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

SIT39-01 Room:105 Time:May 24 09:00-09:15

Expanding-contracting Earth

Taku Tsuchiya[1], Kenji Kawai[2*], Shigenori Maruyama[2]

[1]Geodynamic Research Center, Ehime University, [2]Department of Earth and Planetary Sciences, Tokyo Institute of Technology

The Earth was born from a giant impact at 4.56 Ga. It is generally thought that the Earth subsequently cooled, and hence shrunk, over geologic time. However, if the Earth's convection was double-layered, there must have been a peak of expansion during uni-directional cooling. We computed the expansion-contraction effect using first principles mineral physics data. The result shows a radius about 120 km larger than that of the present Earth immediately after the consolidation of the magma-ocean on the surface, and subsequent shrinkage of about 110 km in radius within about 10 m.y., followed by gradual expansion of 11 km in radius due to radiogenic heating in the lower mantle in spite of cooling in the upper mantle in the Archean. This was due to double-layered convection in the Archean with final collapse of overturn with contraction of about 8 km in radius, presumably by the end of the Archean. Since then, the Earth has gradually cooled down to reduce its radius by around 12 km. Geologic evidence supports the late Archean mantle overturn ca. 2.6 Ga, such as the global distribution of super-liquidus flood basalts on nearly all cratonic fragments (>35 examples). If our inference is correct, the surface environment of the Earth must have undergone extensive volcanism and emergence of local landmasses, because of the thin ocean cover (3e5 km thickness). Global unconformity appeared in cratonic fragments with stromatolite back to 2.9 Ga with a peak at 2.6 Ga. The global magmatism brought extensive crustal melting to yield explosive felsic volcanism to transport volcanic ash into the stratosphere during the catastrophic mantle overturn. This event seems to be recorded by sulfur mass-independent fractionation (SMIF) at 2.6 Ga. During the mantle overturn, a number of mantle plumes penetrated into the upper mantle and caused local upward doming of by ca. 2e3 km which raised local landmasses above sea-level. The consequent increase of atmospheric oxygen enabled life evolution from prokaryotes to eukaryotes by 2.1 Ga, or even earlier in the Earth history.

Keywords: Expanding Earth, Mantle overturn, Global unconformity, Nutrients, Eukaryotes

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SIT39-02 Room:105 Time:May 24 09:15-09:30

Three layers model of continents and whole mantle dynamics

Kenji Kawai[2], Taku Tsuchiya[3], Jun Tsuchiya[4], Shigenori Maruyama[1*]

[1]Earth-Life Science Institute, Tokyo Instittute of Techology, [2]Tokyo Institute of Technology, [3]Geodynamics Research Center, Ehime University, [4]Senior Research Fellow Center, Ehime University

We propose a new model of three layers model of continents, 1) surface TTG continent, 2) mantle transition zone TTG continents, and the third anti-crust with meta-anorthosite right above the CMB in the Archean, and without meta-anorthosite in the upper parts of lower mantle after the mantle overturn at 2.6-2.7Ga. Our model is based on the First Principle Calculation along the geotherms in the Archean and Phanerozoic for the major rocks in the mantle.

The Archean double-layered mantle convection led an inevitable demise of catastrophic mantle overturn at 2.7-2.6Ga, and frozen the basal magma ocean over 90%, to enable the meta-anorthosite as a major rock component in the third continent. However, the subsequent cooling by the dropping cold materials from the upper mantle narrowed the stability field of Al2O3 phase, reducing the density to rise up into the mid-mantle depth around 1500-2000km depth range. This could be a prolonged duration of magmamic activity after 2.7Ga over a few hundred m.y.

SIT39-03 Room:105 Time:May 24 09:30-09:45

Attenuation structure of North America using USArray: A two-station approach for surface-wave amplitude analysis

Kouta Hamada[1*], Kazunori Yoshizawa[2]

[1]Graduate School of Science, Hokkaido University, [2]Faculty of Science, Hokkaido University

Anelastic attenuation of seismic waves provides us with an insight into the distributions of temperature and water in the Earth's mantle. While seismic velocity models have been investigated by many researchers, anelastic attenuation (or Q) models have yet to be investigated in detail mainly due to the intrinsic difficulties and uncertainties in the amplitude analysis of observed seismic waveforms.

In this study, we developed a new method of non-linear waveform fitting to measure inter-station phase velocities and amplitude ratios simultaneously, working with a fully non-linear inversion scheme. We employed the neighborhood algorithm (NA) that enables us to explore the model parameter space so as to fit the two observed waveforms on a common great circle by perturbing both phase and amplitude of the fundamental-mode surface waves.

This method has been applied to observed waveform data from the high-density transportable seismic network in USA (USArray) to collect a large-number of inter-station amplitude and phase speed data in a period range from 25 to 200 seconds. Our preliminary results indicate good correlation with the conventional tomographic results of surface-wave phase speeds and attenuation in North America on a large-scale; e.g., significant slow velocity anomaly and high attenuation in the western United States.

Our measurements also suggest the limitations in the amplitude measurements between two stations; i.e., estimated amplitude ratios are fairly sensitive to some uncertain factors such as the site effects and employed sensor types, despite all the instrument responses have been deconvolved using the response information provided by the IRIS data center. The effects of station correction factors will need to be carefully considered to compensate for the large uncertainties in the observed amplitude data, when we construct tomographic maps of surface-wave attenuation.

