SIT03-01 Room:202 Time:May 21 09:00-09:15

Depth variation of the hemispheric seismic structure of the inner core inferred from global seismic array data

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The Earth's inner core is located at the center of the earth and it is widely considered that it results from the solidification of the liquid iron of the outer core with cooling of the earth. Seismological studies have revealed complex features of the inner core.

In this study, I focus on the hemispherical heterogeneous structure of the inner core. Although the understanding of the attenuation and velocity structures is an important key to give constraint on the physical state and the growth process of the inner core, the depth dependent profiles of the attenuation and velocity have not been well constrained because of the poor resolution due to difficulties in analyzing complex core phase data. I apply a waveform inversion method based on simulated annealing to core phase data observed by globally deployed seismic arrays and estimate continuous attenuation and velocity structure in the top half of the inner core. Moreover, involving frequency dependent attenuation models to inversion, the frequency dependence of attenuation is investigated. Attenuation profiles are estimated by using measured attenuation parameters. Whereas measured attenuation parameters show consistent trend for the data which sample the eastern hemisphere, for western hemisphere there is remarkable difference between the data which sample the inner core beneath Africa (W1) and beneath the north America (W2). Obtained attenuation models suggest hemispherical heterogeneities appear to be confirmed in the top 300 km. The model for the eastern hemisphere has a high attenuation zone at top 150 km and gradually decreases with depth, model for the W1 shows constant low attenuation and model for W2 represents the gradually increase from ICB and have a peak around a 200 km depth. Velocity models are obtained by using traveltime anomaly of differential traveltime between PKP(DF) and PKP(CD, BC). Measured traveltime show the consistent trend within the same hemisphere except for the data that pass through the boundary of two hemispheres. Obtained velocity structures for the eastern hemisphere and for the western hemisphere have about 1% faster and slower than the reference model at the top of the inner core and reach to same velocity at 200 km depth. The results from frequency dependent attenuation analysis suggest that whereas the attenuation for the eastern hemisphere does not depend on the frequency, the attenuation for the western hemisphere show the frequency dependent attenuation. If the cause of the attenuation is considered due to the scattering of the seismic wave, the strongest attenuation and velocity dispersion occur when the wavelength is about the grain size. Adopting this assumption to observations, the grain size in the eastern hemisphere become larger than the western hemisphere and grain size for W2 increase with depth. By applying the waveform inversion approach, it is revealed that hemispherical heterogeneities are restricted in the top 300 km of the inner core and the existence of the heterogeneities in the western hemisphere.

Keywords: seismology, inner core, attenuation, frequency dependence

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SIT03-02 Room:202 Time:May 21 09:15-09:30

Topography of the inner core boundary inferred from frequency dependent amplitude ratio of PKiKP/PcP

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The inner core boundary (ICB) is an important region for understanding the core dynamics. The amplitude ratio of PKiKP/PcP has been used for the inference of the density jump at the ICB as well as the shear velocity at the top of the inner core. Previous studies, however, were hampered by the large scatters of the PKiKP/PcP ratios, which precluded constraining relevant parameters of the ICB structures. We observe and collect a significant volume of PKiKP waves recorded by a dense network in Japan?Hinet, to examine its frequency characteristics and relevance for understanding the core dynamics in the quasi-eastern hemisphere.

We found clear PcP and PKiKP phases on high-pass filtered seismograms of 9 events with magnitude greater than 5.8 around Japan. The location of these events and the Hinet array covers epicentral distance range from 15 to 45 degrees. After the corrections for source radiation, attenuation in the mantle, the reflection coefficients (RC) at the inner core boundary are inferred from the spectral ratios of PKiKP/PcP. We find that RCs for both 1 and 2 Hz at incident angle (IA) of 10 degrees are close to the values predicted from AK135 and that RCs for 2 Hz are about 2 times larger than those for 1 Hz at IAs greater than 20 degrees. A 2D finite difference simulation involving topography with wavelength and height of 1.5 km can explain the above observation. However, another observation that RCs for both 1 Hz and 2 Hz suddenly decrease at IA of 30 degrees requires further modeling.

Keywords: ICB, topography, PKiKP

SIT03-03 Room:202 Time:May 21 09:30-09:45

Lattice preferred orientation of hcp-iron induced by shear deformation

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Many hypotheses have been proposed for origin of seismic anisotropy in the Earth's inner core. Plastic deformation of constituent material (most probably hexagonal-close-packed (hcp) iron) is one of the candidate processes to form the inner core anisotropy (e.g. Sumita and Bergman, 2009). Therefore knowledge of deformation induced lattice preferred orientation (LPO) of hcp-iron is important for understanding of nature of the inner core. Only limited numbers of experimental studies have been reported on deformation induced LPO of hcp-iron because this phase is unquenchable to ambient condition. In the previous studies, hcp-iron was deformed by uniaxial compression, and slip activities in deforming sample were indirectly estimated based on elastoplastic self-consistent modeling (e.g. Merkel et al., 2004). In this study, we have carried out shear deformation experiments on hcp-iron using D-DIA and determined its deformation induced LPO directly.

