si (Nakajima et al., in prep.). We found that both carbon and silicon increase significantly the P-wave velocity of liquid Fe, whereas sulfur has negligibly small effect. The abundances of C and Si in liquid Fe are only less than 1 wt.% and 2 wt.%, respectively, so as to explain the P-wave velocity of the outer core. However, such a small amount of C and Si cannot take into account for the 10 % core density deficit. On the other hands, the presence of 5.8–7.5 wt.% S can mutually explain seismological sound velocity and density of the outer core. Therefore, sulfur can be the most abundant among the light elements in the outer core.

Keywords: Light elements in the Earth's core, Liquid outer core, Sound velocity, High pressure experiments

Effects of light-element impurities on transport properties of liquid Fe-Ni alloy at Earth's core conditions

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It is widely believed that the Earth's outer core consists of liqud iron (or liquid-nickel alloy) with light element impurities. Therefore, electrical and thermal conductivities of liquid iron-nickel alloys are important to understand magnetic and thermal behaviors of Earth.
Several experimental studies investigated the electrical conductivity or resistivity for iron under high pressure (Keeler, 1969 : Bi ,2002 : Ohta, 2016). Also, by using first principles calculations, electrical conductivity for liquid iron and mixtures with silicon and oxygen under high pressure has been investigated. (Pozzo, 2012, 2013 : de Koker, 2012)
Although first principles studies for liquid iron-oxygen and -silicon mixtures have been conducted so far, mixtures with other light elements such as hydrogen and carbon have not been investigated yet. Under this circumstance, in this study, we perform ab initio molecular dynamics simulations for liquid Fe-Ni alloy with H, C, O, S and Si. We calculate electronic and thermal conductivities at Earth's core conditions with using Kubo-Greenwood formulation. By comparing against results of pure system, we discuss effects of light element impurities on transport properties of liquid Fe-Ni alloy.

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Keywords: Ab initio molecular dynamics simulation, Transport properties, Liquid Fe-Ni mixtures

Eddy viscosity of core flow estimated from geomagnetic field data

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The molecular diffusivities of the Earth’s core are very small, so that large-scale fields are diffused much more effectively by small-scale turbulence than by molecular processes. Therefore, geodynamo simulations have replaced the molecular diffusivities by the eddy diffusivities, of which values should appropriately adopted. It should be noted, however, that the eddy viscous diffusion, or the eddy viscosity, is not a property of the core fluid but of the core flow. Hence estimating the eddy viscosity from core flow models is very significant.

Fluid motions near the core-mantle boundary (CMB) cause the secular variation of the geomagnetic field observed above the Earth’s surface. As an inverse problem, core flows can be inferred from geomagnetic field data, or spatial distributions and temporal variations of the geomagnetic field. Most of core surface flows are estimated by use of the diffusionless induction equation; that is, the frozen-flux approximation (Roberts and Scott, 1965) is adopted. The magnetic diffusion term in the induction equation can be neglected for a large-scale magnetic field with time scales much shorter than magnetic diffusion time. At the CMB, however, there exists a viscous boundary layer, where the magnetic diffusion cannot be neglected in temporal variations of geomagnetic field. Hence, Matsushima (2015) has devised a new approach to estimation of core surface flow; that is, the magnetic diffusion is explicitly incorporated within the boundary layer, whereas it is neglected below the boundary layer. Furthermore, core flows are assumed to obey a geostrophic balance or a magnetostrophic balance below the boundary layer.

To investigate relation between core surface flow and core-mantle coupling, a geomagnetic field model, COV-OBS.x1 (Gillet et al., 2015), from 1840 to 2015, has been used to derive a core surface flow model, which would contain any information on phenomena in relation with core-mantle coupling, such as the length-of-day (LOD), and spin-up/spin-down of core flows. A possible correlation between time series of the LOD and the axial component of global vorticity suggests any core-mantle coupling. The phase shift leading to the maximum correlation coefficient between the LOD and the axial vorticity is found to be about 18 years, from which the eddy viscosity can be estimated. Since other core-mantle coupling is not taken into account, such as electromagnetic coupling, the value could be a maximum one.

