Earth’s inner core (329°364 GPa and 5000°6000 K) is known to be composed of hexagonal closed pack (hcp) structured solid Fe-Ni alloy and seismologically anisotropic. Thermoelasticity of hcp (ε) iron is therefore a key to interpreting seismological information of the inner core. Since experimental measurements are still technically impractical, theoretical approaches in particular ab initio density functional computation have substantial roles. There are two different ways to simulate high-P,T elastic constants ($c_{ij}$) of crystals. One is based on the lattice dynamics method + quasiharmonic approximation (Sha and Cohen, 2010a,b) and the other is based on the molecular dynamics method (Vocadlo et al., 2009; Martorell et al., 2013). The former and the latter basically fail to capture higher-order anharmonicity and low-temperature quantum effects, which would be substantial and marginal in subsolidus condition, respectively. Due to these problems, distinct differences can be seen in high-P,T $c_{ij}$ and their temperature dependences calculated by these different approaches. In this study, we performed ab initio molecular dynamics simulations employing a supercell containing 96 Fe, which is 50% larger than in the previous study with 64 atoms (Vocadlo et al., 2009; Martorell et al., 2013), to check the previous results. Technical details for computing high-P,T $c_{ij}$ are basically the same as in our previous studies (Ichikawa et al., 2014; Kawai and Tsuchiya, 2015). We will present temperature dependences of elastic wave velocities and their anisotropies at the Earth’s inner core pressures over 300 GPa.


Keywords: Ab initio calculation method, Hcp iron, Elasticity, Earth’s inner core
Fcc FeHx at core pressure
Fcc FeHx at core pressure

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水素は、地球の中心核に含まれる軽元素の候補として最も重要な元素のひとつである。地球形成初期の核形成時に、水素は選択的に金属コアに分配されたと考えられている (e.g. Fukai, 1984; Okuchi et al., 1997)。しかし、鉄-水素系の相関係に関する研究は比較的低圧力の領域に限定しており (Sakamaki et al., 2009)、実際の地球核において鉄-水素合金がとりうる安定な結晶構造は明らかにされていない。これまで、自由エネルギーの計算から、鉄-水素合金の構造は圧力の増加に伴って二重六方密充塡構造 (dhcp 型) から六方密充塡構造 (hcp 型) へと変化することが予測されているが (Isaev et al., 2007)、未だ実験によって実証されたことはない。そこで本研究では、レーザー加熱式ダイヤモンドアンビルセルによる高温高圧発生と高輝度放射光施設 SPring-8 における X 線回折測定により、鉄-水素合金の dhcp もしくは hcp 構造から fcc 構造への相転移を確認した。実験の結果、約 60 GPa において dhcp 構造から hcp 構造に変化し、約 70 GPa において fcc 構造に変化することが確かめられた。さらに、我々は fcc 構造の鉄-水素合金について 26 -137 GPa で格子体積を取得した。その結果、約 70 GPa において圧力と格子体積の関係および非圧縮率に不連続な変化がみられた。これは、理論計算から予測されている鉄-水素合金の磁気的性質の変化で説明できる可能性がある。今回得られた結果から、地球核の温度圧力条件における鉄-水素合金の結晶構造は従来の模型とは大きく、fcc 構造である可能性がある。

キーワード: 地球核, 水素, fcc 構造
Keywords: core, hydrogen, fcc structure, high pressure, X-ray diffraction
Sound velocities of liquid Fe-Si alloys at Earth’s core pressures by laser-shock compression

Sound velocity at Earth’s core conditions are one of the most important physical properties in Earth science because it can be directly compared with the seismic model [1]. The composition of solid inner core is estimated from the comparison of the model [1] and the extrapolation of sound velocities as a function of density of iron and iron alloys obtained by the static compression experiment [2, 3]. Birch’s law, a linear sound velocity-density relation [4], is used to extrapolate sound velocities to densities in the core condition. On the other hand, the composition of liquid outer core is estimated from the partitioning and solubility data in the inner core boundary condition for the composition of solid core. There has been some works for the sound velocity of iron on the Earth’s core condition by dynamic techniques using explosive [5], gas gun [5, 6], and laser [7]. However, the previous dynamic compression experiments are not enough to reveal the core of Earth, giant planets [8], and super-Earth which is at core pressures over 800 GPa [9]. In this study, we measure the sound velocity and density of liquid iron alloys by shock-compression method using high-power laser at pressures corresponding to super-Earth core pressures.

We conducted shock-compression experiments using a High Intensity Plasma Experimental Research (HIPER) system at the Institute of Laser Engineering, Osaka University. The samples are Fe-Si alloy with 5–13 wt.% Si assuming Si is only light element at the core. This Si content is consistent with the results of previous work by sound velocity measurement [13] and shock-compression experiment [14].

We thank Naoya Yokoyama for his help with the laser-shock experiments and data analysis. Part of this work was performed under the joint research project of the Institute of Laser Engineering, Osaka University.

Keywords: sound velocity, laser, shock wave, Fe-Si alloys, Earth’s core, experiment
The liquid Earth’s outer core is composed mainly of iron (Fe)-nickel (Ni) alloy. Birch (1952) first found that the core is less dense than pure iron based on comparison between seismological observations and experimental measurements of the density of solid iron. This is the so called “core density deficit” problem. He suggested the existence of lighter component(s) in the core, and hydrogen (H), carbon (C), nitrogen (N), oxygen (O), silicon (Si), and sulfur (S) have been identified as likely candidates from cosmochemical and geochemical arguments (e.g., Poirier et al., 1994). The density difference between the outer core and the pure iron has been estimated to be 5-10%, depending on the assumed outer core geotherm (e.g., Anderson and Isaak, 2002). The nature of light elements has remained one of the biggest enigmas for the more than half-century since the Birch’s work (1952). To justify the kind and quantity of the light elements in the core, sound velocity measurements of liquid iron alloying with possible lighter elements are fundamental because they link directly to seismological observations. We have launched the project on the sound velocity measurements for liquid iron alloys at high pressure in externally-heated and laser-heated diamond-anvil cells (DAC). The sound velocity of liquid (Fe,Ni)\textsubscript{3}S was measured via a high resolution inelastic X-ray scattering (IXS) measurements at BL35XU of the SPring-8 synchrotron facility, Japan (Baron et al, 2001). We successfully determined the sound velocity of liquid (Fe,Ni)\textsubscript{3}S up to the pressure of 50 GPa, which corresponds to the center of Mars. With our newly obtained results, we discuss the possibility of sulfur in the liquid cores of Earth and Mars.