Pre-sintered fine-grained ($d < 10$ um) aggregate of bcc-iron was used in the experiments. Shear deformation experiments of hcp-iron were carried out at P = 9-18 GPa and T = 723 K using a D-DIA apparatus, SPEED-Mk.II-D, installed at BL04B1, SPring-8 (Kawazoe et al., 2011). In the deformation experiments, pressure medium of 4.5 or 5.0 mm (Mg,Co)O cube and WC and cBN second stage anvils with 2.5 or 3.0 mm truncation were used. The sample iron was sandwitched between two 45^o-cut Al_2O_3 pistons in the cell assembly. Shear strain rates in the experiments were ~2 x 10^{-4} or ~0.6 x 10^{-4} s^{-1}, and total shear strain is ~2. Development of LPO in the deforming sample was observed in-situ based on two-dimensional X-ray diffraction using an imaging plate detector and monochromatized synchrotron X-ray with energy of 49-51 keV. LPO of sample was determined from the two-dimensional diffraction pattern using a software ReciPro (Seto, 2012).

In shear deformation of single phase hcp-iron, $<0001>$ and $<112^-0>$ axes gradually aligned to be sub-parallel to shear plane normal and shear direction, respectively, from initial random orientation. The $<0001>$ and $<112^-0>$ axes are back-rotated from shear direction by ~30^o. In the experiments where deformation started from fcc-iron, successive phase transformation from fcc phase to hcp phase occurred during shear deformation, and resultant LPO pattern of hcp-iron is similar to that in the single phase deformation. The strength of final LPO in hcp-iron from the experiments with successive phase transformation is stronger than that from the single phase deformation experiments. The above results suggest basal slip $<112^-0>\{0001\}$ is the dominant slip system under the studied deformation conditions. The stronger LPO observed in deformation with successive phase transition may be due to assistance of transformation shear induced by martensitic transformation from fcc to hcp phase.

It has been shown that Earth's inner core has an axisymmetric anisotropy with P-wave traveling ~3% faster along polar paths than along equatorial directions. Although elastic anisotropy of hcp-iron at the inner core conditions is still controversial, recent theoretical studies consistently shows that P-wave velocity of hcp-iron is fastest along $<0001>$ direction at least at low-temperatures (e.g. Sha and Cohen, 2010). In this study, we showed that the basal slip $<112^-0>\{0001\}$ is dominant in deformation of hcp-iron. Therefore it could be suggested that most part of the inner core deforms with shear plane sub-parallel to equatorial plane.

SIT03-04 Room:202 Time:May 21 09:45-10:00

Solubility of silicon in hcp-iron at high pressure and high temperature

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The Earth's outer core is believed to be composed of liquid iron alloy with one or more light elements (e.g., Birch 1952; Poirier 1994). Although a number of elements lighter than iron, including hydrogen, carbon, oxygen, silicon, and sulfur, have been considered by various researchers as potential light elements in the Earth's core, silicon is one of the most attractive candidates for the light element in the core (e.g., Takafuji et al. 2005; Sakai et al. 2006; Ozawa et al. 2008, 2009, Wood et al., 2008). The Earth's inner core is considered to consist mainly of a solid iron-nickel alloy. However, multiple experimental studies revealed that the inner core is also less dense than pure iron, indicating the presence of light components in the inner core (e.g., Jephcoat and Olson 1987; Mao et al. 1998; Lin et al. 2005; Badro et al. 2007). If silicon is indeed a major light element in the liquid outer core, the maximum amount of silicon that can be incorporated in the solid inner core during inner-core solidification is limited by the solubility of silicon in solid iron at the pressure of the inner core boundary. Therefore the phase relations of iron-silicon alloys, especially the solubility of silicon in solid iron at high pressure and temperature, are the key to understanding the composition, structure, and crystallization of the inner core. The phase relations of iron-silicon alloys at high pressure have been extensively studied using a multi-anvil apparatus (Zhang and Guyot 1999; Dobson et al. 2002; Kuwayama and Hirose 2004) and a diamond-anvil cell with in-situ x-ray diffraction measurements (Lin et al. 2002; Lin et al. 2003; Dubrovinsky et al. 2003; Hirao et al. 2004; Asanuma et al. 2008, Lin et al 2009, Kuwayama et al. 2009). Below 200 GPa, the solubility of silicon in solid hcp-iron has been well studied. Solid hcp-iron can contain at least ~10 wt% Si at low temperature, but it decomposed to iron-rich hcp phase and silicon-rich bcc phase at high temperature. The positive slope of the dissociation boundary between hcp to hcp + bcc implies that the solubility of silicon into hcp iron increase with increasing pressure. However, the maximum pressure where the studies on the solubility of silicon in hcp iron have been performed so far is ~200 GPa, quite lower than the Earth's inner-core outer-core boundary conditions. In this study, we performed in-situ x-ray diffraction study on Fe-9.9 wt.% Si using a laser-heated diamond anvil cell up to ~300 GPa. We observed dissociation into a mixture of hcp and bcc phases at about 230 GPa on heating, consistent with the linear extrapolation of the phase boundary previously reported in Kuwayama et al (2009) and Lin et. al. (2009). In contrast, we did not observe the dissociation at higher pressure, indicating that the more than 9.9 wt% Si can be dissolved in hcp iron at the ICB condition. This implies that the inner core should contain some amount of silicon if the outer core actually conations a substantial amount of silicon.