Keywords: eddy viscosity, core surface flow, secular variation, geomagnetic field

Seismological evidence for heterogeneous lowermost outer core (F-layer) of the Earth

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We present seismic evidence for heterogeneous structure in the layer directly above the inner core (F-layer), which suggests a localized concentration of light elements.

In this study, we examined the F-layer structure beneath Australia using core phases on vertical-component seismograms of Hi-net in Japan for earthquakes near the South Sandwich Islands. We analyzed the waveforms using the method developed by Ohtaki and Kaneshima (2015). The method uses two observations that are particularly sensitive to the layer structure and are relatively insensitive to the structure of the other parts of the Earth. The first observation is the frequency dispersion in P-waves that graze or are diffracted at the inner core boundary (PKPbc); the second observation is differential travel times between the P-waves reflected from the inner core boundary (PKiKP) and those that turn above the boundary (PKPbc). The dispersion is sensitive to the velocity gradient just above the inner core boundary, but insensitive to the velocity values in the F-layer. The differential travel time is sensitive to the velocity values between the PKPbc turning depth and the inner core boundary, but insensitive to the velocity gradient in the F-layer. The observed PKPbc dispersion requires nearly constant velocity on the inner core boundary in this region. The observed CD-BC necessitates that cumulative velocity in the F-layer is close to that of PREM. The velocity model which satisfies both the observations has nearly constant and smaller velocities than PREM on the boundary and faster ones above.

This feature is in contrast to the F-layer velocity model for the region beneath the northeast Pacific (FVW) (Ohtaki and Kaneshima, 2015), which has a somewhat gentler velocity gradient and smaller velocities than PREM in the whole F-layer. Velocity in the liquid core has a little dependence on temperature (Ichikawa et al., 2014). Thus the difference in velocities between the two regions is ascribed to the relative abundance of light elements. The reduced velocity gradient on the inner core boundary beneath Australia signifies chemically unmixed materials there. The higher velocities than FVW and also PREM indicate a localized higher concentration of light elements in the F-layer.

Keywords: lowermost outer core (F-layer), Seismic velocity structure, localized light-element enrichment

