

膨張収縮地球 Expanding-contracting Earth

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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

Three layers model of continents and whole mantle dynamics Three layers model of continents and whole mantle dynamics

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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 magmatic activity after 2.7Ga over a few hundred m.y.

USArray を用いた北米大陸の減衰構造：非線形波形フィッティングによる表面波振幅の2点法解析 Attenuation structure of North America using USArray: A two-station approach for surface-wave amplitude analysis

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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.

キーワード: 減衰構造, 非線形波形フィッティング, 表面波振幅, 2点法

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

豪州大陸下の上部マントル鉛直異方性とリソスフェア-アセノスフェア境界 Radial anisotropy and lithosphere-asthenosphere boundary of the Australian upper mantle

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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.

キーワード: 異方性, リソスフェア, アセノスフェア, 表面波, トモグラフィー, 上部マントル

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

マントル遷移層に滞留、660-km層を貫通、下部マントル最上部にトラップされるスラブ Subducted slabs stagnant above, penetrating through and trapped below the 660-km discontinuity

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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.

キーワード: 沈み込むスラブ, 660-km層, マントル遷移層, 深発地震, 地震波トモグラフィ
Keywords: subducting slab, 660-km discontinuity, mantle transition zone, deep earthquakes, seismic tomography

沈み込み帯の運動学的データから見たスラブの深度とダイナミクス Slab dynamics inferred from kinematic observations of the subduction zone with various slab depths

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我々の数値シミュレーション (Nakakuki et al., 2013) は、スラブがマントル遷移層へ滞留すると同時に、海溝の後退が起きることが示唆している。また、いったん滞留したスラブが下部マントルに崩落するメカニズムとして、660km 相変化において細粒化が起き、強度が低下すること (Nakakuki et al., 2010) や、海溝が前進すること (Yoshioka et al., 2010) が考えられている。モデルを検証するために、沈み込み帯の運動やスラブの形状に関するデータを解析した。本研究では、これまでの研究であまり注目されなかったスラブの最大深度、特に 660km 相境界とスラブのダイナミクスとの関係が明らかになるよう注意した。

使用したデータは Lallemand et al. (2005) によりコンパイルされたものである。このデータでは、沈み込み帯を全 158 の区間に分け、以下のようなデータをまとめている。沈み込むプレートの年代、沈み込むプレートの運動速度、スラブ浅部 (<125km) の伏角、スラブ深部 (>125km) の伏角、スラブ先端の深さ、スラブ先端の沈み込み速度、海溝の移動速度、上盤プレートの運動速度、背弧の変形速度、である。まず、スラブをその最大深度が浅いもの (<300km)、上部マントル (300~660km)、660km、下部マントル (>660km)、さらに、スラブ深部の伏角が浅いもの (<45°) と深いもの (>45°) に分ける。その上で、様々なデータをプロットし、相関があるか否かを調べる。その結果、以下のようなことが分かった。(1) スラブが短い沈み込み帯の背弧は圧縮されている。(2) 海溝が高速に後退しているスラブは同程度の熱パラメータを持つプレートより、沈み込むプレートの速度が遅い。(3) 背弧拡大がある多くの沈み込み帯では、スラブの最深点が 660km の深さにある。(4) スラブの最深点が 660km にあるスラブは様々な海溝移動速度、伏角を持つ。(5) 下部マントルに沈み込むスラブは、年代の古い物が多く、下部マントルスラブを持つ沈み込み帯の多くで、海溝が前進している。(6) 上部マントルに沈み込んでいるスラブの伏角は海溝の移動速度や沈み込むプレートの年代と相関を持たない。(7) 下部マントルに沈み込んでいるプレートの角度は年代および海溝の移動速度と強い相関を持つ。(8) 下部マントルに沈み込んでいるスラブでは、西向きの方が浅い伏角を持つ。特に浅部の伏角では明瞭である。

これらの結果から、次のようなスラブのダイナミクスが浮かび上がってくる。(1) プレートの沈み込みは 2 つのプレートの衝突、つまり強い圧縮により始まる。(2) スラブが上部マントルにあるときには、スラブは固定されておらず、自由に移動できる。(3) 海溝が後退するスラブの多くは、我々のシミュレーションと異なり、プレートが表面からはがれ落ちるように運動しており、このようなスラブは急角度を持つ。(4) 上盤プレートの運動に対するスラブの後退、すなわち背弧の拡大は、スラブが 660km 境界と相互作用しているときに起こる。これは、660km 境界の浮力によりスラブの沈み込み運動が妨げられるからと考えられる。(5) 多くのスラブの下部マントルへの崩落は海溝の前進により起こる。その原因の重要なものは沈み込むプレートの年代の増加であると考えられる。(6) 下部マントルスラブは下部マントルにアンカーされる。このため伏角が海溝の運動によって影響される。(7) リソスフェアの全体回転が存在し、下部マントルに沈み込んでいるスラブの伏角に影響している。

キーワード: 沈み込み帯, 背弧海盆, スラブ, 相変化, マントル対流

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

プレート回転運動の解析によるプレート境界の降伏応力とアセノスフェアの粘性率の制限 Yield Stress of Plate Boundary and Viscosity of Asthenosphere: Constraints from Plate Spin Motion

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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 $1 \times 10^{19} \sim 1 \times 10^{21}$ 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., $1 \times 10^{19} \sim 1 \times 10^{20}$ 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.