Keywords: Sound velocity, liquid iron alloy, sulfur, outer core, Martian core
Earth's outer core composition constrained by ab initio thermoelasticites of liquid Fe alloys

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The density deficit of the Earth's outer core indicates substantial amounts of light elements (O, Si, S, C, and H) incorporated in the outer core (Birch, 1952; 1964). The chemistry and amount of the light elements have been strongly debated for over 60 years. Ab initio molecular dynamics (AIMD) simulations have been widely applied to investigate several properties of liquid Fe and Fe alloys (e.g., Alfe et al., 2002; 2007; Badro et al., 2014; Ichikawa et al., 2014). Badro et al. (2014) recently reported a likely compositional model being consistent with seismological data. However, with applying empirical pressure corrections, the model suggests smaller amount of light elements to reproduce the ICB density jump. In our study, adopting the Ichikawa et al. (2014) technique we determined the equations of state (EoS) of the liquid Fe alloys by means of the AIMD method in the P, T condition widely covering the entire outer core condition without any pressure corrections. From the EoS, densities, adiabatic bulk moduli, and finally P-wave velocities were calculated and compared with the seismological data (PREM) (Dziewonski and Anderson, 1981). After examining alloy systems from binary to quaternary, we could find some optimized compositional models. However, these have almost comparable reproducibility to PREM, suggesting that other observables are required to make further constraints on the outer core composition. If considering the observed large ICB density jump additionally, Fe-Ni-Si-O and Fe-Ni-S-O compositions appear the most likely.

Keywords: Earth's outer core compositional models, Ab initio molecular dynamics simulations, Equation of state of liquid Fe alloys
Fine seismic velocity structure of the lowermost outer core determined using outer core sensitive phases

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The liquid outer core of the Earth is regarded as homogeneous and approximately in hydrostatic equilibrium [Stevenson, 1987]. However, a low-velocity layer appears at the base of the outer core (F-layer) [Souriau and Poupinet, 1991; Kennett et al., 1995]. This basal layer may exhibit hemispherical features, as reported by Y u et al. [2005], corresponding to the quasi-hemispherical pattern of the inner core [Tanaka and Hamaguchi, 1997; Wen and Niu, 2002]. The pattern of the inner core is suggested to reflect solidification and melting at the inner core boundary (ICB), which might cause an Fe-rich or Fe-poor layer in the F-layer [Gubbins et al., 2008; Alboussiere et al., 2010; Monnereau et al., 2010]. However, the seismic profile of the F-layer is poorly revealed because of the non-uniqueness of the profiles investigated using previous methods and the interdependence of the F-layer velocity and other seismic properties of the Earth. Thus, a better constrained F-layer velocity is required before discussing its composition.

In this study, we investigated the velocity profile of the F-layer using two new methods: frequency dispersion of the traveltimes of waves that graze or are diffracted at the ICB, and differential traveltimes between waves reflected from the boundary and those that turn above the boundary. The first approach is sensitive to velocity gradients in the layer, while the second is sensitive to velocity excesses or deficits relative to a reference model for the layer; neither approach is sensitive to inner core properties or its radius. We analyzed seismograms of South American earthquakes observed using the Hi-net array [Okada et al., 2004] and the J-array network [J-Array Group, 1993] in Japan. The area investigated in the study is beneath the eastern Pacific, which is placed on the quasi-western hemisphere of the inner core.

Our results show that Vp values in the F-layer are intermediate between those of AK135 and PREM, and that the vertical velocity gradient is larger than that of AK135. Nearly constant velocities in the F-layer are not suited to observations.

Keywords: P-wave velocity in the lowermost outer core, F-layer, Traveltime dispersion of PKPbc, differential traveltimes between PKiKP and PKPbc
Plate tectonics plays a role of global material circulation from the surface of the earth to the bottom of mantle since ca.4.0Ga. This is a due function both to bear habitable planet and to evolve as a habitable planet.

In spite of empirical recognition of importance of plate tectonics, nobody succeeded to synthesize the role of plate tectonics. However, the author completed this task by using following data; (1) geophysical constraints for the mechanism of plate tectonics, (2) petrological and geochemical characteristics of lithosphere, and (3) geologic history of the Earth, specifically the structural and petrological remarks of rock components and dynamics recorded in orogenic belts over the world.