Generation of MAC Waves by Convection in Earth's Core

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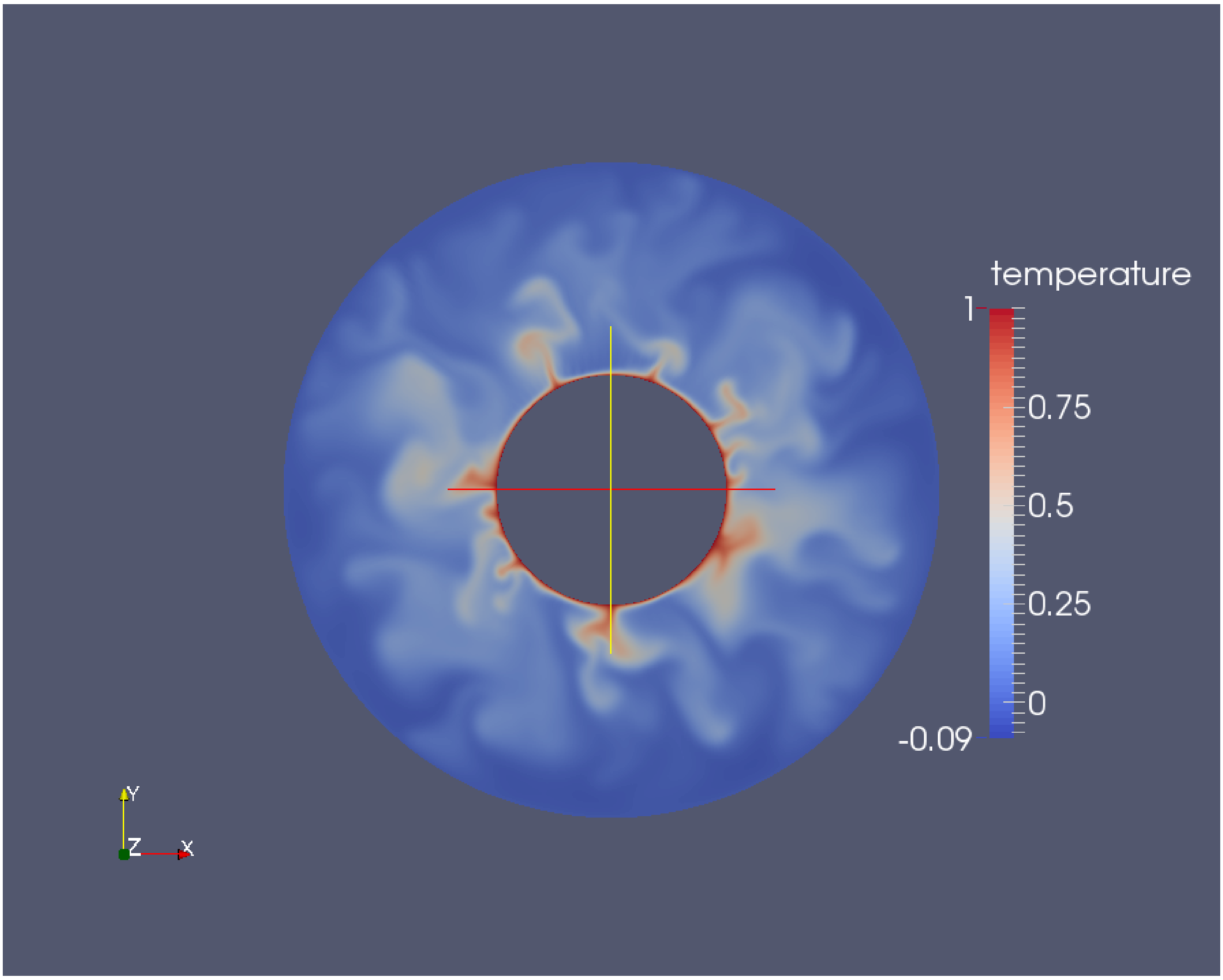
Convection in Earth’ s core generates long-period magnetic waves when the top of the core is thermally stratified. These waves can be detected in magnetic-field observations and the wave properties are used to recover quantitative estimates for the stratification. A description of the waves and wave generation is similar to the problem of acoustic-wave generation in stars, although the largest source of excitation is probably due to buoyant parcels rising into the stratified layer. The influence of inertial and magnetic forces are expected to be much smaller. Numerical dynamo models suggest that convection preferentially excites symmetric waves about the equator, which is compatible with the observations. Estimates of the strength and thickness of thermal stratification imposes tight constraints on the thermal evolution of the core.

Keywords: Secular Variation, Thermal Evolution, Dynamics of Planetary Interiors



Penetration of compositional convection into the upper stably stratified layer in the Earth's outer core

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It is suggested from high-pressure experiments and first principle calculations that the values of thermal conductivity under conditions of planetary cores are larger than those considered so far (Pozzo et al. 2012, 2014; Gomi et al. 2013). By using 1-dimensional thermal balance models with the updated values of thermal conductivity, generation and existence of stably stratified layer in the Earth's outer core is discussed (Gomi et al. 2013, Labrosse 2015). Their results show that a stable layer whose thickness of O(1000km) could be produced when the heat flux across the core-mantle boundary (CMB) is small.

They assume that the region with negative heat flux is stably stratified. This assumption seems to be appropriate when convection is driven only by thermal effects, however, it is not correct for compositional convection, which is driven by buoyancy of light elements released at the inner core boundary through freezing and growth of the inner core. When compositional convection is sufficiently vigorous enough to overcome thermally stable stratification, it would mix up the stable layer and would make it neutral.