キーワード: プレートテクトニクス, プレート境界, アセノスフェア, 粘性率, レオロジー, プレート回転運動

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

熱力学的手法による Mg_2SiO_4 のポストスピネル相転移境界の再決定 Thermodynamic re-determination of post-spinel phase transition boundary in Mg_2SiO_4

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地球深部の 660 km 地震波不連続面は、スピネル型結晶構造を持つ $(Mg,Fe)_2SiO_4$ リングウツダイトが、より高密度である $(Mg,Fe)SiO_3$ ペロブスカイト + $(Mg,Fe)O$ フェロペリクレスに分解していることが原因であると考えられている。このポストスピネル相転移の相転移境界線のクラペイロン勾配は、マントル対流のパターンを考える上で非常に重要なパラメータである。このため、これまで多くの高圧高温実験や熱力学計算により Mg_2SiO_4 のポストスピネル相転移境界線の決定が行われてきた。しかしながら、報告されているクラペイロン勾配の値は $-0.4 \sim -4$ MPa/K と幅広く、まだ十分に制約されていない。特に、熱力学計算により求められたクラペイロン勾配には、使用された熱力学データの精度に問題があったために大きな不確かさが伴っていた。本研究では、 $MgSiO_3$ ペロブスカイトおよび Mg_2SiO_4 リングウツダイトの落下溶解エンタルピー測定を行うことにより、従来よりも信頼性の高い相転移エンタルピーを決定した。さらに、Kojitani et al. (2012a) による最新の Mg_2SiO_4 リングウツダイトの定圧熱容量など、より信頼できる熱力学データセットを用いることにより、 Mg_2SiO_4 のポストスピネル相平衡境界線を熱力学的に再決定した。

落下溶解エンタルピー測定は、カルペー型双子微小熱量計を用いて行われた。試料を室温から 978 K の $2PbO \cdot B_2O_3$ 溶媒に落下させ溶解させた。測定に用いた Mg_2SiO_4 リングウツダイトと $MgSiO_3$ ペロブスカイト試料は、川井型マルチアンビル高圧発生装置を用いて高圧合成した。なお、試料カプセル兼ヒーターには Pt を用いた。 $MgSiO_3$ ペロブスカイトの測定では、アモルファス化を避けるため粉末にはせず、焼結体のまま熱量計中に落下させた。

$MgSiO_3$ ペロブスカイトと Mg_2SiO_4 リングウツダイトの落下溶解エンタルピー (H_{d-s}) は、それぞれ 16.47 ± 0.52 , 128.75 ± 1.99 kJ/mol と得られた。それらに加え MgO の $H_{d-s} = 33.74 \pm 0.99$ kJ/mol (Kojitani et al., 2012b) を用いると、相転移エンタルピーは 78.54 ± 2.28 kJ/mol と決定された。この値は、従来報告されているものよりも $10 \sim 20$ kJ/mol 小さい。また、 $MgSiO_3$ ペロブスカイトと Mg_2SiO_4 リングウツダイトの熱膨張率と定圧熱容量は、格子振動モデルに基づき熱力学的に計算で求めた。本研究の熱力学計算によるポストスピネル相転移境界線は、1873 K で 22.7 ± 0.9 GPa を通る。クラペイロン勾配は、 -1.2 ± 0.3 MPa/K と求められた。この値は、これまでの熱力学計算によるものよりも緩やかであり、近年の高圧その場観察実験により決定されている値と調和的である。本研究による結果は、ポストスピネル相転移境界がマントル対流の障壁となる効果はあまり大きくないであろうことを示唆している。

キーワード: ポストスピネル相転移境界, Mg_2SiO_4 , エンタルピー測定, 熱力学計算, クラペイロン勾配, マントル対流
Keywords: post-spinel phase transition boundary, Mg_2SiO_4 , enthalpy measurement, thermodynamic calculation, Clapeyron slope, mantle convection

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

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Researchers have extensively focused on behaviors of iron (Fe) in Fe-bearing MgSiO₃ 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 Fe²⁺ and Fe³⁺ 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 Fe³⁺ 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 Fe³⁺ and Al³⁺-bearing Pv. Our results show that the configuration with high-spin Fe³⁺ substituted at the Mg site, while Al³⁺ located at its neighboring Si site, has the lowest enthalpy through the whole LM pressure range, showing that the spin transition of Fe³⁺ co-doped with Al³⁺ in Pv is highly unlikely under LM conditions. Then, based on the structural stability, the thermodynamic properties of Fe³⁺- and Al³⁺-bearing Mg Pv will be discussed.

キーワード: First-principles method, internally consistent LSDA+U, thermodynamic properties, Fe- and Al-bearing Mg Pv

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

MgSiO₃ ペロブスカイトの反応帯成長速度 Growth kinetics of MgSiO₃ perovskite reaction rim up to 50 GPa

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Mineral diffusion rates provide important constraints for understanding many physical and chemical processes in the Earth's 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 MgSiO₃ 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 ZrO₂ pressure mediums, a cylindrical LaCrO₃ 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.