The current measurement technique enables us to gather a number of phase and amplitude data at short distances less than 1000 km in an efficient manner, which is of great help in improving the horizontal resolution of the current tomographic models with intermediate/long period surface waves.

Keywords: anelastic attenuation, non-linear waveform fitting, surface-wave amplitude, two-station approach

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SIT39-04 Room:105 Time:May 24 09:45-10:00

Radial anisotropy and lithosphere-asthenosphere boundary of the Australian upper mantle

Kazunori Yoshizawa[1*], Brian L.N. Kennett[2]

[1]Faculty of Science, Hokkaido University, [2]RSES, Australian National University

Deployments of transportable broadband seismic networks in Australia in the last two decades have enhanced the horizontal resolution of seismic images of Australian upper mantle. To delineate 3-D images of the uppermost mantle, seismic surface waves are one of the most powerful tools. While the depth resolution of the fundamental-mode surface waves is generally limited to the top 200 km, higher-mode surface waves have greater sensitivities to much deeper structure, which can enhance the potential of surface wave imaging for the whole upper mantle. We have employed a fully non-linear inversion scheme to estimate path-specific multi-mode phase speeds of surface waves to map the high-resolution 3-D anisotropic shear wave model of Australia, using permanent and transportable seismic stations deployed throughout the continent. The lithosphere-asthenosphere boundary (LAB) beneath the Australian continent is also estimated from the final 3-D model. Although surface waves are inherently not very sensitive to the sharpness of boundaries due to their long-wavelength features, the depth of LAB can be estimated from either the negative peak of velocity gradient or the slowest velocity beneath the lithosphere. The thickness of LAB (or the transition zone from lithosphere to asthenosphere) can be deduced from the sharpness of the velocity gradient. Our new anisotropic Australian model has provided us with an insight into the relationship between the lateral variations of LAB and radial anisotropy. In particular, anomalous radial anisotropy (SH>SV) are found within the lithosphere as well as beneath the LAB in central Australia, where we can find thinner transition to the asthenosphere, indicating the effects of past deformation of the lithosphere as well as horizontal flow in the asthenosphere.

Keywords: anisotropy, lithosphere, asthenosphere, surface wave, tomography, upper mantle

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SIT39-05 Room:105 Time:May 24 10:00-10:15

Subducted slabs stagnant above, penetrating through and trapped below the 660-km discontinuity

Yoshio Fukao[1*], Masayuki Obayashi[1]

[1]IFREE/JAMSTEC

We constructed a new P-wave tomographic model of the mantle using more than ten millions of travel time data. The finite frequency effect of seismic ray was taken into account by calculating banana-donut kernels at 2 Hz for all the first arrival data and at 0.1 Hz for the broadband differential travel time data. Based on this model, a systematic survey was made for subducted slab images around the Circum Pacific including Kurile, Honshu, Izu-Bonin, Mariana, Java, Tonga-Kermadec, southern and northern South America, and Central America. This survey clarified a progressive lateral variation of slab configuration along the arc or through the arc to arc, where a subducted slab is in general in one or two of the following four stages: I. slab stagnant above the 660, II. slab penetrating the 660, III. slab trapped in the uppermost lower mantle (660 to ˜1000 km in depth), and IV. slab descending well into the deep lower mantle. The majority of the slab images are either at stage I or III. We interpret I to IV as the successive stages of slab subduction through the transition region with the 660 at the middle, where I and III are relatively stable or neutral stages and II and IV are relatively unstable, transient stages. In particular, we emphasize III as a distinct stage of slab subduction.The presence of this stage may be a consequence of significant softening of the penetrated slab that has undergone post-spinel phase transition. There is a remarkable distinction in deepest hypocentral distribution between a slab at stage I and a slab at stage II or III. Deepest earthquakes occurring within the slab now stagnant above the 660 are limited to depths above ˜620 km and often aligned subhorizontally. Those occurring in the slab penetrating the 660 extend in depth well beyond ˜620 km and are aligned very steeply. All of these observations point to significance of regarding the uppermost lower mantle as a part of the mantle transition region (Bullen, 1963) from the view point of mantle dynamics.

Keywords: subducting slab, 660-km discontinuity, mantle transition zone, deep earthquakes, seismic tomography

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SIT39-06 Room:105 Time:May 24 10:15-10:30

Slab dynamics inferred from kinematic observations of the subduction zone with various slab depths

Tomoeki Nakakuki[1*]

[1]Graduate School of Science, Hiroshima University

Our numerical study showed that trench backward migration is generated when the slab stagnates around the phase boundary at the 660 km depth (Nakakuki et al, 2013). To verify validity of our models, we have studied relationship between the slab dynamics and depths using kinematic observations of the subduction zone. We use data compiled by Lollemand et al. (2005). The data contain ages, dip angles, maximum depths, motions of the subducting plate, migrations of the overriding plate and the trench, back-arc deformations, and slab descending rates. We classified the observations notifying to the maximum depths and dip angles. Our findings are as follows. (1) The most of overriding plate with a shallow slab is compressional. (2) Back-arc extension often occurs in the subduction zone in which the maximum slab depth is 660 km. (3) The trench advances in the subduction zones with the lower mantle slab except in those at the east coast of American continents. (4) Dip angles of the slab penetrating into the lower mantle correlates with the trench migration. (5) Trench with older lithosphere advances and the older slab has steeper dip angles. (6) (4) and (5) means that tips of the lower mantle slab are anchored to the ambient mantle. (7) Dip angle of shallow slab facing to the west direction is steeper than those facing to the east direction. Implications of these observations to the slab dynamics will be discussed in the presentation.