We propose to use radial distribution of power induced by thermal and compositional buyancy (rate of kinetic energy production) as measure of occurence of thermal and compositional convection. The power consists of the terms proportional to heat flux and compositional flux. The region with positive power is considered that convection is active there because kinetic energy can be produced by buoyancy force. On the other hand, in the region with negative power convection is supressed and stably stratified layer may be produced.

We constructed a 1-dimensional thermal and compositional balance model of the Earth's core, and calculated radial distributions of power for various values of CMB heat flux Q_{cmb}. When $Q_{cmb} > 9.3$ TW, it is suggested that convection occurs in the whole outer core, however, a stable layer with O(100km) thickness could be produced below CMB when $Q_{cmb} < 4.8$ TW.

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Keywords: Thermal conductivity, heat flux, compositional flux, production of kinetic energy

Effects of a thin stably stratified layer below the core mantle boundary on the dynamo action in the core

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By seismic and geomagnetic field observations, a stably stratified layer below the core-mantle boundary (CMB) has been detected. Chemical or thermal origin of the stable stratification is suggested (Helffrich and Kaneshima, 2010; Buffett and Seagle, 2010; Pozzo et al. 2012; Ohta et al. 2016). The geomagnetic field is generated by thermally and chemically driven convection, that is, dynamo action. Assuming the turbulent diffusivity in the core, the co-density has been preferred modeling thermo-chemically driven dynamo. However, the origin of stable stratification cannot be distinguished with the co-density approach. Therefore, thermal and compositional buoyancy must be treated separately. In this study effects of a stable layer of either origin below the CMB are examined, adopting thermochemical double diffusive convection. We have found in a suite of runs that the morphology of dynamos is strongly affected by a thick stably stratified layer (~400 km according to seismic observations) regardless its origin. Then, we focus on the effects of a stable layer, of which thickness is about 150 km close to that detected by geomagnetic observations. We will show results of our dynamo modeling with a thin stably stratified layer of either origin, and discuss its effects on the observed magnetic field and implications for the origin of the stable layer.

Keywords: stably stratified layer, dynamo, double diffusive convection

Crystallization of SiO_2 from the outer core: A possible means of stratification

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The PREM seismic wavespeed model in the outermost core is in near-uniform self-compression. Slight deviations from self-compression constitute evidence for a radial compositional gradient there, and possibly for stable stratification. Based on melting experiments in the Fe-Si-O system in the diamond anvil at outer core pressures and temperatures that show crystallization of SiO_2, we developed a thermodynamic model of SiO_2 saturation in liquid Fe at high pressure and temperature conditions suitable for modeling magma ocean and outer core processes. Conditions in a magma ocean between 30-50 GPa allow for significant incorporation of Si + O in the metal, which, after the core evolves to its present temperature (3500-4500 K at the CMB), leads to exsolution of SiO_2. Using a transition-element hard-sphere model for seismic wavespeeds, we show that the continuous crystallization of SiO_2 at the top of the core produces denser, iron-enriched liquid that mixes downward into the core. The net effects of the density and mean atomic weight change in the mixed region leads to reduced wavespeeds in the top of the outer core that require only a small change in concentration of the SiO_2 component in the liquid, about 0.15 wt%.

Keywords: core, stratification, SiO2 saturation, seismology

Lateral temperature variation through ICB to CMB in geodynamo simulations

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Resent seismic observations suggests that inner core has a seismic anisotropy. This seismic anisotropy suggests aspherical growth of the inner core, and slow viscous deformation of the inner core and latent heat distribution by flow motion are expected to be the origin of the aspherical growth of the inner core. To explain inner core anisotropy and aspherical growth of the inner core, a number of dynamo simulations has been performed with prescribed boundary conditions at ICB to take into account the inner core heterogeneity. To represent thermal structure of the ICB self-consistently, geodynamo simulations are performed with considering the heat equation throughout the inner and outer core.