Keywords: Core, iron, light element

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SIT03-05 Room:202 Time:May 21 10:00-10:15

Amount of sulfur in the inner core based on sound velocities and EOS of Fe3S at high pressures

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The structure and seismic properties of the Earth's inner core have not been understood well. The observation of shear wave velocities in the inner core raised an issue because the observed shear wave velocities were unexpectedly low (Cao et al., 2005). Due to lack of the knowledge about elastic properties of the core materials, it is difficult to interpret the observed seismic wave velocities.

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 inner core materials 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, under the core conditions, only Fe_3S coexists with hcp-Fe as a subsolidus phase (Kamada et al., 2010, 2012). Therefore, it is essential to study the V_P of Fe_3S to understand seismic and chemical properties of the Earth's core. The EOS of Fe_3S is also important to estimate the density deficit of the inner core.

In this study, a synthesized Fe_3S or a foil made from Fe and FeS powder mixture was used as a starting material. A symmetric diamond anvil cell was used to generate high pressures. IXS experiments were performed at the beamline 35XU of SPring-8, Japan (Baron et al., 2000) and X-ray diffraction experiments were performed at the beamline 10XU of SPring-8. V_P of Fe_3S were measured up to 85 GPa and the EOS of Fe_3S were determined to 200 GPa. The present results suggest that VP of Fe_3S follow the Birch's law. According to sound velocity measurements, it is needed to take account of temperature dependence on V_P to explain the inner core V_P. The amount of sulfur in the inner core was estimated to be 13.5 at% based on 4th order Birch-Murnaghan EOS. This amount of sulfur is much larger than the previous estimation (e.g., Chen et al., 2007). Therefore, there might be some other light elements in the core, such as O and/or Si.

Keywords: Fe3S, Inner core, sound velocity, equation of state

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(May 19-24 2013 at Makuhari, Chiba, Japan)

SIT03-06 Room:202 Time:May 21 10:15-10:30

Sound velocity of iron-light-element alloys at high pressure and temperature and composition and thermal state of the in

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Sound velocity is the most accurate observable properties of the earth's interior and can provide important clues on structure and composition of the core. In spite of their importance, the sound velocity data of the core materials at high pressure are still very limited due to technical difficulties.

We measured the compressional velocity of hcp-iron and other iron-light element alloys by the inelastic X-ray scattering (IXS) method using DAC at high pressure and temperature. We measured the velocity up to 174 GPa at room temperature to 91 GPa at temperatures to 1000 K using the external heating diamond anvil cell. We also measured the compressional velocity and density of Fe0.83Ni0.09Si0.08 alloy to 151 GPa and Fe3S up to 85 GPa at room temperature. Inelastic X-ray scattering spectra were taken at BL35XU, Spring-8.

The present compressional velocity-density relation of hcp-Fe at 300 K is consistent with recent IXS results obtained by Mao et al. [2012] and Antonangeli et al. [2012]. This work shows almost no temperature effect, i.e., Birch's law is applicable up to the temperature of at least 1000 K at c.a. 91 GPa. We obtained the following Birch's law by fitting our results and the recent hcp-Fe data-sets at 300 K: Vp [km/s] = 1.174(+-0.031)d[g/cm3] ? 3.591(+-0.326). The compressional velocity and density curves for hcp-Fe0.83Ni0.09Si0.08 alloy, Fe3S and hcp-Fe of Birch's law locate above those of the PREM inner core in the velocity-density diagram. Thus these observations indicate following two possibilities, i.e., hcp-Fe has a large temperature effect on Birch's law as was suggested by some theoretical works [Vocadlo et al., 2009; Sha and Cohen, 2010] or the inner core contains some amounts of heavy elements such as Ni with a negligible temperature effect on Birch's law. In the latter case we need higher temperature of the inner core in order to reduce the density of iron-nickel alloy to match the PREM inner core density. The amount of light and heavy elements of the inner core for a given inner core temperature, i.e., a plausible composition-temperature model of the inner core will be presented.

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Keywords: Inelastic X-ray Scattering, Sound veolcity, hcp-Fe, Diamond anvil cell, High Pressure and Temperature, Inner core

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SIT03-07 Room:202 Time:May 21 10:30-10:45

Understanding the Lunar core: past, present and future

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The central core is a major part of a planet and satellite, contributes to the bulk composition of the major elements and plays a role of a dynamo engine. Formation of a core is thought to be a natural sequence of global differentiation in an expected magma ocean of the planet during its formation and evolution. Understanding the core is therefore a key issue in earth and planetary sciences. The moon has a very small iron core or no core, which is a consequence of the small mean density less than 3.5 g/cm^3. The fact is strong evidence of the giant impact hypothesis in which the moon forms mainly from the mantle materials of a colliding planetary embryo. Recent global mapping of the lunar surface magnetic field indicates existence of a systematic magnetic field that can be produced by an ancient fluid motions of a liquid core: the lunar core dynamo. Thus, characterizing the lunar core on its size and composition is important for understanding the formation and evolution of the moon. Determination of the core size was the central objective of the former Lunar-A project constructing a seismometer network with hard landing probes named penetrator.

