Japan Geoscience Union Meeting 2012
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プレート境界を通したプレート回転運動のダイナミクス
Dynamics of plate spin motion through plate boundary

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Compared with other planets, the Earth has a variety of special features. One of them is plate tectonics. Because of the feature, the Earth's surface has unique motions such as strike-slip motion along plate boundary and spin motion of a plate. Regarding strike-slip motions, they lead to vorticity along the plate boundary and we can consider the vorticity as an infinitesimal spin motion. Therefore, both strike-slip motion and spin motion of a plate are spin motions and consequently we would state that it is spin motions that characterize plate tectonics and the Earth. However, the dynamics of spin motion is not well understood, thought the plate spin motion must include vital information about plate tectonics, especially the dynamics of plate boundary which is the most intricate problems in this field. Hence, we here focus on the dynamics of plate spin motion.

To begin with, we analyzed the basic equation of mantle convection since plate tectonics is a part of mantle convection as the thermal boundary layer and we will grasp the dynamics of plate tectonics from that of mantle convection. The analysis shows that the effect associated with the horizontal viscosity variation of the surface is indispensable to generate vorticity or plate spin motion. As a parameter of the horizontal viscosity variation, we make use of individual plate size since a plate size expresses the distance between hard plate center and soft plate boundary and is therefore one of simple parameters to consider the influence of the horizontal viscosity variation. Dividing observed Euler poles into two components: spin Euler pole associated with spin motion of a plate and straight Euler pole associated with straight motion of a plate, we revealed that the potential energy generated by subduction excites the plate motion, particularly the straight motion, in a large scale motion and the straight motion transmits into the spin motion through the plate boundary, especially in a small scale motion, mainly less than 1000 km of the radius of plate. In addition to the individual plate analysis for plate spin motion, the global plate motion analysis called spherical harmonic expansion also demonstrates the transmission from the straight motions into the spin motions in a small scale motion.

These results suggest that while small plates have high spin motions since they receive the force to spin through the plate boundary without large deformation, i.e., low strain rate, large plates do not have high spin motion since the force to spin does not well transmit because of the large deformation, i.e., high strain rate, along the plate boundary which we call a "strike-slip" boundary. This difference of force transmission, or strain rate, along plate boundary in plate size might be associated with the difference of the stress along the plate boundary; for example, we need larger stress along plate boundary in order to spin larger plates. In other words, this difference might be attributed to the rheology of plate tectonics, especially along plate boundary. Estimating the stress to spin, we will obtain the rheology of plate boundary from observation, that is, plate motion, which advances the theory of plate tectonics substantially.

キーワード: プレートテクトニクス, プレート境界, ダイナミクス, プレートの回転運動, トロイダル・ポロイダル運動, 渦度
Keywords: plate tectonics, plate boundary, dynamics, plate spin motion, toroidal-poloidal motion, vorticity of plate tectonics

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マルチモード表面波による大陸リソスフェアの 3 次元イメージング
3-D Imaging of Continental Lithosphere with Multi-mode Surface Waves

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Developments of high-density seismic arrays and techniques of seismic tomography in the last a few decades have enhanced the horizontal resolution of seismic images of the Earth's interior. Seismic surface waves are one of the most powerful tools to map 3-D images of the uppermost mantle, although its depth resolution is limited to the top 200 km as long as we use readily measurable fundamental-mode surface waves that are normally sufficient to map oceanic lithosphere with the thickness of about 100 km or less. On the other hand, high-resolution imaging of continental lithosphere, whose thickness tends to exceed 200 km beneath major cratonic areas, requires higher-mode data with greater sensitivities to the deeper structure. The use of higher-mode surface waves is, however, not straightforward, since several modes overlap in time and cannot be separated in a seismogram, particularly at short distances commonly used in regional-scale tomographic studies.

We present recent progress on the high-resolution regional-scale mapping of the continental upper mantle using multi-mode surface waves, with a particular focus on the 3-D imaging of radial anisotropy of shear wave speed as well as the lithosphere-asthenosphere boundary (LAB) beneath continental areas. Surface waves are inherently not very sensitive to the sharpness of boundaries due their long wavelength. The depth of LAB, however, can be estimated from the peak of negative gradient of a velocity model, while the thickness of LAB can be deduced from the sharpness of the velocity gradient. Using the recent continental tomography models of Australia and North America, we investigate the relationship between the distribution of LAB beneath the continents and the strength of radial anisotropy, which implies a significant correlation between the present-day plate motion and faster SH wave speed anomaly in the asthenosphere beneath the estimated LAB.