In the present model, we assume that the inner core is electrically insulated and co-rotate with mantle to compare the results with the simulation without considering the inner core. To compare simulations with the boundary condition at ICB, we assume no heat sources in the outer core. For the thermal boundary condition at CMB, a homogeneous heat flux is applied. To simplify the model, we assume that the same thermal diffusivity for the inner core and outer core. To sustain the average temperature in the outer core, a constant heat source is introduced in the inner core. We compare the simulations results with the simulations results using fixed heat flux or temperature condition at ICB. We performed four cases of the simulations with changing Rayleigh number to investigate dependency of the thermal structure on the Rayleigh number.

The results show that the time averaged thermal structure at ICB is likely to the simulation results with homogeneous heat flux boundary conditions. The time averaged lateral temperature variation is approximately 26% of the average temperature difference between ICB and CMB, while lateral heat flux variation is only 6% of the average heat flux at the ICB. We also observe small scale temperature and heat flux variations; however, these components vary with time. In addition, the length scale of the heat flux variation is smaller than the temperature variation at ICB. Furthermore, There is small dependence of the Y_2^0 component of the temperature variation on the Rayleigh number. This lateral temperature variation also generate intense lateral variation at CMB. We observe that temperature inside of the tangent cylinder is higher than the other area. This variation increasing with the Rayleigh number, while the temperature variation is homogenized with increasing the Rayleigh number. This temperature variation at CMB is not observed in the simulations without magnetic field, and meridional circulation inside of the tangent cylinder in the dynamo case is stronger than the non-magnetic cases. we conclude that the Lorentz force near the ICB sustains the meridional circulation and lateral temperature variation at ICB and ICB.

Keywords: Geodynamo simulation, ICB, CMB

Has Earth’s Plate Tectonics Led to Rapid Core Cooling?

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Earth’s mantle and core are convecting planetary heat engines. The mantle convects to lose heat from secular cooling, internal radioactivity, and core heatflow across its base. Its convection generates plate tectonics, volcanism, and the loss of ~35 TW of mantle heat through Earth’s surface. The core convects to lose heat from secular cooling, small amounts of internal radioactivity, and the freezing-induced growth of a compositionally denser inner core. Until recently, the geodynamo was thought to be powered by ~4 TW of heatloss across the core-mantle boundary. More recent determinations of the outer core’s thermal conductivity (Pozzo et al., 2012; Gomi et al., 2013) would imply that >15 TW of power should conduct down its adiabat. Secular core cooling has been previously thought to be too slow for this, based on estimates for the Clapeyron Slope for high-pressure freezing of an idealized pure-iron core (cf. Nimmo, 2007).

The ~500-1000 kg m^{-3} seismically-inferred jump in density between the liquid outer core and solid inner core allows a direct estimate of the Clapeyron Slope for the outer core’s actual composition which contains ~0.08±0.02 lighter elements (S,Si,O,Al, H,…) mixed into a Fe-Ni alloy. A PREM-like 600 kg m^{-3} density jump yields a Clapeyron Slope for which there has been ~774K of core cooling during the freezing and growth of the inner core, cooling that has been releasing an average of ~21 TW of power during the past ~3 Ga. If so, core cooling could easily have powered Earth’s long-lived geodynamo. Another implication is that the present-day mantle is strongly ‘bottom-heated’, and diapiric mantle plumes should dominate deep mantle upwelling. This mode of core and mantle convection is consistent with slow, ~37.5K/Ga secular cooling of Earth’s mantle linked to more rapid secular cooling of the core (cf. Morgan, Rüpke, and White, Frontiers, 2016). Efficient plate subduction, hence plate tectonics, is a key ingredient for such rapid secular core cooling.

We also show how a more complete thermodynamic version of Birch’s accretional energy calculation predicts that accretion with FeNi-sinking-linked differentiation between an Earth-like mantle and core could naturally generate a core that, post-accretion, was both hotter than overlying mantle and ~1000K hotter than today.