Seismology provides us the most efficient way to reveal the internal structure of the moon like as on the earth. Seismic waves excited by an event can be a light illuminating the interior of the moon. Since the Lunar-A project was canceled, seismic data recorded by the Apollo project are only the data that human beings have ever obtained. In the project, four seismic stations was built from 1969 to 1972 and formed a triangle network with a side of about 1,000 km, and had been operated for five and half years. During the observation period, more than 10,000 seismic events were detected by the network. The data has been used for interpretations on the deep structure of the moon. However, the deeper part of the moon has not been revealed since most of moonquakes are located in the near side of the moon and the span of the seismic network is about 1,000 km at most. Moreover long lasting codas of direct P- and S-waves conceal signs from the core.

Entering 21th century, high performance computing resources are available in many scientific fields. Using such a resource, re-interpretation of the Apollo seismic data has been performed in this decade. Some researches reported a detection of reflection and transmission waves from the core and determined the core size of 300~400 km which is consistent with the other estimations using geodetic and electromagnetic data. However, after complicated processing of data, the detection is still marginal or questionable. To clear the existence and size of the core of the moon, we must deploy a wider seismic network using seismometers with higher performance. Technologies of Lunar-A type penetrator and broadband seismic sensor able to operate under extreme environment are necessary for a future exploration of the lunar deep interior. At last, I introduce future mission plans using the technologies.

Keywords: moon, internal structure, core, seismology, moonquake, exploration

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SIT03-08 Room:202 Time:May 21 11:00-11:15

First 23-41 Ma relative geomagnetic paleointensity records in the equatorial Pacific

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In order to reveal the earth's history, in particular the evolution of the earth's outer core, it is inevitable to investigate the intensity of the paleomagnetic field, namely, geomagnetic paleointensity. Paleointensity can be recovered independently from volcanic rocks and marine sediments. Volcanic rocks give absolute paleointensity sporadically in time, and a number of data have been reported back to as old as ˜ 3.5 Ga according to the latest database (PINT database updated on August 2012; after Biggin et al., 2010). In contrast, marine sediments provide relative paleointensity (RPI) continuously in time, and stacked time series have been published only back to ˜ 3 Ma (e.g. PISO-1500 record for the last 1500 kyr, Channell et al., 2009; Sint-2000 record and PADM2M model for the last 2000 kyr, Valet et al., 2005, Ziegler et al., 2011; EPAPIS-3Ma record for the last 800-3000 kyr, Yamazaki and Oda, 2005). Obtaining RPI records further back in time is an important subject in earth science.

Integrated Ocean Drilling Program (IODP) Expedition 320/321 recovered sedimentary sections at Sites U1331 and U1332 from the equatorial Pacific. We conduct paleomagnetic and rock magnetic measurements on the Sites U1331 and U1332 sediments to recover first Oligocene and Eocene RPI records in the equatorial Pacific. The sedimentary sections extend mainly from the late Oligocene to the late Eocene for Site U1331 (29.166-41.358 Ma), and from the early Oligocene to the late Eocene for Site U1332 (23.030-41.358 Ma). They are precious materials for RPI studies, as there have been only one RPI record reported so far which covers the Oligocene period (Deep Sea Drilling Project (DSDP) Site 522 record from South Atlantic; Hartl et al., 1993; Tauxe and Hartl, 1997).

Our measurements revealed that the main magnetic carriers are low-temperature oxidized magnetites and variations of their concentration are within about a factor of six. When the sedimentary sections are divided into Oligocene (23.0-33.7 Ma) and Eocene (34.5-41.4 Ma) intervals, ratios of anhysteretic to saturation isothermal remanent magnetization do not vary large. RPI is estimated separately for each interval.

In both the Sites U1331 and U1332 RPI records, it is recognized that chron boundaries always associate with intensity minima. The records also show cyclic highs and lows even during stable polarity periods. These features are the same as those reported for the last 3 million year RPI records. The probable cryptochron C18n.1n-1, which is characterized by common marked intensity lows in the RPI records, is found at the age of 39.094-39.114 Ma for Site U1331 and 38.958-38.983 Ma for Site U1332.

The two records show consistent variation with the RPI reported from Site U1333, which is in the vicinity of Sites U1331 and U1332. They can be reasonably correlated with the RPI record reported from DSDP Site 522 in South Atlantic (After Hartl et al. (1993) and Tauxe and Hartl (1997)). One interesting feature is that the RPI during the chron C12r appears to be consistently high compared with that during other Oligocene intervals. Further investigations based on new records are necessary in the future to make conclusion whether or not this is a true manifestation of the ancient geomagnetic field.