As the result, basic condition for the operation of plate tectonics and following 6 roles of plate tectonics were summarized. The reason why plate tectonics is operated on the Earth is because mid-oceanic ridge is hydrated to enable plate to subduct which is helped by the lubricant water-rich fluids on the bottom of lithosphere. Roles of plate tectonics are (1) Global material circulation of CO2 and H2O, (2) Role of tectonic erosion, (3) Production of nutrients-source rocks at subduction zone, (4) Driving force of Earth’s magnetic field, (5) The buffer of Earth’s system, and (6) The controller of thermal history of the Earth.
Hemispherical structures have been found in the inner core (Tanaka and Hamaguchi, 1997; Waszek et al., 2011; and the references therein), the outer core (Tanaka and Hamaguchi, 1993; Yu et al., 2005), and the mantle (Iwamori and Nakamura, 2012). While seismic velocities characterize the core hemispherical structures, the mantle east-west hemispheres have been proposed based on geochemistry, rather than south-north division as has been long argued for (Hart, 1984, known as “Dupal anomaly”). In order to better characterize and interpret the mantle geochemical hemispheres in both spatial and compositional domains, and to discuss whether the hemispherical structures in the core and mantle have any dynamical linkage or not, a total of 6854 young basalt data consisting of five isotopic ratios of Sr, Nd and Pb from almost all tectonic settings (mid-ocean ridge, ocean island, arc and continent) have been statistically analyzed (Iwamori and Nakamura, 2015).

As a result, it has been found that the continental basalts are mostly distributed only in the eastern hemisphere, while other basalts are distributed evenly. Using multivariate analysis (Independent Component Analysis, ICA), two independent compositional vectors have been extracted, which explain most of the sample variance (95%). Therefore, almost all young basalts from various tectonic settings plot on a single isotopic compositional plane, and can be explained solely by two elemental differentiation processes (e.g., melting and aqueous fluid-rock interaction, Iwamori and Albarede, 2008). One of the independent components (IC2) represents ‘anciently subducted aqueous fluid component’ stored for 300 to 900 million years in the mantle, and defines the fluid component-rich (=positive IC2) eastern hemisphere, while the western hemisphere shows the opposite polarity. We have also found a striking geometrical similarity between the IC2 and the inner core hemispheric structures (Iwamori and Nakamura, 2015): the eastern hemisphere shows positive IC2 in the mantle and high seismic velocities in the inner core. Combining these constraints, we propose ‘top-down hemispherical dynamics’: focused subduction within and around the supercontinent has created a fluid component-rich hemisphere with a lower temperature, compared to the oceanic mantle. The colder hemisphere seems to have been anchored to the asthenosphere during the continental dispersal, and may affect the temperature and growth rate of the inner core, resulting in the coupled hemispherical structures in the mantle and the core.

Keywords: mantle, core, supercontinent, hemispherical structure, isotope, independent component analysis
Slab dynamics and water transport in the lower mantle

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Keywords: free convection, subducting slab, slab buckling, lower mantle structure, water transport
Mapping the North American continent with inter-station phase and amplitude data of surface waves

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The investigation of a three-dimensional upper mantle structure using seismic surface waves has been generally based on the measurements of phase delay. The lateral heterogeneity in the Earth, however, not only affects the phase of surface waves, but also modulates their amplitude through focusing/defocusing effects. Such amplitude anomalies caused by elastic focusing are dependent on the second derivative of phase velocity across the ray path, and thus they are sensitive to short-wavelength structure than the conventional phase data, which should be useful for improving the lateral resolution of phase velocity models. In this study, we collect a large-number of inter-station phase velocity and amplitude ratio data working with a non-linear waveform fitting technique using USArray seismograms. Phase velocity maps of North America are then constructed using both phase and amplitude data of both Rayleigh and Love waves to check the validity and utility of inter-station amplitude measurements for enhancing the quality of the phase velocity models.

The phase velocity maps derived only from phase data reflect large-scale tectonic features well; e.g., slow anomalies in the tectonically active western U.S. and fast anomalies in the eastern cratonic region. To the contrary, phase speed models derived from amplitude data tends to emphasize smaller-scale structures characterized by strong lateral velocity gradients; e.g., significant slow anomalies in Snake River Plain and Rio Grande Rift, where the local amplification due to elastic focusing has been observed at USArray stations. Our results indicate that inter-station amplitude-ratio data reflect the effects of the second derivatives of phase velocity distribution well, and are extremely useful for reconstructing shorter-wavelength elastic structures. Thus, the measurements of inter-station amplitude ratios across a dense seismic array can be used to enhance the horizontal resolution of phase velocity models of surface waves.

Keywords: surface wave, phase velocity, amplitude, tomography, North America
Detection of an asthenospheric thermal event: approach from lithospheric mantle xenoliths

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Convective mantle heat flux through the continental lithosphere is not well constrained because of high heat generation in the overlying continental crust (Sclater et al., 1980; Pollack et al., 1993; Jaupart et al., 2007; Jaupart and Mareschal, 2007). Its proper estimation and its temporal variation through the earth’s history is important to know the overall rate of heat loss from the convecting interior of the earth (Labrosse and Jaupart, 2007; Korenaga, 2008), although the earth is thought to be losing most of its internal heat through the oceanic lithosphere (~70%; Jaupart et al., 2007; Mareschal et al., 2012). The sub-continental lithosphere-asthenosphere boundary (LAB) is the interface through which entropy transported to the asthenosphere beneath the LAB via mantle convection from the depth of the earth is passed on to the entropy transfer in either steady or transient state through the sub-continental lithosphere (Jaupart and Mareschal, 2007; Michaut and Jaupart, 2007; transient important). There are three important mechanisms of entropy transfer through the LAB: heat conduction, solid-state flow, and magmatism (Jaupart and Mareschal, 2007). The upper most zone of the asthenosphere acts as the upper thermal boundary layer of the convecting mantle and that the heat was transferred via heat conduction in the continental lithosphere with or without LAB modification (thickening or delamination/thermal erosion of the lithosphere; Moore et al., 1999; Jurine et al., 2005). Another important aspect of the sub-continental LAB is that it roughly corresponds to a boundary where melting and segregation of melt take place either via decompressional melting in the asthenosphere or melting of the lithospheric mantle induced by the heat input or material influx. This implies that entropy can be transferred from the convecting interior to the lithosphere via magmatism involving heat release or absorption by melting, crystallization, and open-system reactions. It is important to know where magmas are generated and crystallized during its ascent to the earth’s surface in the continental region in order to evaluate the role of magmatism in heat transfer through the sub-continental LAB. If a magma generated in the asthenosphere releases heat directly on the earth’s surface ending as volcanic eruption and intrusion, then heat loss via magmatism is at maximum efficiency (Ogawa, 1988). Contrary to this, if the magma releases heat within the lithosphere or crust by freezing all the melt there, it heat up the host layer. In this case, the enhancement of heat loss via magmatism depends on the depth of magma freezing, though it is higher than exclusively conductive heat transfer.