Keywords: subduction zone, back-arc basin, subducted slab, phase transition, mantle convection

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SIT39-07 Room:105 Time:May 24 10:30-10:45

Yield Stress of Plate Boundary and Viscosity of Asthenosphere: Constraints from Plate Spin Motion

Takeshi Matsuyama[1*], Hikaru Iwamori[1]

[1]Department of Earth and Planetary Sciences, Tokyo Institute of Technology

Although more than 40 years have passed since the advent of plate tectonics and some essential problems remain unresolved, such as the generation of plate tectonics from mantle convection, the recent progress in theoretical studies has revealed several important factors to generate plate tectonics, in particular importance of the rheological properties of lithosphere and asthenosphere (e.g., Solomatov and Moresi, 1996; Tackley, 2000; Bercovici, 2003). While numerical simulations quantitatively estimate the rheological properties necessary for generating plate tectonics (e.g., Solomatov and Moresi, 1997; Tackley, 2000; Richards et al., 2001), it is difficult to verify the result from the observational data. In this study, by analyzing the spin motion of the plates comprehensively, we have successfully obtained the relationship between yielding stress of lithosphere and viscosity of asthenosphere, in which dynamic equilibrium of spin motion and the plate size are key as will be explained below.

First, we divide observed plate motions into two components: spin motions and straight motions. For plates without a slab, spin motion of a plate is a result of dynamic equilibrium between the driving force from neighboring plates via the plate boundary associated with shear stress and the resistive force of mantle drag via the bottom area associated with flow and viscosity of asthenosphere. Consequently, we have found that the small plates, or microplates, rotate relatively fast and the large major plates rotate much slower, indicating that there is a critical size between the small plates and the large ones at which plate boundary cannot transmit the motions from one plate to another because shear stress increases with the plate size and accordingly exceeds the yielding stress along the plate boundary. Our analysis suggests a critical diameter (scale or size) of 1000 km, above which spin motion suddenly drops.

For the equation of dynamic equilibrium in spin motion of a plate 1000 km in diameter, using the yielding stress obtained by a numerical simulation, about 10 ~ 200 MPa (Tackley, 2000), we obtain a reasonable range of viscosity of asthenosphere, approximately 1 x 10^19 ~ 1 x 10^21 Pa s, which means that the observational constraint is consistent with the results from numerical simulations for generation of plate tectonics. Note that the yielding stress given by numerical simulations represents the critical stress to deform an intact part of lithosphere instantaneously, rather than a part of the former plate boundary; therefore, we should use the lower value of yielding stress for our theory, which leads to the soft asthenosphere, e.g., 1 x 10^19 ~ 1 x 10^20 Pa s, and implies a mechanism to soften mantle just below the plates, such as melting, as suggested by some authors (e.g., Kawakatsu et al., 2009).

For future works, in order to clarify the nonlinear mechanism to soften lithospheric boundaries, including the effect of grain size and water, a comparative study to investigate the difference between the boundary along a small plate, where plate motion transmits linearly, and that along a large plate, where softening occurs, will be useful to understand the origin of plate tectonics.

Keywords: plate tectonics, plate boundary, asthenosphere, viscosity, rheology, plate spin motion

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SIT39-08 Room:105 Time:May 24 11:00-11:15

Thermodynamic re-determination of post-spinel phase transition boundary in Mg2SiO4

Hiroshi Kojitani[1*], Toru Inoue[2], Masaki Akaogi[1]

[1]Dept. of Chemistry, Gakushuin Univ., [2]GRC, Ehime Univ.

It is widely accepted that the 660-km seismic discontinuity in the deep Earth is caused by the decomposition of $(Mg,Fe)_2SiO_4$ ringwoodite with spinel structure to higher density assemblage of $(Mg,Fe)SiO_3$ perovskite + (Mg,Fe)O ferropericlase. The Clapeyron slope of the post-spinel transition boundary is a very important parameter to discuss pattern of mantle convection. Several previous studies in Mg_2SiO_4 by high-pressure high-temperature experiments and thermodynamic approaches have reported the slope values in a range from -0.4 to -4 MPa/K. However, it has not yet been constrained tightly. Particularly, the phase transition boundary calculated thermodynamically in the previous works included large uncertainty because of less precise thermodynamic data used in the calculations. In this study, we determined more accurately phase transition enthalpy than previous works by measuring drop-solution enthalpies for $MgSiO_3$ perovskite and Mg_2SiO_4 ringwoodite. By using the newly obtained phase transition enthalpy and more reliable thermodynamic data set, containing new data on high-temperature heat capacity of Mg_2SiO_4 ringwoodite by Kojitani et al. (2012a), the phase transition boundary of Mg_2SiO_4 was re-determined thermodynamically.

The drop-solution enthalpy measurements were performed using a Calvet-type twin micro-calorimeter. Samples were dropped from outside of the calorimeter at room temperature into $2PbO.B_2O_3$ solvent at 978 K. High-pressure syntheses of $MgSiO_3$ perovskite and Mg_2SiO_4 ringwoodite samples were made using a Kawai-type high-pressure apparatus. Platinum was used for a heater and sample capsule. $MgSiO_3$ perovskite sample was not ground into powder to avoid possible amorphization. Instead, sintered pieces of $MgSiO_3$ perovskite were used for the enthalpy measurement.