SIT03-09 Room:202 Time:May 21 11:15-11:30

Rock-magnetic artifacts on long-term relative paleointensity variations in sediments

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Long-term changes of geomagnetic field intensity, including possible dependence on lengths of polarity intervals, provide fundamentally important information for understanding the geodynamo. A positive correlation between paleointensity and polarity interval length was previously suggested from an Oligocene (ca 23-34 Ma) relative paleointensity record at Deep Sea Drilling Program Site 522 in the Atlantic Ocean, which is the only continuous paleointensity data set published so far for this age interval. We have conducted a paleomagnetic study of Eocene to Oligocene sediments at three sites in the eastern equatorial Pacific Ocean. Our objectives include revisiting the issue of the paleointensity-polarity length correlation. Magnetic properties of the sediments meet the frequently used criteria for reliable relative paleointensity estimation. Although short-wavelength normalized remanence intensity fluctuations associated with polarity boundaries and possible geomagnetic excursions agree among the three sites, long-term changes are inconsistent. Apparent positive correlation between normalized intensity and polarity length was observed, but the normalized intensity has an obvious anti-correlation with the ratio of anhysteretic remanent magnetization (ARM) to isothermal remanent magnetization (IRM), which is mainly controlled by the relative abundance of biogenic and terrigenous magnetic minerals. Furthermore, the normalized intensity correlates with sedimentation rate. These facts indicate a lithological contamination on the normalized intensity records. The dependence on ARM/IRM and sedimentation rate is also evident at Site 522. It is inferred that variations in sedimentation rate and the relative abundance of biogenic magnetite on depositional remanent magnetization acquisition efficiency may not be well compensated by the normalization. It is therefore premature to conclude that stronger geomagnetic fields were recorded during longer polarity intervals from currently available normalized intensity records.

SIT03-10 Room:202 Time:May 21 11:30-11:45

Observations of the early geomagnetic field by paleomagnetism and possible temporal trend in paleointensity

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The nature of the ancient geomagnetic field constrains the core evolution. Here we present the Paleoarchean magnetic record in single silicate crystals obtained using DC SQUID magnetometry and IR heating techniques. So far, the oldest geomagnetic field intensity records were from 3.44 Ga and 3.2 Ga rocks from the Kaapvaal craton (Usui et al., 2009; Tarduno et al., 2007, 2010). Among those two, the estimated virtual geomagnetic dipole moment is lower for 3.44 Ga by ca. 50% than for 3.2 Ga, which in turn is comparable to the modern field. This led some to hypothesize growing field intensity with time during this period. On the other hand, analysis of a database implies opposite trend of decreasing field intensity with time from Archean to Proterozoic, though the accuracy of the individual record in the database may be questioned. To clarify the nature of the ancient field, we examined granitic rocks from ca. 3.3 Ga Mt. Edgar complex from the Pilbara craton using the single crystal technique. Analysis of feldspar crystals from some sites yielded paleointensity data that pass experimental reliability criteria. Rock magnetism of the feldspar crystals indicated the presence of near single-domain, pure magnetite inclusion. The blocking temperature is high enough for the remanence to survive the low grade regional metamorphism. Because the single crystals measured were unoriented, we do not yet have constraints on paleolatitude to calculate a virtual dipole moment. Nevertheless, assuming an equatorial paleolatitude, the estimated paleofield is only ca. 60% of the modern value; higher paleolatitude would indicate even lower dipole moment. Together with the existing data from the Kaapvaal craton, our results support growing geomagnetic intensity during Paleoarchean. This implies a delayed onset of the geodynamo.

Keywords: geomagnetism, paleomagnetism, early Earth, paleointensity, single crystal, Archean

Japan Geoscience Union Meeting 2013
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SIT03-11 Room:202 Time:May 21 11:45-12:00

Core surface flow modeling with geomagnetic diffusion

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Estimation of fluid motion in the Earth's liquid outer core enables us to understand a realistic geodynamo mechanism, to examine the thermal structure at the core surface, and to constrain the effect of core-mantle boundary (CMB) on the flow. Most of core flow models have been derived from geomagnetic field models based on the frozen-flux approximation, where the magnetic diffusion term in the induction equation can be neglected for a time scale much shorter than the magnetic diffusion time scale. However, the effect of magnetic diffusion is found to be more significant than that of magnetic induction inside the boundary layer at the CMB. Hence, to model the core surface flow, we presume that the magnetic diffusion is effective inside the boundary layer. On the other hand, below the boundary layer, we neglect the magnetic diffusion in the induction equation as in the frozen-flux approximation. It is likely that the viscous force plays an important role in the boundary layer. We therefore presume balance among the pressure gradient, the Coriolis force, and the viscous force in the equation of motion inside the boundary layer. Below the boundary layer, we presume that the flow is in a geostrophic state. The radial dependence of horizontal components of core surface flow is represented in terms of the boundary layer compatibility condition. Thus the core surface flow is modeled with geomagnetic diffusion.