In order to examine heat transfer near the sub-continental LAB, it is important to scrutinize the thermal state and its temporal and spatial variability of the mantle material near the LAB and concomitant magma formation and its subsequent magmatism. Fortunately, we have many samples from the continental lithosphere as mantle xenoliths, though xenoliths from the asthenosphere are limited. The continental lithospheric mantle has long history of its formation and modification, but we can extract not only thermal records when xenoliths were entrapped by erupted magmas (mantle geotherm) but also their temporal change before the entrapment by carefully looking at reaction processes took place responding to various thermal and chemical changes taking place in the vicinity of the LAB.

Keywords: asthenosphere, lithosphere, thermal event, mantle xenolith, mineral zoning
マックスウェル粘弾性力学方程式の従来とは別の見方に立つ定式化
An alternative formulation of the dynamics equation system of Maxwellian viscoelastic media

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岩石からなる地殻・マントルやグリーンランド・南極に存在する氷床は普通の意味では固体であるにもかかわらず、長
い時間では「流動する」とみされ、その動きは支配する法則として粘性流体に対する Navier-Stokes 方程式が採用され
る（例えば McKenzie, Roberts and Weiss, 1974, ほか無数）。これは物理学として正しいのであろうか？

文献により歴史を振り返ると、氷期終期後の地殻の上昇を扱った Haskell(1935) やその同僚でマントル対流を論じた
Pekeris(1935) など先駆的研究を参照しながら、McKenzie はプレートテクトニクス時代のマントル対流研究の基礎づけと

Creep under low stress is by diffusion and has a linear relation between stress and strain rate: it also obeys the Navier-Stokes equation. Therefore the viscosity of the mantle may be calculated from solid state theory and also from the slow deformation of the Earth.

ここでは粘性流動の物理的な基礎、として固体物理や材料工学で知られているクリブ現象、即ち固体に剪断応力をかけ
続けるとそれに応じたずれ変形が生じ、時間と共にそれが大きくなる現象を固体の「流れ」とみなしていることがわか
る。上記の文献、即ち「応力-歪（速度）関係」を流体力学方程式の内部力をとして採用する、と言っているとされる。


即ち、方程式中の応力をせん断歪速度で表現し、その係数を粘性率と呼ぶのである。ところが、流体運動方程式で
粘性の効果は「運動量拡散」を表すことは数学的に物理的に明らかで、この小論や固有地球科学研究で想定される大き
な粘性、たとえば 10**12 Pa・sec を使う中、全マントル内に光速をも超える速さで運動量が拡散することを意味し、この
論は物理学として受け入れられない。（Forte, 2007; Treatise on Geophysics, Vol.1, 1.23, p813 に計算あり。しかし、こ
の事実に驚いたり、おしかったしたりしていない。）

上記の英語でも、日本語でも、“応力-歪（速度）関係”という時、どちらかが原因でどちらかが結果かでない。“固体
の流動”から思い浮かぶようにクリブ現象では外から加える力が原因で、実際、粘性率を求める実験では剪断応力を
与えた上でその結果生じるクリブ速度が測定されている。これに対し、流体力学方程式における応力-歪速度関係は
逆で、歪速度（速度シアー）が原因となって生じる応力を方程式の粘性項で表現することが求められているのである。
この関係は考慮していない原因であろう。

このような問題を起こさない「新しい定式化」を昨年の学会で発表したが、若手から一時姿をみると、固体地球物
理学者は懐然としないようであった。今回定式化の超難を繰り返すとともに上記観点や、弾性力と粘弾性力という「二
つの応力が一つの物体の中で働いているという不思議」などの基本疑問を中心に説明したい。

従来と異なる見方に立った定式化の概要を筒吹き書きする次の通り（昨年発表のまとめ）。
・Maxwell によるばねとダッシュポットの模型による構成則に基に展開された粘弾性の力学方程式系を再検討した。
応力の時間発展を表す構成方程式は物理的根拠が不明である。
・新しい見点ではばねとダッシュポットの模型を考えると、力の源はばねのみで、ダッシュポットの役割は粘性力では
なく、ばねの原点の位置の時間変化を記述するものとみなせる。
・この見方に立って連続体への翻訳を考えると、応力の源は弾性歪のみでよく、一方、これまでの構成則は「弾性歪が
時と共に塑性歪に転化する」ということを表す、と翻訳できる。
・このことは日常経験からも明らかであり、工学 (材料力学) の教科書で、弾塑性体における Reuss の構成則 (1930) と
呼ばれるものと同じである。実験的に検証されていると記られる。
・それゆえ、Maxwell 構成則に代わり、この構成則を物理的基礎に立つ法則とし、連続体の運動方程式とあわせて「弾
塑性体」の基礎方程式系とするのが適切である。
・非弾性の場合の基礎方程式系は、塑性変位の時間変化（弾性変位の原点の変化）を「流れ」とみなすと、ゆっくり変
化する現象については粘性流体の方程式と数学的に同等となる。したがってその解は見かけ上粘性流体の運動となるが
粘性は見かけのものにすぎない。
・発散のある圧縮弾性体現象、相変化が起こらない限り、塑性変位を転化するのは偏差成分 (deviatoric component)
のみと考えられるから、単純に粘性流体と同様に考えない。
・発散を含む一般的の場合、時間的にゆっくり変わる現象に対しては、運動方程式 (力のバランス) は準弾性平衡を保っ
tたまま、塑性歪 (偏差成分) が弾性歪の偏差成分に比例して増加するような時間変化をする。