Drop-solution enthalpies for $MgSiO_3$ perovskite and Mg_2SiO_4 ringwoodite were obtained to be 16.47 +/- 0.52, 128.75 +/- 1.99 kJ/mol, respectively. Combining them with drop-solution enthalpy for MgO of 33.74 +/- 0.99 kJ/mol (Kojitani et al.. 2012b), the phase transition enthalpy for the post-spinel transition was determined as 78.54 +/- 2.24 kJ/mol. This value is 10~20 kJ/mol smaller than the previously reported ones. Thermal expansivities and heat capacities for MgSiO3 perovskite and Mg_2SiO_4 ringwoodite were calculated thermodynamically based on the lattice vibrational model calculation. The post-spinel transition boundary calculated in this study passes through 22.7 +/- 0.9 GPa at 1873 K. The obtained Clapeyron slope is -1.2 +/- 0.3 MPa/K at 1873 K, which is gentler than those from the previous thermodynamic calculations, and is consistent with those determined by recent high-pressure in situ X-ray diffraction experiments. The result of this study implies that the post-spinel transition boundary is less effective in impeding mantle convection than previously evaluated.

Keywords: post-spinel phase transition boundary, Mg2SiO4, enthalpy measurement, thermodynamic calculation, Clapeyron slope, mantle convection

SIT39-09 Room:105 Time:May 24 11:15-11:30

Investigation on thermodynamic properties of Fe- and Al-bearing MgSiO3 perovskite: an internally consistent LSDA+U study

Xianlong Wang[1*], Taku Tsuchiya[1]

[1]Geodynamics Research Center,Ehime University

Researchers have extensively focused on behaviors of iron (Fe) in Fe-bearing $MgSiO_3$ perovskite (Pv) and postperovskite (PPv) at high pressure and high temperature to better understand the thermodynamic properties of the Earth's lower mantle (LM). Effects of Fe^{2+} and Fe^{3+} on the thermodynamic properties of Pv and PPv were already clarified in our previous work through first-principles simulations [1,2,3]. However, corresponding effects of aluminum (Al), which is believed to be another important impurity in the LM minerals and can increase the concentration of Fe^{3+} significantly in silicate Pv, are still not clear. In this work, by taking use of first-principles method combined with the internally consistent LSDA+U method and quasi-harmonic approximation (QHA), the thermodynamic properties of Fe- and Al-bearing Pv under several pressures, from 0 GPa to 180 GPa, are investigated. At the beginning, we will discuss stability of the structures and spin-configurations of Fe^{3+} and Al^{3+}-bearing Pv. Our results show that the configuration with high-spin Fe^{3+} substituted at the Mg site, while Al^{3+} located at its neighboring Si site, has the lowest enthalpy through the whole LM pressure range, showing that the spin transition of Fe^{3+} co-doped with Al^{3+} in Pv is highly unlikely under LM conditions. Then, based on the structural stability, the thermodynamic properties of Fe^{3+}- and Al^{3+}-bearing Mg Pv will be discussed.

Keywords: First-principles method, internally consistent LSDA+U, thermodynamic properties, Fe- and Al-bearing Mg Pv

SIT39-10 Room:105 Time:May 24 11:30-11:45

Growth kinetics of $MgSiO_3$ perovskite reaction rim up to 50 GPa

Masayuki Nishi[1*], Yu Nishihara[1], Tetsuo Irifune[1]

[1]Geodynamics Research Center, Ehime University

Mineral diffusion rates provide important constraints for understanding many physical and chemical processes in the Earths interior, including mantle rheology and chemical transportation. For many mantle silicates, Si is the slowest diffusion species and the rheology of the lower mantle is considered to be controlled by Si diffusion in perovskite. However, recent experimental studies have indicated that Mg lattice diffusion in perovskite is also extremely slow and has very similar diffusivity to Si. Although the characteristic lattice diffusivity of Mg in perovskite has been found, little is known about the rate of its grain boundary diffusion. Furthermore, there is no experimental data on the pressure dependence of diffusivity in perovskite. In this study, we examined the growth kinetics of the polycrystalline perovskite rim between periclase and stishovite under lower mantle conditions up to 50 GPa. Based on the experimental results, the grain boundary diffusivity in $MgSiO_3$ perovskite and the chemical transportation in the mantle are discussed.

We performed high-pressure and high-temperature experiments using a Kawai-type high-pressure apparatus (Orange 3000 and MADONNA II) installed at Ehime University, Japan. Single crystals of periclase and a fine powder of quartz were used as the starting materials for the reaction experiments. In order to determine the mobile component controlling the overall reaction progress, a small amount of Pt powder was placed onto the flat surface of the periclase. The sample assembly was composed of sintered (Mg,Co)O and ZrO_2 pressure mediums, a cylindrical $LaCrO_3$ heater, a molybdenum electrode, and a graphite sample capsule. Thicknesses of reaction layers and corresponding grain widths were measured by a Field-Emission Scanning Electron Microprobe (FE-SEM) (JEOL JSM-7000F) equipped with an Energy Dispersive Spectrometer (EDS) at Ehime University. Raman spectroscopy revealed that the reaction rim consisted of perovskite.

The Pt-markers were always observed at the perovskite-periclase interface in the run products. This indicates that the rim growth is controlled by the diffusion of Mg or O in perovskite and Si is the slowest diffusion species in this system. The growth rate of perovskite in this study is not parabolic but slower. Using the kinetics of coupled rim growth and grain coarsening, we calculated the grain boundary diffusion coefficient of Mg which possibly controls the rim growth. The grain boundary diffusion coefficient of Mg in the perovskite was determined to be ˜4-5 orders of magnitude faster than that of Si. We found that the bulk diffusivity of Mg in polycrystalline perovskite is affected by the grain boundary when we consider the possible grain sizes and temperatures in the lower mantle. Accordingly, grain boundary diffusion in perovskite may be an effective mechanism for chemical transportation of divalent cations in the lower mantle.