Keywords: core surface flow, magnetic diffusion, geomagnetic field

SIT03-12 Room:202 Time:May 21 12:00-12:15

Double diffusive convection in the Earth's core and the morphology of the geomagnetic field

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Convection in the Earth's outer core is driven by thermal and compositional buoyancy. Thermal convection is driven by superadiabatic part of temperature gradient within the core coming from secular cooling of the core, latent heat release upon solidification of iron at the inner core boundary, and possibly decay of radioactive elements such as potassium. Compositional convection occurs due to ejection of light elements into the outer core at the front of inner core solidification. Conventionally, temperature and composition are collapsed into one variable called codensity instead of treating them separately, assuming the eddy diffusivity due to turbulence. However, it is not evident to what extent the codensity approach is applicable to the Earth's core. Moreover, it is impossible to separate contributions from the two agents to the flow dynamics in the codensity approach. Here we examine effects of co-existence of the two buoyancy sources on core dynamics and morphology of the geomagnetic field using numerical dynamo models with double diffusive convection at thermal Prandtl number, PrT = 0.1 and compositional Prandtl number, PrC = 1. We find that the morphology of the magnetic field is determined by fraction of the two driving mechanisms. Dipolar magnetic field is maintained as long as power injected by compositional buoyancy explains at least 30-40% of the total. Otherwise, non-dipolar fields grow instead of the dipolar field because of increasing influence of inertia. The dominantly dipolar structure of the present geomagnetic field suggests that fraction of power injection by compositional convection in the present geodynamo exceeds the threshold.

Keywords: core, geomagnetic field, dynamo, double diffusive convection

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SIT03-13 Room:202 Time:May 21 12:15-12:30

Effects of small-scale buoyancy in geodynamo simulations

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Flow and magnetic fields in the Earth's outer core are expected to have a vast range of length scale from the size of the outer core to the thickness of the boundary layers. Limited spatial resolution in geodynamo simulations prohibits solutions with the full range of scales. Consequently, subgrid scale (SGS) models are required to account for the effects of the unresolved fields on the large scale solution. Each nonlinear term in the geodynamo problem requires a SGS model; this includes the SGS heat flux, Reynolds stress, SGS Maxwell stress, and SGS magnetic induction. We perform large-eddy simulations (LES) of a dynamo in a rotating spherical shell using the dynamic scale-similarity model. However, LES result underestimates the large-scale magnetic energy by nearly 0.5 times with that from a fully resolved simulation on a finer grid.

We seek to identify the energy pathway in LES for geodynamo problems to identify the problem of the underestimation of the large scale magnetic energy in the present LES. In LES, energy is transferred between the large scales and small scales by the nonlinear terms in the governing equations. On the other hand, buoyancy forces are thought to be responsible for driving vigorous convection in the Earth's liquid core, but there is no direct energy transfer between scales by buoyancy because the buoyancy force is linear in temperature, which ensures that large-scale temperature anomalies drive large-scale flow and small-scale temperature anomalies drive small-scale flow. We investigate the effects of the small-scale buoyancy on the large scale magnetic field generation in the dynamo simulations.

To evaluate effects of the small-scale buoyancy in a dynamo simulation, we perform a fully resolved simulation using spatially filter to the buoyancy force at each time step to remove small-scale contributions. We find that the small-scale buoyancy is a likely explanation for the low magnetic energy in the LES because we obtain very similar results to the LES solution in this resolved simulation with filtered buoyancy.

A clue to the energy pathway is found in our SGS model for the Reynolds stress, which shows a positive (upscale) transfer to kinetic energy to the large scales in a region around the tangential cylinder, consistent with the results inferred from a fully resolved calculation. We assume that some of SGS buoyancy flux is transferred to the large scale kinetic energy through the Reynolds stress. By increasing the amplitude of the Reynolds stress by a factor of four, we obtain substantial improvements in the simulation over the standard LES.

We discuss a parameterization of the Reynolds stress which relies on a local estimate of SGS buoyancy flux in the dynamo simulations. The local SGS buoyancy flux can be approximated using the SGS heat flux, which is routinely calculated in the standard LES, so the modified parameterization requires few additional computations.

Keywords: Geodynamo simulation, Sub-grid scale modeling

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SIT03-14 Room:202 Time:May 21 12:30-12:45

Rotating magnetohydrodynamic waves and convection: Implications for geomagnetic secular variation

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The geomagnetic field has significantly changed on several timescales. A prominent feature of the geomagnetic secular variation is the westward motion of the non-dipole part of the field, especially clear in the Atlantic hemisphere with timescales of 10^2 - 10^3 years. Convection-driven MHD dynamo simulations have reproduced westward drift and also its spatial dependence. A possible mechanism causing the drift is propagation of rotating MHD waves in the Earth's core. Though the hypothesis has been proposed and discussed since 1960s, the wave properties are not fully understood.