キーワード: 表面波, リソスフェア, アセノスフェア, 大陸, 異方性
Keywords: surface waves, lithosphere, asthenosphere, continent, anisotropy

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上部マントルにおける含水レールゾライトの部分融解実験と大陸クラトン下マントル
HYDROUS MELTING OF LHERZOLITE AND CRATONIC MANTLE

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大陸クラトン下のマントルは海洋やオフクラトンのマントルに比べて Mg と Si に富んでいるという特徴的な化学組成を有している (例えば Boyd, 1989)。Walter (1998) によって、この様な化学組成のマントルはパイロライト的のレールゾライトの単純な部分融解の残留岩としては説明できないことが示されている。一方、レールゾライト-H2O 系では FeO 成分が入っていない実験（例えば Litasov et al. 2007）や FeO 成分は含まれているが H2O だけでなく CO2 を 2wt%ほど含んだ実験（Inoue and Sawamoto,1992 を再検討した結果、CO2 が含まれていた事が判明）が報告されている。本研究では、FeO 成分を含んだ含水レールゾライトの部分融解実験を上部マントルの広い圧力範囲で行い、含水条件下でクラトンのマントルが生成された可能性について検討した。出発物質は以下の主要 10 成分のパイロライト組成+H2O になるように合成した。SiO2, TiO2, Al2O3, Cr2O3, Fe2O3, CaCO3, Na2CO3, K2CO3, NiO の粉末を秤量、混合し、大気圧中 1000 ℃で脱ガスを行った。その後、酸素分圧が QFM にコントロールされた還元炉において 1500 ℃で融解、急冷してガラス化したものに MgO および Mg(OH)2 の粉末を加え、2wt%と 8wt%の異なる含水量の出発物質になるように調整した。高温高圧実験には、愛媛大学設置のマルチアンビル型高圧発生装置 (ORENGE 1000) を使用し、3-8 GPa の圧力において 1000〜1600 ℃の温度範囲で実験を行った。本研究ではすべての温度圧力条件で液相が存在していた。H2O が 2wt%の場合は、融解度が上がるにつれて単斜輝石, ザクロ石, 斜方輝石, かんらん石の順番に融解していく。一方、H2O が 8wt%の場合、圧力の上昇とともにかんらん石の安定領域が縮小し、斜方輝石の安定領域が拡大、６ GPa 以上で、かんらん石に代わって斜方輝石がリキダス相になることがわかった。実際、クラトン下からのマントル捕獲岩の組成はその他の地域のマントルゼノリスに比べ opx/ol が高く、この実験結果からクラトン形成に水が影響していたのではないかと考えられる。

キーワード: 含水レールゾライト, 上部マントル, クラトン, 部分融解, エンスタタイト
Keywords: hydrous lherzolite, high pressure and temperature experiments, craton, partial melting, enstatite

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マントルかんらん岩の溶融の熱力学計算への圧力依存性の導入
Thermodynamic Calculation of polybaric Melting of Mantle Peridotite

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Partial melting is an essential process for both material differentiation and heat transportation of the Earth. Numerical forward calculation is useful approach to predict melting in the dynamic system such as the magma ocean that may have developed from surface to lower mantle depth, and the present day subduction zone where fluid addition, mantle convection and melting are tightly coupled. Thermodynamic calculation by system energy minimization is a general approach to describe dynamic melting of such multi component and multi phase system, because that can provide an internally consistent relation of phase relation and mass and energy balance during melting.

We have developed a straightforward algorithm for calculating phase equilibria of multicomponent system by energy minimization of the system, together with thermodynamic configuration to describe a molar Gibbs free energy of silicate melt. The thermodynamic model constructed with the algorithm and melt thermodynamic configuration successfully reproduced melting phase relation of mantle peridotite at 1 GPa. We have expanded a calibration database of the thermodynamic model up to 3 GPa to conduct a polybaric melting calculation, which is dominant in natural tectonic settings (e.g., mid-ocean ridges and hotspots).