Keywords: core heat loss, mantle convection, plate tectonics, subduction, accretion energetics

Iron-carbonate interaction in the lower mantle and at the core-mantle boundary

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The presence of carbonates in the deep Earth strongly depends on the oxygen fugacity, controlled by oxidation state of iron in minerals and melts. A large part of the lower mantle can be significantly reduced with detectable amount of Fe^0. Therefore, subducted carbonates would interact with Fe^0 dispersed in the ambient mantle. However, the mechanism of this interaction remains controversial. We investigated the $MgCO_3$–Fe^0 system at 70–145 GPa and 800–2600K using *in situ* X-ray diffraction in a diamond anvil cell. $MgCO_3$ crystals and Fe foil (99,9%) were used as the starting materials. Formation of wustite (FeO), ferropericlase $(Mg_{0.6}Fe_{0.4})O$, carbide (Fe_7C_3) and diamond was observed. Three different modifications of FeO were detected: B1 at T = 1100–2600K and 70–145 GPa, rB1 at T<1100 K and P<136GPa; and B8 at P = 143-145 GPa. Interestingly, we observed coexistence of wüstite and ferropericlase, which may suggest an existence of immiscibility gap in FeO-MgO system at P > 70 GPa. Mg-carbonate reduction can be presented by following reaction: $6MgCO_3 + 19Fe = 8FeO + 10(Mg_{0.6}Fe_{0.4})O + Fe_7C_3 + 3C$. The formation of diamond was confirmed by TEM study of run products at 100-145 GPa. The studied carbonate-iron reaction supports formation of the (Fe,Mg)O, carbide and diamond in the lower mantle and at the Earth’ s core-mantle boundary indicating that subducted carbonates transported to the core-mantle boundary would be reduced to carbide or diamond. Similar reaction may occur in the Fe-CaMg-carbonate systems. Using these data we propose that core-mantle boundary is important to produce diamond and Fe-carbide.

Keywords: Mg-carbonate, carbide, diamond, lower mantle, core-mantle boundary

Composition of the core: Geochemical and mineral physics constraints

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The Earth’s core is believed to contain certain amount of light elements based on seismological observations and mineral physics data. The major potential candidates of the light elements of the core are considered to be S, Si and O. Recent studies on the Fe-Si-O system revealed that Si and O have mutual avoidable nature in metallic liquid (1,2), and precipitation of silicates such as SiO_2 or $FeSiO_3$ occurred during cooling of the liquid core (e.g., (3)). Therefore, the composition of the inner core coexisting with metallic liquid outer core should be ether Fe-O-S or Fe-Si-S alloy, i.e., coexistence of Si and O are prohibited to occur in the core crystallizing metallic solid inner core.
Our sound velocity measurements of FeO revealed that O is not likely to be the major light element of the inner core (4). Thus the most plausible candidates of the light elements in the core are likely to be S and Si, without O.
Based on our measurements of the sound velocity of iron (5), iron-silicon alloy (6), and Fe_3S (7), and the solid-liquid partitioning in the Fe-Si-S system at high pressure and temperature, we constrained the composition of the inner and outer cores. The present experiments on the solid-liquid partitioning of S and Si revealed that the major element of the inner core is silicon whereas that in the outer core is sulfur. The present results on sound velocity measurements and solid-liquid partitioning of iron alloy indicate that an iron alloy with about 5 wt.% of Si and 0.1 wt. % of S can explain the physical properties of the PREM inner core at the ICB condition, whereas the outer core contains both S and Si (about 7 wt.% S and 3 wt% Si) without O.

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Keywords: Inner Core, Outer core , composition, light elements, sound velocity

High-*P*,*T* Elasticity of Iron-Light Element Alloys

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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 light elements such as carbon (e.g., Chen et al., 2014). In this study, we perform ab initio molecular dynamics simulations of iron-light element alloys with potential candidates of Si, C, and H and examine their high-P,T elasticity to identify the viability of iron alloys in the inner core.