Keywords: MgSiO3 perovskite, lower mantle, rim growth kinetics, grain growth, diffusion

SIT39-11 Room:105 Time:May 24 11:45-12:00

Effect of light elements on partitioning of potassium between liquid iron alloys and silicate melts

Kosui Watanabe[1*], Eiji Ohtani[1], Seiji Kamada[1], Masaaki Miyahara[1]

[1]Division of Earth and Planetary Materials Science, School of Science, Tohoku University

The Earth's core is mainly composed of Fe and its density is smaller than that of pure Fe under the core conditions. Therefore, the core has been considered to contain light elements, such as H, S, Si, C, and O (e.g., Poirier, 1994). It has been suggested that the core might include radioactive elements as heat sources (e.g., Labrosse et al., 2001). Potassium (K), one of the radioactive elements, is depleted in the mantle compared to C1-chondrite. Volatile elements are depleted as well but the quantity of depleted potassium is more than the other volatile elements (e.g., Corgne et al., 2007). Therefore, there is a possibility that K is included into the Earth's core.

Several partitioning experiments on K between liquid iron and silicate melts have been performed using a multi anvil press (MA) and a diamond anvil cell (DAC). Explored pressures in the MA experiments were limited to be less than 26 GPa (e.g., Ito et al., 1993). Although DAC experiments were conducted up to 135 GPa (Hirao et al., 2005), the metallic composition was pure Fe. The compositions of the metal were only pure Fe or Fe-FeS system in the previous studies. We carried out partitioning experiments between iron-light element (O, C, or Si) alloys and silicate melts as candidate materials of the core using a laser heated DAC (LHDAC).

Chemical compositions of starting materials of metals are powder mixtures of Fe and FeO ($Fe_{75}O_{25}$), Fe and FeSi ($Fe_{75}Si_{25}$), and Fe_3C. A silicate phase of the starting material is a natural Adularia ($KAlSi_3O_8$, Switzerland). A symmetric type DAC was used to generate high pressure and a Nd:YAG laser or a fiber laser was employed to generate high temperature. Pressure was measured based on Raman T_{2g} mode at the culet of the diamond anvil (Akahama & Kawamura, 2004) and temperature was measured by a spectrometric method using radiation spectrometry. Pressure conditions were between 25 and 50 GPa and temperature conditions were between 2500 and 4500 K. Recovered sample were cut by a focused ion beam (FIB) system and analyzed by an electron probe micro analyzer (EPMA).

The effect of temperature on distribution coefficients of K, D_K, in Fe-C system was slightly positive, which is consistent with previous studies on temperature effect on D_K. C and Si do not change D_K significantly compared to pure Fe under explored pressure conditions. On the other hand, the effect of O in liquid Fe on D_K is positive, which is the same as the effect of S (Bouhifd et al., 2007). O (and S) may increase the amount of K in the Earth's core although Si and C may not affect on the amount of K in the core. Therefore, S and O are the important light elements with respect to the amount of potassium in the core.

Keywords: potassium, light elements, high pressure, high temperature, Earth's core, partitioning coefficients

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SIT39-12 Room:105 Time:May 24 12:00-12:15

Effects of light elements on metal-silicate partitioning of siderophile elements

Yoichi Nakajima[1*], Daniel J Frost[2], David C Rubie[2]

[1]RIKEN SPring-8 Center, [2]University of Bayreuth

The most important constraints on processes and conditions of core formation in the early history of the Earth are provided by the chemistry of the Earth's mantle combined with experimental data on the partitioning of a wide range of elements between metal and silicate. Up to data, the element partitioning has been insensibly studied under variety conditions of pressure, temperature, oxygen fugacity. In addition to these physical parameters, the light elements in the present Earth's core are also expected to have an influence on element partitioning behaviors during core formation. In this study, we investigate the effects of Si, O and S on the element partitioning for Ni, Co, W, V, and Cr between liquid metal and silicate melt.

The partitioning experiments were performed at 15-25 GPa and at 2700-3000 K using a Kawai-type multianvil apparatus. The partitioning coefficients between liquid metal and silicate melt were obtained from chemical analyses using an electron microprobe. We evaluate the results with the Wager's activity model for metal alloys which takes into account mutual interactions between Fe, Si, S, O and the siderophile elements of interest. The distribution coefficients for Ni and Co decrease by ~0.2 log units by adding 8 wt% Si to metal, whereas O has negligible influence for both elements at the present experimental conditions ($<$1.2 wt% O). The addition of 3 wt% S decreases coefficients for Co by ~0.3 log units whereas its effect on Ni is relatively small. The Si content has less and negligible effect on V and Cr partitioning, respectively. In contrast, both S and O can make V and Cr more siderophile. The influence of Si is significantly emphasized in the W partitioning and the partitioning coefficient for W decreases by 2 order magnitude with the addition of 8 wt% Si.

The recently prevailing view of core formation is that the core forming metal segregated continuously from silicate magma ocean through the Earth's accretion history (e.g. Rubie et al., 2011 EPSL). In addition, the accreting materials on proto-Earth could have changed with a time from highly-reducing to oxidizing and finally volatile-rich, which may result in the progressive change of dominant light elements of core forming metals from Si-rich to O and/or S-rich. As shown in this study, the change of dominant light elements could affect the element distributions in relevant phases during core formation.