To get insight into the mechanism, we perform a linear analysis on thermal instability in presence of rotation and an imposed magnetic field and analyze the wave properties associated with the thermal convection. Here, to treat analytically, we adopt a cylindrical annulus model with sloping boundaries, which qualitatively reproduces features in a spherical shell/sphere with magnetic fields being absent. Recently-proposed influence of thermal boundary conditions is also explored.

We find that, while the inviscid approximation gives a slow retrograde (westward)-propagating wave (MC- or MAC-Rossby wave), dissipative effects make it more various. When magnetic diffusion is much faster than thermal diffusion, convection sets in with a prograde (eastward)-propagating slow wave, whose timescale is expected to be the order of 10^9 - 10^{10} years in the Earth's core. Retrograde slow waves excite when magnetic diffusion is slower than thermal diffusion. Their timescales are very long and the inviscid MC/MAC wave presents the shortest one, the order of 10^2 - 10^3 years. This slow mode is compatible with the observed direction and timescale of the geomagnetic drift.

SIT03-15 Room:202 Time:May 21 14:15-14:30

Effects of thermal conductivity on thermal and magnetic evolution of Earth's core

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Recent high pressure experiments and theory suggested that the thermal conductivity of Earth's core material could be much higher value compared to 15 years ago, which varies from 40 W/mK [Stacey and Anderson, 2001] to 150 W/mK [e.g. Pozzo et al., 2012; de Koker, 2012]. The thermal conductivity of Earths core directly affects the adiabatic heat flow from the core. When the heat flow across the core-mantle boundary (CMB) is smaller than the adiabatic heat flow, the magnetic activity of Earths core cannot account for the thermal convection only (secular cooling). In order to explain continuous magnetic history suggested from the paleomagnetism constraint [e.g., Aubert et al., 2009], the compositional effects caused by inner core growth would be important. Here we investigate thermal and magnetic evolution of Earth's core based on a coupled model of thermo-chemical multiphase mantle convection and global heat balance of Earth's core [Nakagawa and Tackley, 2010; 2012]. Main conclusion is that the magnetic evolution of Earth's core is slightly influenced by the thermal conductivity of Earth's core because the CMB heat flow calculated from mantle convection is generally higher than the adiabatic heat flow from the core, which ranges 5 to 15 TW. For the case that the thermal conductivity of Earth's core could be assumed as 200 W/mK, the continuous magnetic evolution caused by dynamo actions would be maintained by the compositional convection due to the inner core growth.

Keywords: thermal conductivity, thermal evolution, magnetic evolution, core-mantle heat flow, compositional convection

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SIT03-16 Room:202 Time:May 21 14:30-14:45

Thermodynamics of melting relations in the system Fe-FeO

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Thermodynamics of melting relations in the system Fe-FeO was investigated to the outer core-inner core boundary (ICB) pressure from a self-consistent thermodynamic database for Fe and FeO phases which was evaluated from the latest static high-pressure and -temperature experiments. With the ideal solution model assumed for liquids at the ICB pressure condition, the eutectic temperature is 3680 K, which contradicts the results of the DAC experiments showing a solid assemblage Fe+FeO was stable up to 4200 K. Then, non-ideality of mixing for liquids was assessed to make the eutectic temperature consistent with the experiments. I will present a new solution model for the liquids in the system Fe+FeO in order to predict the eutectic composition under the core pressures, which compositions would put the limit of the oxygen content in the core because the density of solid FeO is too small to match the inner core density. From the Gibbs free energy for the Fe-FeO liquids, I calculated the density, sound velocity, and adiabatic temperature gradient of a hypothetical oxygen-bearing outer core. From the calculated density and sound velocity, I will discuss if oxygen can be a major light element in the core or not.

Keywords: core, thermodynamics, Fe-FeO, high-pressure

SIT03-17 Room:202 Time:May 21 14:45-15:00

Melting relation in the Fe-S-Si system at high pressure and temperature: Implications for the Earth's core

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The Earth's core is mainly composed of iron alloy. Its density is, however, smaller than that of pure iron. Therefore, the light elements are required in the core to account for the core density deficit (Birch, 1964). The potential light elements have been considered to be S, Si, O, C, and H (Poirier, 1994). Alloying light elements significantly affects the physical properties of iron and depresses its melting temperature (e.g., Boehler, 1996). Sulfur and silicon are considered as major light element components based on cosmochemical study (McDonough, 2003) and high pressure partitioning experiments (e.g., Sakai et al., 2006). Therefore, the melting relationship of the Fe-S-Si system is the key information to clarify the thermal and compositional structure of the Earth's core. In the case of the Fe-S-Si ternary system, there are no experimental data at high pressure and the phase and melting relations have not been clarified in detail under core conditions. In this study, the melting relationships of the Fe-S-Si system were determined up to 60 GPa using a laser-heated diamond anvil cell combined with in situ X-ray diffraction technique. Chemical analyses of the recovered samples were also carried out to determine the partitioning of the elements in the samples.