キーワード: MgSiO₃ ペロブスカイト, 下部マントル, 成長速度, 粒成長, 拡散
Keywords: MgSiO₃ perovskite, lower mantle, rim growth kinetics, grain growth, diffusion

高温高圧下における溶融金属鉄 - 珪酸塩融体間のカリウム分配への溶融鉄中軽元素の影響

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

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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 ($\text{Fe}_{75}\text{O}_{25}$), Fe and FeSi ($\text{Fe}_{75}\text{Si}_{25}$), 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.

キーワード: カリウム, 軽元素, 高圧力, 高温, 地球の核, 分配係数

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

金属-シリケート間の親鉄元素分配に対する軽元素の影響 Effects of light elements on metal-silicate partitioning of siderophile elements

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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.

キーワード: 元素分配, 軽元素, 核形成

Keywords: element partitioning, light elements, core formation

地磁気移動性磁場と核表層部の成層性

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

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地球磁場は移動性磁場と停滞性磁場とで構成される。移動性磁場の特徴のひとつは、鉛直磁場が球関数表示で主として sectorial 項 ($n=m$ の扇球関数) からなる、ことである。

移動性磁場は双極子磁場と表層流との相互作用によって生成されと考える。Sectorial 分布の磁場は sectorial 型のトロイダル流によって誘導される。Sectorial 型トロイダル流は核マントル境界での電流に関する境界条件「境界直交成分がゼロ」より導かれる流れである。しかしポロイダル流に対する境界条件の制約はトロイダル流に対するのと異なるため、sectorial 型以外の磁場がポロイダル流によって誘導される可能性が残る。ポロイダル流の効果を抑制するものとして考えられるのは核表層部が成層構造をしていることである。

成層性が強くて Brunt-Vaisala 周波数が地球回転周波数程度であると、ポロイダル流はおよそ Brunt-Vaisala 周波数で振動する流れとなる。誘導される磁場強度は振動数に逆比例するから、magnetostrophic 周波数の極めて低周波数で振動するトロイダル流による磁場に比べると圧倒的に微弱になる。したがって地表で観測可能な磁場はトロイダル流による sectorial 型磁場に限られることになる。つまり sectorial 型移動性磁場生成には核表層部の成層構造が極めて重要な役割を果たすといえる。

キーワード: 地磁気移動性磁場, 西方移動

Keywords: geomagnetic drifting field, westward drift

135 GPa までの Fe-Ni-Si および Fe-Ni 合金の融解関係 Melting relations of Fe-Ni-Si and Fe-Ni alloys up to 135 GPa

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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 Al₂O₃. A high pressure device is a symmetric diamond anvil cell. A foil of the starting material was sandwiched by Al₂O₃ powder. The sample was compressed to a desired 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.

キーワード: 高圧, 軽元素, ケイ素, Fe-Ni-Si, Fe-Ni 合金の融点, 核マントル境界, 内核境界

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

高圧下における Fe-S および Fe-Si の音速測定 Sound velocity measurements of liquid Fe-S and Fe-Si at high pressure

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P-wave velocity (V_P) is one of the most useful physical properties to understand the structure 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 apparatus (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 measurements were carried out using the pulse-echo-overlap method. P-wave signals with a frequency of 37 or 42 MHz were generated and received by a 10° 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.

キーワード: 高圧, 核, 音速, 液体, Fe-S, Fe-Si

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

レーザー衝撃圧縮による 800GPa までの $\text{Fe}^{75}\text{Ni}^{15}\text{Si}^{10}$ 合金の音速 Sound velocities of $\text{Fe}^{75}\text{Ni}^{15}\text{Si}^{10}$ alloys up to 800GPa by laser-shock compression

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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 $\text{Fe}^{75}\text{Ni}^{15}\text{Si}^{10}$ up to 800 GPa. Comparing to the sound velocity of liquid Fe at same density, the sound velocity of $\text{Fe}^{75}\text{Ni}^{15}\text{Si}^{10}$ 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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キーワード: 音速, 外核, レーザー, ニッケル, シリコン

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

地球核条件下の鉄合金の音速と密度の線形関係と固体-液体間の関係 Sound velocity measurements for iron alloys at Earth core pressures and universal relations between solid and liquid

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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, FeS₂, and Fe₃C) 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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キーワード: 音速, レーザー, 衝撃波, 鉄合金, 地球核, 実験

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

内部抵抗加熱式ダイヤモンドアンビルセルを用いた地球核物質の高温高圧実験 Internally-heated diamond anvil cell experiments on Earth's core materials

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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 ($> 3000\text{K}$), but the heating stability may be affected by many factors during the heating and the temperature uncertainty is large ($\pm 200\text{K}$). The external-heating system can stably heat the sample and the temperature uncertainty is small ($\pm 10\text{K}$) but it is limited to lower temperatures ($< 1300\text{K}$). 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

内核の結晶構造 The crystal structure of the Earth's inner core

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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 crystallizes to an hcp structure at inner core conditions.

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