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Keywords: Iron-light element alloy, Ab intio computation, Inner core

Constraint on composition and size of lunar Fe-Ni-S core

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In order to constrain S content in the lunar core and to estimate the structure of lunar interior, we compared measured V_P and r data of liquid Fe-alloys at the lunar core condition with observed geophysical data. We have measured sound velocity and density of liquid Fe-Ni-S using ultrasonic pulse-echo and X-ray absorption methods combined with multianvil apparatus up to 14 GPa. The obtained sound velocity and bulk modulus significantly decreased with increasing S content at the lunar core condition (5 GPa, 1800 K). Estimated Fe-Ni-S lunar core model from the present elastic properties will be compared with the previous interior models of Moon (Garcia et al. 2011 and Weber et al. 2011).

Keywords: Core, Moon, Sound velocity

Thermoelastic properties of iron-carbide melts under high pressure: implication for carbon in the lunar interior

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Carbon is one of the possible light elements in lunar interior. Thus, it is important to understanding the effect of density and sound velocity of liquid Fe at high pressure in order to evaluate the presence of carbon in lunar core. Simultaneous measurements of P-wave velocity and the density of liquid Fe-C have been conducted up to 3.4 GPa and 1850 K. Addition of carbon decreased the V_P of liquid Fe by about 2% at 3 GPa and 1700 K and reduced Fe density by about 2% at 2 GPa and 1700 K. The V_P of liquid Fe-3.5 wt% C decreased linearly with increasing temperature at constant pressure. The bulk modulus of liquid Fe-C and its pressure (P) and temperature (T) effects were precisely determined from directly measured r and V_P data to be $K_{0,1700K}$ = 83.9 GPa, dK_T/dP = 5.9(2), and dK_T/dT = –0.063(8) GPa/K. The effect of carbon in the Birch (r–V_P) plot decreases with increasing pressure. Based on the directly measured V_P and r of liquid Fe-C, elastic properties, such as K, dK/dT, and dK/dP, were determined precisely. These properties can explain differences in dV_P/dT of Fe-C, Fe, and Fe-S.

Keywords: Moon, Outer core, liquid, sound velocity, density, bulk modulus

A textural and chemical view of melting of the Sahara 97072 (EH3) meteorite at 5 GPa and different temperatures