Keywords: element partitioning, light elements, core formation

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SIT39-13 Room:105 Time:May 24 14:15-14:30

Geomagnetic drifting field in favor of stratification at the top of the Earth's core

Takesi Yukutake[1*], Hisayoshi Shimizu[2]

[1]None, [2]Earthquake Research Institute, University of Tokyo

Geomagnetic drifting field mainly consists of sectorial harmonics. The problem is why only the sectorial fields are observed in the drifting field, while the other types of field are not.

In order to solve this problem, we examined the interaction of the surface flow of the core with a dipolar field, and found two are important. One is the boundary condition on the electric current at the core mantle boundary (CMB), and the other is existence of stable stratification at the top of the core.

The core is assumed to be a perfect conductor with a free surface. At the CMB the electric current normal to the boundary must vanish. This requires that the toroidal flow should be sectorial type, which induces sectorial types of poloidal magnetic field through interaction with the dipolar field.

In a stably stratified layer where the Brunt-Vaisala frequency is as high as the Earth's angular frequency, gravitational force strongly acts on the poloidal flow to produce fluid oscillations with the same order of frequencies as the Brunt-Vaisala frequency. Oscillations with such high frequencies, particularly with frequencies near harmonics of the Earth's angular frequency, are difficult to discern from various phenomena with similar frequencies on the Earth's surface. Furthermore magnetic field with such frequency is by far weaker than that of magnetostrophic oscillation of the toroidal flow whose frequency is very low, because the field intensity is inversely proportional to the frequency. These are supposed to be the reason why the harmonic components other than sectorial are invisible in the drifting field. It is, therefore, concluded that the stable stratification is necessary at the top of the core to suppress the effect of the poloidal flow on the drifting field.

Keywords: geomagnetic drifting field, westward drift

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SIT39-14 Room:105 Time:May 24 14:30-14:45

Melting relations of Fe-Ni-Si and Fe-Ni alloys up to 135 GPa

Akihiro Takahata[1*], Eiji Ohtani[1], Seiji Kamada[1], Masaaki Miyahara[1], Tatsuya Sakamaki[1]

[1]Division of Earth and Planetary Materials Science, School of Science, Tohoku University

The density deficit of the Earth's core was proposed based on the comparison between seismic study and high-pressure experiments. Therefore, the Earth's core consists of not only Fe-Ni alloys but also light elements, such as H, C, O, Si, and S (e.g., Birch, 1952). Therefore, densities and phase relationships in the Fe-light element(s) have been studied well. Silicon, in particular, is one of the most abundant elements in the Earth (e.g., Ringwood, 1959; Birch, 1964). In addition, the solubility of silicon into liquid iron increases with increasing pressure and temperature, and hence there is a possibility that the silicon can solve into outer core by reaction with the lower most silicate mantle (Takafuji et al., 2005; Sakai et al., 2006). Lin et al. (2003) reported that the outer core contains about 8-10 wt% Si and the inner core contains about 4 wt% Si. However, there are some discrepancies in the melting relationships of Fe.

Therefore, the thermal structure of the Earth's core has not been known well yet. For better understandings of the thermal structure of the core, a key point is that the core is composed of the solid inner core and the liquid outer core, suggesting that the temperature at the ICB is the melting temperature of the core material. We focused on the melting relationships of the core materials to constrain the thermal structure of the core. In this study, melting temperature of the Fe-Ni alloy and the Fe-Ni-Si alloy were measured under high pressure conditions to estimate the thermal structure of the Earth's core.

Starting material are Fe-4.8 wt%Ni-4.0 wt% Si alloys and Fe-5.2 wt% Ni alloys. Pressure medium is powdered Al_2O_3. A high pressure device is a symmetric diamond anvil cell. A foil of the starting material was sandwiched by Al_2O_3 powder. The sample was compressed to a desire pressure first. Then, the sample was heated by a double-sided laser technique by employing Nd:YAG laser or fiber laser. Temperature was measured using the radiation from the sample. Pressure measurement was conducted by using Raman T_{2g} mode at the culet of diamond anvil (Akahama and Kawamura, 2004).

Determination of the melting temperature is based on the change in the temperature generation efficiency (e.g., Asanuma et al., 2010; Lorad et al., 2010), the observation of the dendritic quench texture of the recovered sample at 135 GPa using FE-SEM/STEM, and monitoring the in-situ radiation from the sample. The melting experiments of Fe-4.8 wt%Ni-4.0 wt% Si were performed in the P-T ranges of 20-135 GPa and 1000-4000 K. The melting experiments of Fe-5.2wt% Ni were performed in the P-T ranges of 20-135 GPa and 1000-5000 K.

The melting temperature of Fe-Ni-Si alloy was 3720 K at 135 GPa (CMB pressure), and that of Fe-Ni alloy was 4330 K. The effect of silicon on the melting temperature of Fe-Ni alloy is large and decreases 600 K at the CMB condition. The effect of silicon on the melting temperature of Fe-Ni alloy is large and decreases by 600 K at the CMB condition. Based on the melting curve of Fe-4.8 wt%Ni-4.0 wt% Si, we estimated the temperature at the ICB and CMB to be 4980 K and 3820 K assuming that the composition of the inner core is Fe-4.8 wt%Ni-4.0 wt% Si.