Construction of equation of state of silicate melt is an essential factor to evaluate multi pressure melting. We employ two different configurations for volumetric parameters of silicate melt to investigate better approach to predict melting relation at high pressure. In the first configuration, molar volume of silicate melt end-component is represented by the difference from the volume of corresponding solid end-component (dV), and the dV is calibrated with the results of previously reported melting experiments. We also employed a set of 1 bar experimental volumetric parameters (Lange and Carmichael, 1990) for the equation of state of silicate melt, which is commonly used to calculate melt volumetric property. In this case, standard state molar volume of melt end-component is calibrated with the calibration data set. In both configurations, dCp, which is the difference in molar specific heat between the corresponding melt and solid end-components, are also calibrated and ideal solution are assumed for silicate melt. The tested system consists of SiO2-Al2O3-FeO-Fe3O4-MgO-CaO and includes olivine, clinopyroxene, orthopyroxene, and spinel with silicate melt. Thermodynamic parameters and enthalpy, entropy and temperature of fusion at 1 bar for solid end-components are taken from previous studies.

Our thermodynamic calculation with calibration of dV successfully reproduced experimentally determined multi pressure melting reaction of mantle spinel lherzolite at 1-3 GPa (Hirose and Kushiro, 1993), including systematics between pressure-temperature-composition of the system and melt composition and melting degree. On the other hand, calculation result with parameter of derive larger misfit with experimental result. Our model with calibration of dV makes better prediction than pMELTS (thermodynamic model to calculate phase relation of melt present system), in terms of temperature-phase proportion including melt fraction. pMELTS did not calibrate melt volumetric parameters and utilized volumetric parameters. It is deduced that our configuration, in which thermodynamic parameters for melt is calibrated based on the difference from the corresponding solid end-component at melting P-T conditions, is useful approach, rather than extrapolation from standard state properties of simple systems as have been often employed in the previous studies.

キーワード: 熱力学, 溶融, マントル, 相平衡
Keywords: Thermodynamics, melting, mantle, phase equilibra

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マントル遷移層条件下での含水 MORB, 含水 Harzburgite の相関係
High pressure phase relations of hydrous MORB and hydrous Harzburgite in the mantle transition zone

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1 はじめに

海洋プレート（スラブ）は地球深部へと沈み込み、マントル遷移層付近に停滞している様子が地震波トモグラフィーから確認することができる。スラブは上部から MORB, harzburgite,lherzolite と層構造を形成していると考えられており、高温高圧下でのこれらの岩石の相転移の様子、すなわち安定相関係を調べることはスラブダイナミクスを議論する上で重要である。一方、含水化した沈み込むスラブは地球深部へと水を運搬し、マントル遷移層にまで水を運搬する可能性が指摘されてきている。地球深部における水の存在は相転移境界の変化、融点の低下、粘性の変化など様々な物性に影響を与える。そのため、より現実的な地球内部の様子を議論するためには水の影響を考慮した含水系での実験が重要であると考えられる。本研究では、スラブ物質の相転移に伴う水の影響を明らかにするため、マントル遷移層条件下で含水 MORB, 及び含水 harzburgite の安定相関係を調べた。そしてその結果を無水条件下の結果と比較することにより地球深部水の影響について考察した。

2 実験方法

出発物質には天然の玄武岩をもとにした MORB 組成のもの（以下 MORB）と 1 気圧下で酸化物混合体から雰囲制御して合成した Harzburgite 組成のもの（以下 Harzburgite）を用いて、それぞれの含水量が 2 wt%となるように水酸化物を混合したものを使用した。高温高圧合成実験にはマルチアンビル型高圧発生装置 ORANGE2000 を用いた。実験条件は 15 - 23 GPa、1400、1600 ℃である。加熱保持は 3 時間行い、その後急冷回収した。回収した試料は走査型電子顕微鏡 (SEM-EDS) を用いて像観察及び化学組成の分析を行い、また顕微ラマン分光を併用して相の同定をした。そして得られた化学組成をもとにマスバランス計算を行い各実験条件での鉱物の体積比を求めた。