1/2
Keywords: plate-mantle coupled system dynamics, mantle convection, Maxwellian viscoelastic medium, viscoelastic medium dynamics, elastico-plastic medium dynamics.
外核最上部の密度成層した層に存在する軸対称MAC波の境界モード
The boundary mode of axially symmetric MAC waves can exist in the stratified layer at the top of the Earth’s outer core

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外核最上部には、地震学的な観測（例えば、Helfrich & Kaneshima(2010), Kaneshima & Helfrich(2013)）から理論的な推測により、軽い物質によって密度成層した層がありそうだ、ということが分かってきた。その原因としては、Helfrich(2014)では、初期地球にあった密度成層の特質であると考えられ、水が存在する。この密度成層した層には、磁力（Magnetic force）・浮力（Archimedes force）・コリオリ力（Coriolis force）等のバランスによって生成されるMAC波が存在する。Braginsky(1993)では、地磁気の60年変動を説明するために、そのMAC波を軸対称に近づけた場合の近似解が理論的に示されている。ここでの層のモデルは、外核も層内の構造において密度の不連続があり、層内では浮力振動数が一定であるようなものと推定されている。（しかし、最近の地震学の観測では、このような密度の不連続はなくそうだと言われている。）そのため、その南半球方向の位相速度はアルフレーン波速度と浮力パラメータの積となり、c_{tot} = V_{A} \cdot B_{0} = V_{A} \cdot N / f, ここで c_{tot} は南北位相速度、V_{A} はアルフレーン波速度、B_{0} は浮力パラメータ、N は層の浮力振動数、f はコリオリパラメーターである。鉛直構造は層の重ねあわせで表される。また、減衰率は磁気抵抗率に比例する。南北位相速度は浮力振動数に比例するので、観測から南北位相速度が分かれば、浮力振動数が推定できる。南北波数 l=2 の基本モード周波数を地磁気の60年変動と合わせると、浮力振動数は地球の自転角速度の2倍ほどになる。

私たち、Braginsky(1993)では想定されたモデルと方程式系に、密度不連続のある層境界に局在した解（ここでは境界モードと呼ぶことになる）の存在することを見出しこれ。この解は、Braginsky(1993)の解に比べて時間スケールが小さく、もっぱら振幅に変化するためで、したがって位相が異なる方向に進行。周波数は Braginsky(1993)の解のように層内の浮力振動数には依存しない。周波数と鉛直波数は層境界における密度不連続の大きさ、南北波数などに依存している。鉛直構造は層境界から離れるにつれて振幅が小さくなるような波形である。密度不連続や南北波数が大きいと、波は時間的にも空間的にも減衰が大きくなる。そのため観測で見つかるには、密度不連続層の厚さが小さいことが必要であり、南北波数が小さい波が見つかやすくであろう。仮に、南北波数 l=2 の境界モードの振動数を地磁気の60年変動と合わせると、密度の比の割合は 10^{-4} 程度になる。なお、この波は、磁気抵抗率が小さいほど、時間的にも空間的にも減衰するという層内伝播する波とは逆の性質を持っている。境界モードであるので、境界面を振動させれば、励起されることも決れない。

キーワード: MAC波,外核最上部, H層
Keywords: MAC waves, the top of the Earth’s outer core, H layer
Effect of sulfur on the reaction between iron and water under high pressure and temperature

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Keywords: Earth’s core, light element, hydrogen, synchrotron
Measurement of thermal conductivity of mantle minerals at pressures of the transition zone to the lower mantle

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Knowledge of thermal diffusivity or thermal conductivity of the mantle is vital for study of the dynamics of the Earth. So far we have measured thermal diffusivity and thermal conductivity of upper mantle minerals, i.e. olivine and garnet and hydrous phases, i.e. serpentine and talc. All those data were obtained by the experiments at pressures up to 10 GPa and temperatures to 1100 K. The measurements were conducted by a pulse-heating method of one-dimensional heat flow using the Kawai-type apparatus at the Institute for study of the Earth’s interior, Misasa. This current method is a predominant one for study in deep Earth’s materials under pressure. It has some advantages as follows: (1) comparatively small amount of samples (2) applicable to materials with anisotropy in thermal conduction (3) simple cell assembly. Moreover, this method enables to obtain specific heat capacity under pressure.

In order to expand pressure range the cell assembly is needed to advance by reducing its dimensions. A new cell-assembly similar to our previous one is designed for a sample of 2.6 mm in diameter and 0.6 mm in thickness. This smaller cell is installed in a 14 mm edged octahedral pressure medium in 7 mm truncated anvils. This cell enables to make measurements of the thermal properties at pressures exceeding 15 GPa, which will covers the condition in the mantle transition zone. The cell will be also applied to pyroxene samples of which sizes are necessarily limited. Test measurements were made using garnet samples. The results agree well with those of the previous experiments using the larger (18-11 and 14-8) cell, and the extrapolations to zero-pressure coincide to values of other methods. Thus, the pulse heating method will be applied for thermal property measurements of wadsleyite, ringwoodite and majorite. Using large anvils (>46 mm), the method is probable to measure the thermal conductivity of MgSiO₃ perovskite (bridgmanite). However, measurements at high temperature still have somewhat problems in precision. Materials of impulse heater and external furnace should be re-considered. The precision of measurements should be improved by well-controlled machining of the cell assembly and by refining the data acquisition system.