The sample composition used in this study were $Fe_{80.1}S_{12.7}Si_{7.2}$(Fe-8wt.%S-4wt.%Si) and $Fe_{74.4}S_{18.5}Si_{7.1}$(Fe-12wt.%S-4wt.%Si), which are in the range of the amounts of the light elements to explain the density deficit in the Earth's core. The sample foil was sandwiched between NaCl or Al_2O_3 pellets, which worked as the pressure medium, and the thermal insulator. An experimental pressure was determined from the pressure dependence of the edge of the T_{2g} Raman band of the culet of the diamond anvil (Akahama and Kawamura, 2004) and the lattice parameters of NaCl with using the equation of states of the NaCl B1 phase (Brown, 1999) and NaCl B2 phase (Fei et al., 2007). In situ X-ray diffraction experiments were conducted at the BL10XU beamline at the SPring-8 facility (Ohishi et al., 2008).

On the basis of diffraction patterns, Fe(hcp/fcc) which contains silicon and Fe_3S are stable phases under subsolidus conditions. First Fe_3S melts at a solidus temperature, and Fe-Si alloy coexists with partial melts above the cotectic temperature in this system. This melting sequence is consistent with the study of the Fe-Fe_3S system observed earlier by Kamada et al. (2010). The solidus temperature is significantly lower than the melting temperature of pure Fe (Ma et al., 2004) and close to the eutectic temperatures of the Fe-Fe_3S system (Morard et al., 2008), suggesting that the effect of 7.2 at.% silicon on the eutectic temperature in the Fe-Fe_3S system is minor. Based on the present results, the temperature at the core-mantle boundary should be greater than 2630(160) K and the temperature at the boundary of the inner and outer cores is estimated to be 4500(320) K, assuming that sulfur and silicon are the only light elements in the Earth's core. We also determined the elemental partitioning from chemical analyses. The results in this study provide important constraints on the chemical and thermal structure of the Earth's core.

Keywords: Earth's Core, core-mantle boundary, inner core boundary, laser-heated diamond anvil cell, Fe-S-Si system

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SIT03-18 Room:202 Time:May 21 15:00-15:15

The effect of carbon on density and elastic property of liquid Fe-C under high pressure

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The Earth's outer core is composed of the molten Fe alloys. Seismological and experimental studies show that the Earth's outer core is approximately 10% less dense than molten iron at the core pressure and temperature conditions, implying that some light elements, such as S, Si, O, H and C, exist in the outer core. Carbon is one of the plausible candidates of the light element in the core. Based on the effect of pressure on carbon solubility into molten iron and its thermodynamic calculation, carbon is expected to exist in the Earth's core. In this study, we measured the density of liquid Fe-3.5wt%C using X-ray absorption method and discussed the effect of carbon on the molar volume and elastic parameter (i.e. bulk modulus and thermal expansion coefficient)

High-pressure experiments were performed using a DIA-type cubic anvil press (SMAP-I) installed at the in-vacuum undulator beamline BL22XU at SPring-8 synchrotron radiation facility in Japan (Sakamaki et al., 2009, 2011; Nishida et al., 2011). We clarified the effects of pressure and temperature on the liquid density in the pressure and temperature range of 1.8-6.5 GPa and 1600-2200 K. The present results revealed that the density of liquid Fe-C shows an abrupt change at 5.5 GPa and 1800 K. This abrupt density change may be caused by the phase change of Fe_3C side. Incongruent melting takes place in Fe_3C and a solid phase (i.e., liquidus phase) coexists with the melt changes from graphite to Fe_7C_3 at around 5 GPa (Nakajima et al., 2009). This change in liquidus phase at 5 GPa may also affect the structure of liquid Fe-C. The effect of the structural change of the liquid Fe-C is important for considering an abundance of carbon in Earth's outer core.

We fitted the present data below 5 GPa using the Birch-Murnaghan EOS and obtained $K_{0,1500K}$ = 55.3(2.5) GPa, $(dK_0/dP)_T$ = 5.2(1.5), and thermal expansion coefficient = 0.86(4)$*10^{-4}$ K^{-1}. The estimated K_{0T} of liquid Fe-3.5wt%C (55.3 GPa) was lower than that of liquid iron (K_{0T}=85.1 GPa)(Anderson and Ahrens, 1994).

Comparing the present density with that of the previous studies which reported by Terasaki et al. (2010, JGR) for C=6.6 wt% and Sanloup et al. (2011, EPSL) for C=5.7 wt%, the compositional dependency of the liquid density can be estimated, The molar volume variation with C content is concave from the tie line between molar volumes of Fe and C end members (i.e., ideal mixing line), suggesting that excess molar volume (V_{ex}) of liquid Fe-C is negative at high pressure. This tendency is consistent with that observed at 1 atm (Ogino et al., 1984). The negative excess molar volume may indicate that inter-atomic distance of Fe decreases by occupying of carbon at the interstitial site. The density of liquid Fe-C shows non-ideal mixing behavior. Thus, the amount of carbon in the core may possibly be larger than the previous estimates if the non-ideal mixing behavior is maintained up to the core condition.

Keywords: High pressure and High temperatute, density, liquid Fe-C, molar volume, bulk modulus, thermal expansion coefficient