3 結果・考察

本研究により含水系 (H2O=2 wt%) の MORB と Harzburgite の相関係がマントル遷移層に相当する条件下で決定された。MORB ではマントル遷移層に相当する広い圧力範囲で garnet (Gt) と stishovite (St) が主な安定相として存在していたが、下部マントルに相当する 23 GPa 以上になると Gt が分解し MgFePv, CaPv, Cf が安定な相として出現した。一方、Harzburgite では 18 GPa 付近で wadsleyite (Wd) が ringwoodite (Rw) に変化、23 GPa 付近でポストスピネル相転移が確認された。さらに 15 GPa から 21 GPa の圧力領域で akimotoite (Ak) が安定に存在していた。

今回得られた研究と過去に報告された無水条件での実験結果を比較すると、MORB の無水条件では Gt の相転移境界が 25 GPa から 30 GPa の広い圧力範囲にわたり起きているのに対し、含水条件下では 22 - 23 GPa の狭い圧力範囲内で相境界が急激に起こることが確認された。一方 Harzburgite においては、無水条件では Gt がマントル遷移層条件下で存在しているのに対し、含水条件では Ak に置き換わっていることが確認された。このようにスラブ中における水の存在はその構成岩石の相転移境界すなわち安定相関係を著しく変化させており、スラブの密度等の物性にも大きな影響を及ぼしていることになる。

キーワード: 高圧相関係, 含水 MORB, 含水 Harzburgite, マントル遷移層条件
Keywords: high pressure phase relation, hydrous MORB, hydrous Harzburgite, the mantle transition zone

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地球深部物質の高圧下における光学測定のための超小型キュービックアンビル装置の開発
A miniature cubic anvil apparatus for optical measurement on deep earth minerals under high pressure

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A miniature cubic anvil apparatus was developed for optical measurement on deep earth minerals with relatively large volume under high pressure, and preliminary experiments were conducted to 3.6 GPa at room temperature with optical visual observation and ruby fluorescence measurement. In the apparatus, a cubic pressure medium was squeezed with six tungsten carbide anvils, which are driven with a pair of guide blocks by tightening four sets of screws. Optical access on the sample was made through holes in axial anvils and the guide blocks as well as optical windows made of Al_2O_3 single crystals embedded in the pressure medium. The apparatus is compact and light, ~53 mm in diameter and height and ~530 g in weight, and the features of the apparatus benefits easy application of the apparatus to various types of standard optical measurement systems. The optical measurement on the sample with relatively large volume should greatly contribute to advancements of studies relevant to high-pressure behaviors of deep earth minerals.

キーワード: キュービックアンビル装置, 光学測定, 地球深部物質, 高圧, 光学顕微鏡観察, ルビー蛍光法
Keywords: cubic anvil apparatus, optical measurement, deep earth mineral, high pressure, optical visual observation, ruby fluorescence measurement

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SS-precursors observed by NECESSArray: Lehman discontinuity beneath the northeastern Pacific ?

SS-precursors observed by NECESSArray: Lehman discontinuity beneath the northeastern Pacific ?

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We analyze SS-precursors from aftershocks of the 2010 Chilean (Mw 8.8) earthquake recorded by NECESSArray. Slant-stacked seismograms of 13 shallow events recorded by ~120 stations of NECESSArray show a strong signal above the 4-sigma noise level about 85 sec before the arrival of the parent SS-phase. This may be originated from the Lehman discontinuity located at a depth of ~200km, but the polarity may be reversed. While signals from 410km- and 660km-discontinuity are well resolved, no signal for the G-discontinuity deeper than 60km is observed. The G-discontinuity (or seismic LAB) beneath the bounce point of the SS-phase (northeastern Pacific) may be shallower than 60km or absent.

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高圧力条件での SiO_2 - Al_2O_3 ガラスの音速測定
Sound velocity measurements of SiO_2 - Al_2O_3 glass under high-pressure