Keywords: mantle minerals, thermal diffusivity, thermal conductivity, high-pressure, Kawai-type apparatus
Lattice diffusion in MgO crystal from first principles simulation

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Rheological property is critical to understanding the mantle convection. Diffusion creep might be the dominant deformation mechanism in the Earth’s lower mantle and super-Earths’ mantle (e.g., Karato, 2011). Thus several experimental and theoretical studies have tried to measure lattice diffusion coefficients under pressure, which are both still technically difficult. There are two theoretical approaches to calculate self-diffusion coefficient in solids. One is based on the static lattice energy calculation and the other is based on the molecular dynamics simulation. In the former case, it is difficult to evaluate attempt frequency and in the latter case, atoms are hardly mobile in actual computation time at the Earth’s lower mantle and super-Earths’ mantle temperatures. These two approaches were previously applied to MgO, one of major deep mantle constituents (Ita & Cohen, 1997; Ito & Toriumi, 2007). However reported pressure dependences of the self-diffusion coefficients are contradictive with each other particularly at high pressure over 80 GPa.

In this study, we develop a new theoretical method to calculate self-diffusion coefficient in crystals with charged vacancies (Schottky pair) within the first principles framework. This method was then applied to NaCl-type MgO. We found that the calculated pressure dependences of the self-diffusion coefficients in MgO are consistent with those of Ita & Cohen (1997). Diffusion creep viscosity of MgO was then estimated using calculated diffusion coefficients. Our activation volumes are consistent with experimental values at low pressure (Van Orman et al., 2003) and decrease rapidly with increasing pressure. It suggests that super-Earths’ mantle would not be quite viscous and the constant activation volume extrapolation leads to overestimation of viscosity in the deep mantle.

This method is widely applicable to other materials including bridgmanite, post-perovskite and CsCl-type MgO, which are important to analyze more realistic planetary interior dynamics.

Keywords: MgO, lattice diffusion, Earth’s lower mantle, super-Earths’ mantle, first principles
Are LLSVPs formed in the Earth’s lowermost mantle by the subduction of oceanic crusts?

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Abstract:
We conducted a series of numerical experiments of thermo-chemical mantle convection where a subduction is preferentially induced at a continental margin, in order to verify a hypothesis that the Large Low-Shear Velocity Provinces (LLSVPs) in the Earth’s lowermost mantle are formed by subduction of oceanic crust. In this study, we adopted a model of two-dimensional rectangular box of 2900 km height and aspect ratio 6 with reflective boundary condition in the horizontal direction. We placed an immobile lid as a model of surface supercontinent which covers a third of the top surface. We also put a thin layer of chemically dense materials as a model of oceanic crust, which may sink into the deep mantle along with cold descending flows from the top surface.

Our calculations showed that the subducted oceanic crusts are preferentially provided under the continent when the subduction at the margin of continent is stable. However, stable subduction caused strong convection and significantly stirred the mantle under the continent. Therefore, subducted oceanic crusts were distributed almost uniformly under the continent without accumulating on the CMB. On the other hand, the cases with unstable subduction at the margin of continent showed a long-wavelength mantle convection structure which has an ascending plume along the side wall under the continent and a descending plume at the opposite side wall. The large-scale flow gathered subducted oceanic crusts under the continent and formed large piles on the CMB.

Our results suggest that the LLSVPs are hardly formed in the presence of stable plate tectonics like the current one where a stable plate motion including subduction stirs the mantle very effectively. In other words, the formation of large thermochemical piles which are equivalent to the LLSVPs should have been completed before the plate tectonics is well established, assuming that subducted oceanic crusts are the origin of LLSVPs.

Keywords: mantle convection, numerical simulation, LLSVP, plate subduction
Experimental presentation of plate subduction using paraffin wax

Experimental presentation of plate subduction using paraffin wax

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Experimental approaches using analogue materials have been widely used to understand kinematic behaviors of tectonic plates. Previously molten paraffin in a tank inside a hot water bath has been used. Although tectonic plate-like behaviors, such as inclined subduction and trench migration, have been observed, the “plate” in this case was too thin to reproduce the lithospheric strength and the heat balance through the thermal boundary layer of the Earth. In order to simulate the plate and its motion as a well-developed thermo-mechanical boundary layer on top of vigorously convecting mantle, we have developed a tank apparatus and performed preliminary experiments using paraffin wax.

To control the complex heat and convection processes and for easy observation we constructed a glass tank with an inner size 120x23x4cm. The walls are constructed from double pane glass with panes separated by air gap to reduce heat loss, and reinforced with aluminum plates and bars. The paraffin was melted from bellow by a copper heat-sink containing 24 ceramic heating elements. To reduce heat loss to the back wall, the wall was isolated with 8cm thick foam. At the boundary layer where the paraffin wax was sticking as it cooled down we applied NiCr wire heater to the inner walls. All heating sections were controlled by variable controllers. We cooled the top layer of the wax with a cold air flow carefully controlled with thin foam plates from a vat filed with liquid Nitrogen.

The biggest challenge was the “frosting” effect especially on the front uninsulated wall that prevented the “subduction” of the forming “crust” to deeper levels. External wall temperature was 65 °C, 70 °C was measured at the boundary level by the wire heater, while the wax inside the tank was at 80 °C. Some external force was necessary to initiate a start of subduction. The maintenance of balance between the various heaters, the wall temperature, the wax temperature and the cooling rate was critical for the successful completion of the experiment.