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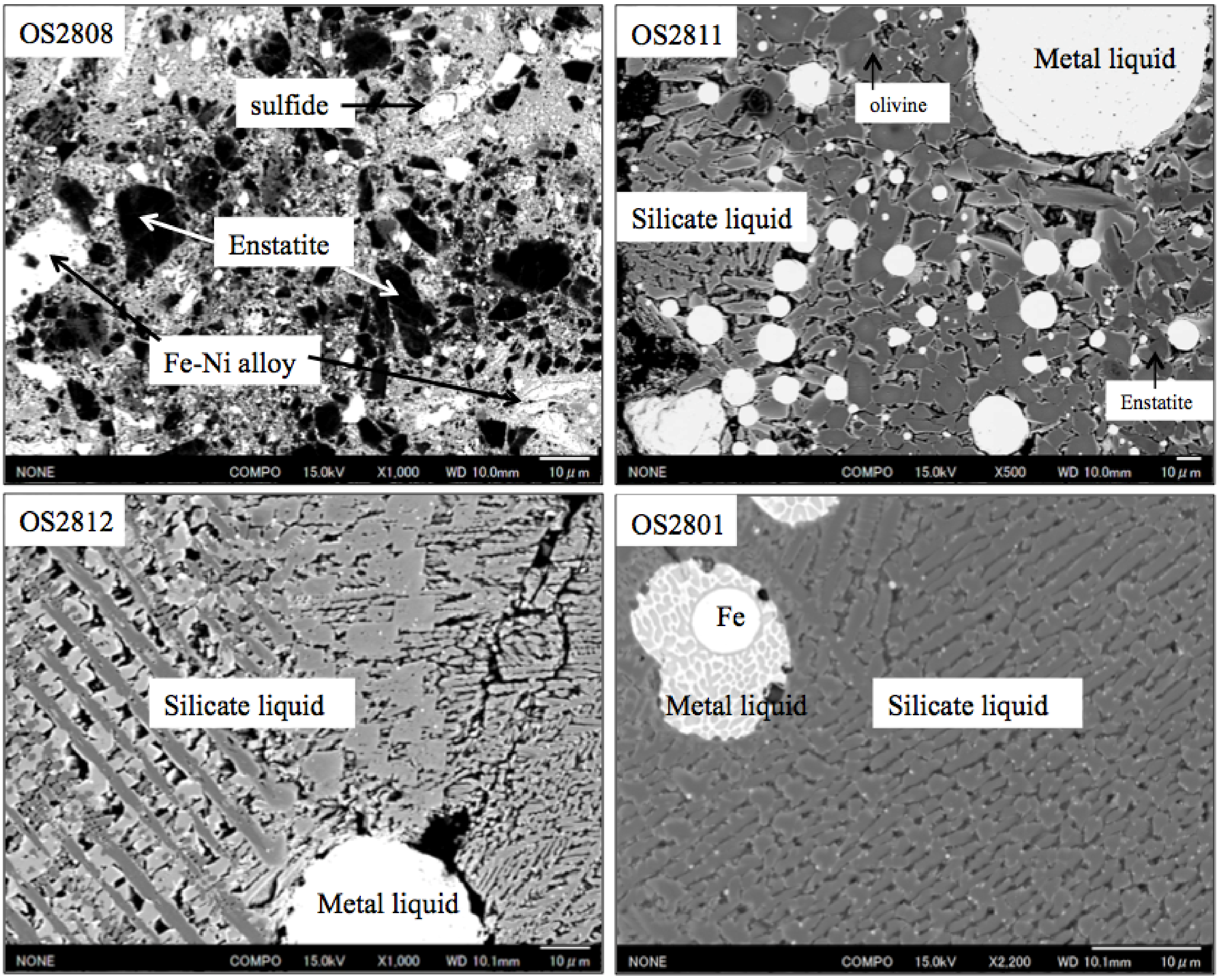
Melting interval of (Fe, Ni)-sulfide and silicate was studied with heating experiments on the Sahara 97072 (EH3) meteorite at 5 GPa and 1000-1700˚C using multi-anvil apparatus. Results from our experiments show that: (1) (Fe, Ni)-bearing sulfide is completely molten at 1200˚C; (2) partial melting of silicate begins at 1400˚C; and (3) the Sahara 97072 meteorite is completely melted at 1600˚C. At 5 GPa, both pyroxene and olivine appear to be stable near the liquidus as the first liquidus phase, indicating that 1600˚C and 5 GPa is very close to the pyroxene-olivine cotectic.
Overheating the Sahara 97072 meteorite sample to 1650 and 1700˚C causes (Fe, Ni)-alloy exsolved from (Fe, Ni)-sulfide, and the spherical shape of the (Fe, Ni)-alloy indicating that the exsolution happened during heating rather than quenching. The coexisting of (Fe, Ni)-alloy and S-rich metallic phase at higher heating temperature could be results of the decrease of portioning coefficient of S between metallic liquid and silicate liquid with temperature or the volatility loss of S at overheating conditions. The silicate liquid in these two experiments shows smaller $Mg^{\#}$ than the completely melt condition, indicating a relatively larger Fe content in the silicate liquid, which is consistent with the decreased bulk content of metallic liquid. Results from these experiments suggest that the relatively small planetary bodies with elevated sulfur content would have likely experienced sizable core stratification during early melting event as a result of the segregation of (Fe, Ni)-alloy from (Fe, Ni)-sulfide.

Keywords: enstatite chondrite, partial melting, core formation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OS2811
Metal liquid
olivine
Silicate liquid
Enstatite
NONE COMPO 15.0kV X500 WD 10.0mm 10 μm
OS2812
Silicate liquid
Metal liquid
NONE COMPO 15.0kV X1,000 WD 10.1mm 10 μm
OS2801
Fe
Metal liquid
Silicate liquid
NONE COMPO 15.0kV X2,200 WD 10.1mm 10 μm