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Determination of the structure and physical properties of silicate melt under high pressure and high temperature is an important key to understand the Earth's evolution and the gravitational stability of melts in Earth's deep interior. Natural silicate melts mainly consist of SiO_2 with various chemical components. Aluminum is one of the most abundant elements in the natural silicate melts, and the Al_2O_3 contents can be as high as 12 mol.% in magmas. To understand the effect of Al_2O_3 on the compression behavior of silicate melts is therefore essentially important. There have so far been a number of experimental studies of glasses, as the analogue of melts, in the binary system of SiO_2-Al_2O_3 with various experimental techniques. Previous experimental results obtained by NMR, IR, Raman and X-ray diffraction spectroscopies showed that SiO_2-Al_2O_3 glasses with 0.4 to up to 12.0 wt.% Al_2O_3 contain high coordinated (5-, and 6-fold coordinated) Al sites (e.g., Sen and Yaungman, 2004, Okuno et al., 2005), which significantly affects the density of SiO_2-Al_2O_3 glasses (Okuno et al., 2005; Linh and Hoaug, 2007). However, there are few experimental studies about the structures and physical properties of SiO_2 - Al_2O_3 glasses under high pressure toward an implication for the Earth's evolution and geophysical phenomenon in Earth's deep interior due to experimental difficulties.

To understand the effect of Al_2O_3 on the compression behavior of SiO_2-Al_2O_3 glasses under high pressure, *in-situ* high pressure Brillouin scattering measurements of acoustic wave velocities were carried out at room temperature in a symmetric diamond anvil cell. Brillouin scattering is highly sensitive to the structural change regardless of the state of the sample (glass, liquid and crystal) and its result of silicate glasses can provide us with the information leading to the changes of structure and density in silicate melts in the temperature and pressure range corresponding to the Earth's mantle. We synthesized SiO_2 - Al_2O_3 glasses with several compositions by levitation method using CO_2 laser and performed structure analysis of them by X-ray diffraction at BL04B2, SPring-8. Brillouin scattering measurements of acoustic wave velocity were carried out up to 60 GPa.

Our results showed that the velocity-pressure curve of the sample with lower alumina contents has very similar trend to that of SiO_2 glass. In contrast, we observed the anomalous sound velocity evolution for the samples with higher alumina contents, which strongly suggests the drastic change of compression behavior of SiO_2-Al_2O_3 glass.

In this presentation, we will present those new experimental results on the compressional behavior of SiO_2-Al_2O_3 glasses including the results obtained by synchrotron X-ray diffraction measurements, and discuss about the possible implications for the magmas in deep Earth's interior.

Keywords: Structure of silicate glass and melt, Brillouin scattering, Acoustic wave velocity measurement

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NECCESSArray データとグローバルカタログデータのジョイントトモグラフィー法
The method for joint tomography using both NECESSArray and global bulletin data

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In the last SSJ, we presented the results of our delay time tomography using the triplicated data observed by NECESSArray. Our tomography used the array analysis method by Iritani et al. (2010, GRL) in measuring traveltimes, which enables accurate phase identification and retrieval of the information of secondary phases. However, because the method can be applied only to the array data, its application was so far restricted to regional tomography, and corrections of the effects of structures outside the studied region were not straightforward.

In this study, we propose a new tomography method to apply our method to global tomography. The basic idea is to use both array waveform data (e.g., NECESSArray data) and global bulletin data (e.g., EHB data). The measurements of traveltimes for the former dataset are identical to what we have done in our previous tomography. The traveltime data in the latter dataset are used with modified phase associations. We assume that the phase type of the first arrivals of the bulletin data should be identical to that for the nearby event used in the analyses of the array waveform data. Such modifications can be applied only to the regions where we have dense arrays, however, because the phase misidentification can be greatly suppressed, the accuracy of the obtained model should be improved in these regions. If we focus only on the structures in these regions, they are assumed to be the results of the regional tomography with accurate corrections of the outside effects.

We applied this method to the NECESSArray data and the EHB bulletin data. At the time of the presentation, we plan to show how much improvements we can achieve by modified phase associations. We also plan to compare the models with and without NECESSArray data and discuss the plausibility of the features which are pointed out in our previous study.