Keywords: High pressure, Light element, Silicon, Fe-Ni-Si and Fe-Ni alloys melting temperature, Core mantle boundary, Inner core boundary

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

SIT39-15 Room:105 Time:May 24 14:45-15:00

Sound velocity measurements of liquid Fe-S and Fe-Si at high pressure

Keisuke Nishida[1*], Hidenori Terasaki[2], Masashi Ushioda[1], Moe Sakurai[1], Souma Kuwabara[2], Yuji Higo[3], Ken-ichi Funakoshi[3], Eiji Ohtani[4]

[1]Department of Earth and Planetary Sciences,Tokyo Institute of Technology, [2]Graduate School of Science, Osaka University, [3]Japan Synchrotron Radiation Research Institute, [4]Department of Earth and Planetary Materials Science, Graduate School of Science, Tohoku University

P-wave velocity (V_P) is one of the most useful physical properties to understand the struc-ture and dynamics of the liquid core of the Earth, terrestrial planets and satellites. These liquid cores are thought to contain the light element such as S and Si. Thus, it is important to understand effect of S and Si on V_P in liquid Fe. Direct V_P measurement of liquid Fe-alloy at high pressure using ultrasonic was developed by Nishida et al. (2013). V_P of liquid Fe57S43 were reported up to 5.4 GPa. Here we report the results of direct V_P measurements of liquid Fe84S16, Fe50S50, and Fe82Si18 up to 5.4 GPa.

High-pressure experiments were performed using a 1500-ton Kawai-type multi-anvil appa-ratus (SPEED-1500) at the BL04B1 beamline, SPring-8, Japan. The starting materials were pellets consisting of a mixture of Fe and FeS, or Fe and FeSi powders. Single-crystal sapphire or sintered Al2O3 was used as a buffer rod and a backing plate with an hBN capsule. V_P meas-urements were carried out using the pulse-echo-overlap method. P-wave signals with a fre-quency of 37 or 42 MHz were generated and received by a 10^o Y-cut LiNbO3 transducer. The series of reflected signals were acquired using a digital oscilloscope. The sample lengths at high pressure and high temperature were determined from the X-ray radiographic image.

The V_P of liquid Fe84S16, Fe50S50, and Fe82Si18 increased almost linearly with increasing pressure. The V_P of liquid Fe82Si18 was faster than that of liquid Fe (Anderson and Ahrens, 1990) and Fe-S. The V_P of liquid Fe-S decreased with increasing S content.

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

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SIT39-16 Room:105 Time:May 24 15:00-15:15

Sound velocities of $Fe^{75}Ni^{15}Si^{10}$ alloys up to 800GPa by laser-shock compression

Naoya Yokoyama[1*], Ryota Hosogi[1], Tatsuhiro Sakaiya[1], Tadashi Kondo[1], Keisuke Shigemori[2], Youichiro hironaka[2]

[1]Graduate School of Science, Osaka University, [2]Institute of Laser Engineering, Osaka University

The Earth's outer core is considered to be composed of iron (Fe) with few percent of nickel (Ni) and light elements (such as silicon (Si), sulfur (S), oxygen (O), hydrogen, and carbon etc.) The sound velocity of Fe alloy is important to consider the composition of Earth's outer core because it can be directly compared with seismic data. The sound velocity measurement of liquid Fe-S-O using gas gun has been reported [1]. As a result, the effect of O for the sound velocity is stronger than that of S. Although Si and Ni are very important elements in Earth's outer core, the effect of Si and Ni for liquid Fe on the outer core conditions has never been reported. In this study, we have measured the sound velocity of laser-shocked $Fe^{75}Ni^{15}Si^{10}$ up to 800 GPa. Comparing to the sound velocity of liquid Fe at same density, the sound velocity of $Fe^{75}Ni^{15}Si^{10}$ is higher about 20%.

We performed laser-shock experiments at the GEKKO-HIPER Laser system in Institute of Laser Engineering, Osaka University. The laser-shock compression can generate pressures of 400-800 GPa which are much higher pressures than previous works by gas guns [1, 2].

The sound velocity of the alloys was measured by side-on radiography [3]. In this technique the time variation of the X-ray shadow of target is recorded on X-ray streak camera by using x ray irradiated from the side of target. The sound velocity is obtained from the time variation of the X-ray shadow because the rarefaction wave propagates target material with the sound velocity (See experimental details [3]).

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Keywords: Sound velocity, Outer core, Laser, Nickel, Silicon

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SIT39-17 Room:105 Time:May 24 15:15-15:30

Sound velocity measurements for iron alloys at Earth core pressures and universal relations between solid and liquid

Tatsuhiro Sakaiya[1*], Naoya Yokoyama[1], Ryota Hosogi[1], Tadashi Kondo[1], Hidenori Terasaki[1], Keisuke Shigemori[2], Yoichiro Hironaka[2]

[1]Graduate School of Science, Osaka University, [2]Institute of Laser Engineering, Osaka University

When we consider the structure of Earth's interior, the sound velocity is one of the important physical properties of the interior materials because it can be directly compared with the seismological data which can yield the physical properties of the Earth's interior. Although it needs to measure the sound velocity of the interior material under high pressure and temperature, the sound velocity measurement of the materials on the condition over 200 GPa and 4000 K, such as the core condition, is technically difficult in static compression technique (e.g. diamond anvil cell: DAC) (1-4). Therefore, in such high pressure and temperature, dynamic compression technique, such as gas gun, is used. Although some works about the sound velocity of pure iron have been done by gas gun (5-7), it is not enough to discuss about the Earth's core which consists of iron alloy. Although Badro et al. (8) and Fiquet et al. (9) measured compressional sound velocity for several iron alloys (FeO, FeSi, FeS, FeS_2, and Fe_3C) at room temperature by inelastic x-ray scattering (IXS) at the DAC, the sound velocity data of liquid iron alloy is very few (10, 11).