We observed continuous subduction and clear “crust” forming with subsequent “subduction”. We can say that our experiment properly reproduces the general features of plate motion of the earth. Artificially fracturing or weakening the boundary layer and applying a vertical, downward external force were required to initiate subduction in addition to collision of the plates. The thickness of the plate was the primary parameter controlling subduction behavior and plate motion. The plate showed elastic and plastic behavior depending on its thickness and temperature. A cold and thick “plate” did not subduct even after applying an external force, and formed a stagnant lid. A hot and thinner “plate” did not show continuous subduction behavior, plate motion stopped soon after subduction was initiated, possibly because the slab pull force from the thinner partially subducted slab was too weak. Our experiment results suggest that the driving force of subduction and plate motion is slab pull, not the thermal convection of the molten paraffin or ridge push. We will present photos and videos of the observed processes.

Improvements to the tank and heating elements design are necessary to provide better and easier control over the experiments.

Keywords: analogue experiment, plate subduction, paraffin wax, glass walls tank, slab pull
Numerical experiments on mantle convection of super-Earths with variable thermal conductivity and adiabatic compression

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Recently, many extra-solar planets have been discovered by improved observation technologies. Some of these planets, called super-Earths, have small masses (up to 17 times the Earth’s) and high mean density (>5000 kg/m3). Numerical modeling of mantle convection of super-Earths plays an important role in studying the occurrence of plate tectonics and the surface environments on these planets. On the other hand, when considering mantle convection of super-Earths, it is also important to take into account the difference in (hydrostatic) pressure in the mantles. Since super-Earths have high inner pressure, there must exist a strong change in physical properties and the effect of adiabatic compression. While the effects of physical properties have been intensively studied so far, those of adiabatic compression have not been well studied in the previous models of mantle convection of super-Earths. Here we conduct numerical experiments of thermal convection of highly compressible fluid in a two-dimensional rectangular box whose thermal expansivity and conductivity are dependent on depth, viscosity is dependent on temperature, in order to elucidate the mantle convection on super-Earths.

Our numerical experiments showed the change in convecting flow patterns depending on the temperature-dependence in viscosity, regardless of the depth-dependence in thermal conductivity. When a viscosity is sufficiently dependent on temperature, horizontal flow becomes dominant in the mantle, with a very weak activity of hot plumes from the base of the mantle. This flow pattern is quite similar to the ”stratosphere” in the field of meteorology. In addition, we found that the occurrence of ”stratosphere” is enhanced for a strong depth-dependent thermal conductivity. One reason for this is that high conductivity at depth significantly reduces the difference in temperature between the basal thermal boundary layer and isothermal core. Our study therefore suggests that the depth-dependent thermal conductivity is one of the most important agents which control the mantle dynamics of super-Earths.

Keywords: super-Earths, mantle convection, adiabatic compression, thermal expansivity, thermal conductivity, viscosity
In order to investigate the long time-scales of the global core formation process in a growing planet, we are developing the Stokes flow simulation code using MIC based techniques for material transport with a free-surface treatment. We are interested in the dynamical change of the internal structure after solidification of magma ponds/oceans during the core formation under a self-gravitating field, especially because it might lead to an initial heterogeneous structure in the deep mantle.

However current numerical solution method is difficult to solve the system coupled with the energy equation because the numerical system becomes stiff when the dynamical balancing time scale for the increasing/decreasing load by surface deformation is very short compared with the time scale associated with thermal convection. Any explicit time integration scheme will require very small time steps; otherwise, serious numerical oscillation (spurious solutions) will occur.

In this work, we propose to treat the advection as a coordinate nonlinearity, coupled to the momentum equation, thereby defining a fully implicit time integration scheme suitable for stiff problems [Furuichi and May, Compt. Phys. Commun 2015]. We utilize a Jacobian free Newton Krylov (JFNK) based Newton framework to solve the resulting nonlinear equations. We also investigate efficient solution strategies to reduce the computational cost to evaluate the nonlinearity on MIC advection.

These implicit methods are implemented within FD framework [Gerya and Yuen, 2003]. We examine the solution quality and efficiency of these methods by performing numerical experiments we have performed a series of numerical experiments which clarify the accuracy of solutions and trade-off between the computational cost associated with the nonlinear solver and time step size.

Keywords: core formation, Stokes flow, free surface, implicit time integration, JFNK
To systematically investigate the spatial variation of seismic anisotropy around Japanese islands, we measured splitting parameters (fast polarization direction $\phi$, delay time $\delta t$) of teleseismic SKS phases observed by Hi-net (Ogawa et al., 2014, SSJ). The results indicated regional scale variations of splitting parameters that are apparently related to subduction systems. In order to investigate detailed anisotropic structures (fabric in mantle wedge, subducting slab, and asthenosphere), we conducted forward modeling using synthetic seismograms. We modeled the SKS phases by the ray theory. We assumed that the SKS ray is straight and that each region has homogenous anisotropy. We rigorously calculated the phase velocity in each region by solving the Christoffel matrix. The preliminary analysis indicates that the measured splitting parameters appear to be primarily affected by the A-type fabric in subducting slab (oceanic lithosphere) whose a-axis aligns in the direction of the fast axis observed at the surface by using our OBS data.

キーワード: 地震波異方性, モデリング

Keywords: seismic anisotropy, s-wave splitting, modeling
Constraining radial anisotropy in the upper mantle with multi-mode surface waves

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The radial anisotropy of shear waves represents the differences in the propagation speeds between vertically polarized shear waves (SV) and the horizontally polarized ones (SH), and can be a key to the understanding of the dynamic processes in the upper mantle. Seismic surface waves are the most powerful tool to determine the spatial distribution of the radial anisotropy. Some recent studies have revealed the existence of a layer with strong radial anisotropy (with SH > SV) beneath the lithosphere; e.g., under the Pacific plate (Nettles & Dziewonski, 2008, JGR) and the Australian continent (Yoshizawa, 2014, PEPI). This is, however, not always the case and there are also some studies on radial anisotropy that do not show such a clear layer with SH > SV beneath the lithosphere. These differences may be related to the differences in model parameterization.