We performed laser-shock experiments of liquid iron alloys at HIPER system of Gekko-XII laser in Institute of Laser Engineering, Osaka University (12). We measured the sound velocities of iron alloys (Fe-Ni-Si system) under Earth's core conditions. The sound velocities were measured by side-on radiography (13). Our data of sound velocity and density for pure iron and the data from previous studies of liquid iron (5, 6, 14) indicate a linear sound velocity-density relation, at least up to 800 GPa, which is in good agreement with Birch's law (15). The sound velocity for iron alloys and the data from previous studies of liquid iron alloyed with O and S (10, 11) were linearly related to the density of the alloy, suggesting that Birch's law is also applicable to the liquid phase of iron alloys. Our work and the previous results (3, 5, 6, 10, 11, 14) suggest that generally the sound velocity as a function of density has the same slope ratio of approximately 1.5 between the solid and liquid phases for iron, iron alloys, and Earth's core (17). The sound velocity in the liquid phase is about 10% lower than in the solid phase at melting point density. These relations between solid and liquid along the Hugoniot are universal for metals.

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Keywords: sound velosity, laser, shock wave, iron alloy, Earth's core, experiment

SIT39-18 Room:105 Time:May 24 15:30-15:45

Internally-heated diamond anvil cell experiments on Earth's core materials

Tetsuya Komabayashi[1*]

[1]Dept. Earth Planet. Sci., Tokyo Tech.

I will review the recent technical development of the so-called internally heated diamond anvil cell (DAC) experiments on Earth's core materials. As iron is the primary phase of the Earth's core, its phase relations have been extensively investigated for the last 50 years, mostly by means of high-pressure experiments. For high-temperature DAC, high temperature can mostly be achieved by either a laser-heating or an external-heating system. Laser-heating produces very high temperatures ($>$ 3000K), but the heating stability may be affected by many factors during the heating and the temperature uncertainty is large (+- 200 K). The external-heating system can stably heat the sample and the temperature uncertainty is small (+- 10 K) but it is limited to lower temperatures ($<$ 1300 K). We have developed a resistive internal-heating technique, in which thin iron (alloy) foil served as a heater and a sample simultaneously. By resistance heating, it produces much more stable heating than the laser-heating technique and much higher temperature than the external-heating system. Together with an angle-dispersive high-resolution X-ray diffraction method, we have carried out high-P-T in-situ measurements of the gamma-epsilon transition in Fe and Fe-Ni alloy. Accurate determination of the gamma-epsilon transition boundary is essential for assessing the phase diagram of iron at high pressure and temperature. In addition, it is quite useful for testing and deriving a thermodynamic model of the pure iron because many of the thermodynamic parameters for the gamma and epsilon phases cannot be directly measured. In addition, I will also present new data of Fe-Si alloy from the internally-heated DAC.

Keywords: high-pressure experiment, diamond anvil cell, resistive-heating, internal-heating, Earth's core

SIT39-19 Room:105 Time:May 24 15:45-16:00

The crystal structure of the Earth's inner core

Shigehiko Tateno[1*], Kei Hirose[1], Yasuo Ohishi[2]

[1]Tokyo Institute of Technology, [2]Japan Synchrotron Radiation Research Institute

Determining the crystal structure of the Earth's inner core is a key piece of information required to decipher the complex seismic structures observed there. Although recent static ultrahigh-pressure and -temperature (P-T) experiments (Tateno et al. 2010) revealed that iron adopts the hexagonal closed-packed structure up to 377 GPa and 5700 K under inner core P-T conditions, the effect of impurity element(s) on the stable crystal structure still remains controversial. We have studied stable form of Fe-10wt.%Ni and Fe-9wt.%Si in the inner core conditions by synchrotron X-ray diffraction measurements in-situ at ultrahigh P-T in a laser-heated diamond-anvil cell at BL10XU, SPring-8.

We found that hcp phase of Fe-Ni alloy is stable throughout the experimental conditions to 340 GPa and 4700 K, which is evident from the spotty diffraction ring (Tateno et al., 2012). Any other phases such as body-centered cubic (bcc) or face-centered cubic (fcc) phases was not observed. Similarly, we found wide stability of hcp-structured Fe-Si alloy. Pressure-volume data of hcp Fe-9wt.%Si to 305 GPa was collected after laser annealing at 1300-3000 K depending on pressure, which was fitted to Vinet's equation of state. Subsequently, phase relations of Fe-Si alloy was investigated from 320 GPa at 2000 K to 410 GPa at 5900 K. Appearance of diffraction peak from bcc in addition to hcp was observed above 5000 K, indicating decomposition to the mixture of Si rich bcc and Si poor hcp phase. This shows limited solubility of Si in hcp being close to 9wt.% in the inner core conditions. Si content in the inner core has been proposed to be 3-5wt.%, which is much less than maximum solubility in hcp phase (e.g., Alfe, 2002; Badro et al., 2007). If silicon is major light element in the inner core, Fe-Ni-Si alloy crystalizes to an hcp structure at inner core conditions.

Keywords: high pressure, DAC