For the inversions of multi-mode phase speeds of Rayleigh and Love waves for radial anisotropy of shear waves, we can use either set of model parameters for the representation of the anisotropic S velocity; i.e., (A) SV velocity (Vsv) and SH velocity (Vsh), or (B) SV velocity (Vsv) and radial anisotropic parameter $\xi = (Vsh/Vsv)^2$. The choice of model parameters for inversion is arbitrary, but, through synthetic experiments, we have confirmed that this difference causes non-negligible effects on the reconstruction of radial anisotropic properties of shear waves. This is mainly caused by the differences in the sensitivity kernels of Love-wave phase speeds to Vsv, Vsh and $\xi$.

For the set of parameters (B) [Vsv, $\xi$], Love waves always have the largest sensitivity to Vsv with suppressed sensitivity to $\xi$, and the kernel shapes for both Vsv and $\xi$ are nearly identical. On the other hand, for the parameterization with (A) [Vsv, Vsh], Love wave phase speeds are controlled primarily by the kernels for Vsh, which have the largest sensitivity to Love wave phase speeds with little influence from Vsv, which can be better (and independently) constrained by Rayleigh waves.

Such intrinsic differences in the sensitivities of surface waves can lead to the different results in the estimation of radial anisotropy. Our synthetic experiments suggest that the parameterization with [Vsv, Vsh] would be preferable particularly when the radial anisotropy with SH > SV is caused by anomalously slow SV velocity, which is consistent with the recent anisotropy models reported in the fast moving Pacific and Australian plates. We have also found that the strong dependence of the retrieved anisotropy on the initial model, when we use [Vsv, $\xi$] as model parameters.

Keywords: radial anisotropy, surface waves, upper mantle, lithosphere, asthenosphere
日本列島下の遠地地震 P 波・S 波トモグラフィー
Telesismic P- and S-wave tomography beneath Japan Islands

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日本列島は、4つのプレートが隣接し相互に作用しあう複雑なテクトニクスを有しているため、その地下構造は非常に不均質である。これまでに近地地震データを用いた数多くの地震波トモグラフィー研究により、詳細な日本列島下の3次元速度構造の推定がなされてきた。しかしながら、その研究対象領域は地殻や上部マントルといった浅部に限られており、日本列島深部(深さ200-700 km)の構造を推定した研究は少なく、その構造はあまり分かっていない。日本列島深部の構造を調べることは、沈み込むスラブやマントル上昇流の深部での様子や相互の関連などを理解できると考えられ、マントルダイナミクス解明において非常に重要である。

本研究では、遠地地震の相対走時残差を用いた遠地地震トモグラフィーにより日本列島深部のP波、S波の速度構造を推定した。P波を用いた同様の研究は過去にも行われてきたが(例えば、Zhao et al., 1994, 2012; Abdelwahed and Zhao, 2007 など)、S波を用いた研究は少ない。P波とS波両方のデータを用いることで、速度構造だけでなくボアソン比の分布も得られ、日本列島深部の構造をより詳細に把握することができる。

本研究で用いた遠地地震の相対走時残差は、P波においては、先行研究(Zhao et al., 1994, 2012; Abdelwahed and Zhao, 2007)により集められた日本からの震央距離30～100゜の地震360個中から、日本全土で観測されており、かつ100点以上の観測点で観測された130個の遠地地震と、震源の分布がなるべく均等になるように新たに読み取った38個地震の計168個の速変地震より約6万個のP波走時データである。S波においては、震源の分布が均等になるように選んだ56個の速変地震より約4万個のS波データを使用した。また、浅い速度構造を補正するために、気象庁の一元化カタログから100点以上で観測された速変地震約3千個を用いた。解析手法には、近地地震と遠地地震のデータを同時にインバージョンすることができるZhao et al. (1994, 2012)のトモグラフィー計算プログラムを用いた。

得られた結果より、P波、S波ともに背弧側から続く低速度異常層が観測され、これはマントルウェッジ内のコーナーフローであると考えられる。関東地方以西においては、内陸における地殻速変地震の震源が沿った高速度異常を観測でき、沈み込むフィリピン海スラブと考えられる。特に九州地方になるとこの高速度異常は深さ400 km 程度まで達する様子がP波、S波の両方で見ることができ、フィリピン海スラブは九州下ではマントル遷移層まで沈み込んでいると考えられる。発表ではこれに加え、ボアソン比やマントル深部物質の物理に関する R 値(dlnVs/dlnVp)を求めることが、日本列島の深部構造をより詳細に議論したい。
Cape Verde ホットスポットとマントルプーム
Seismic evidence for a mantle plume beneath the Cape Verde hotspot

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The Cape Verde hotspot is located in the African plate, about 2000 km east of the nearest plate boundary. It is composed of a group of late Cenozoic oceanic islands resting on a broad bathymetric swell on mature (>110 Ma) oceanic lithosphere. This hotspot has a positive surface heat flow, high geoid anomaly, and long-term volcanism. The last known volcanic eruption occurred at Fogo volcano in 1995.

We determined P- and S-wave tomography of the upper mantle beneath the Cape Verde hotspot using arrival-time data measured precisely from three-component seismograms of 106 distant earthquakes recorded by a local seismic network. Our results show a prominent low-velocity anomaly imaged as a continuous column <100 km wide from the uppermost mantle down to about 500 km beneath Cape Verde, especially below the Fogo active volcano, which erupted in 1995. The low-velocity anomaly may reflect a hot mantle plume feeding the Cape Verde hotspot.

キーワード: Cape Verde, ホットスポット, マントルプーム, 地震波トモグラフィー, マントル遷移層
Keywords: Cape Verde, hotspot, mantle plume, seismic tomography, mantle transition zone