キーワード: トモグラフィー, 地球内部構造
Keywords: tomography, Earth’s internal structures

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下部マントル圧力下でのカルシウムシリケイトペロフスカイトの弾性波速度測定と最下部マントルの地震学的異常の解釈
Sound velocity measurements of CaSiO3 perovskite to 133 GPa and implications for lowermost mantle seismic anomalies

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We report the measurements of aggregate shear velocity (VS) of CaSiO3 perovskite (CaPv) at high pressure (P) between 33 and 133 GPa and room temperature (T) on the basis of Brillouin spectroscopy. The sample had a tetragonal perovskite structure throughout the experiments. The measured P?VS data show the shear modulus and its pressure derivative at ambient condition to be G0 = 115.8 GPa and G' = 1.20, respectively. The zero-pressure shear velocity is determined to be VS0 = 5.23 km/sec, in good agreement with the previous estimate inferred from ultrasonic measurements on Ca(Si,Ti)O3 perovskite at 1 bar. Our experimental results are also generally consistent with earlier calculations on tetragonal CaPv. According to the very recent predictions, such tetragonal CaPv has similar velocities to the cubic phase. These indicate that shear and longitudinal velocities of CaPv are much lower than those of the other lower mantle minerals such as MgSiO3-rich perovskite and ferropericlase. While primitive mantle includes certain amount of CaPv, a depleted peridotite (former harzburgite) layer in subducted oceanic lithosphere is deficient in CaPv and enriched in ferropericlase in the lower mantle. Such harzburgite exhibits 1.2% faster VS and 0.8% slower bulk sound velocity (VB) than the primitive mantle at lowermost mantle P-T conditions. The observed fast VS and slow VB anomalies in the D" layer underneath the circum-Pacific region may be attributed in large part to the presence of subducted harzburgitic materials.

キーワード: CaSiO3 ペロフスカイト, 下部マントル, S 波速度, ブリルアン散乱, ハルツバージャイト
Keywords: CaSiO3 perovskite, lower mantle, shear velocity,, Brillouin spectroscopy, harzburgite

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グローバルトモグラフィーによるスラブとマントルプルームの詳細構造
Imaging the subducting slabs and mantle plumes with high-resolution global tomography

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Global seismic tomography has been used to determine the 3-D whole-mantle structure, which has provided important information on the deep structures of the subducting slabs and mantle plumes as well as deep Earth dynamics. Tomographic images under the hotspot volcanoes such as Hawaii, Iceland and Tahiti exhibit low-velocity anomalies, which may reflect hot mantle plumes (e.g., Zhao, 2004, 2009). Zhao et al. (2009) investigated the upper-mantle structures under the intraplate volcanoes in China (Mt. Changbai and Mt. Wudalianchi). Their results suggest that these intraplate volcanoes are related to the big mantle wedge above the stagnant Pacific slab under East Asia. In this work, we have tried to determine a more detailed 3-D mantle structure by using global tomography. In Zhao (2004, 2009), the thickness of the subducting Pacific slab was imaged to be 200-250 km due to the lower resolution. While high-resolution local and regional tomography under the Japan Islands shows the slab thickness to be 85-90 km (Zhao et al., 2009, 2011; Huang et al., 2011). To obtain a high-resolution whole-mantle tomography, we have tried to adopt a much denser flexible-grid with a grid interval of 50 km in depth and 100-200 km in lateral direction. We used five kinds of ISC P-wave data (P, pP, PP, PcP and P-diff phases), and adopted a flexible-grid model parameterization (Zhao, 2009; Yamamoto and Zhao, 2010). The 1-D iasp91 Earth model was adopted to be the starting model for the tomographic inversion. In this work we have used about 1.7 million P-wave arrival times from about 13000 earthquakes. By using many kinds of seismic phases, the spatial resolution of the tomographic images has been much improved for the upper mantle under the oceanic regions. The preliminary results show a similar pattern of whole-mantle tomography as the previous models, but both the subducting slabs and mantle plumes exhibit sharper images than those revealed by the previous studies.

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NECESSArray, F-net データを用いて検出された、太平洋低速度領域西北縁における D”不連続面
D” discontinuity in the northwestern edge of the Pacific Large Low-Velocity Province detected by NECESSArray and F-net

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Broadband seismic recordings from the stations of NECESSArray and F-net are analyzed to investigate the shear-wave velocity discontinuity at the top of D” layer across the northwestern edge of the Pacific Large Low-Shear-Velocity Province (LLSVP). In this study, we focus on the nature of the D” discontinuity across the edge of the LLSVP by detecting a precursor to ScS phase at epicentral distances of 65o to 85o. Transverse component seismograms from earthquakes occurred in the Kermadec, Fiji, and Vanuatu regions are assembled and analyzed. Employing linear and phase-weighted vespagram (Schimmel and Paulssen, 1997), we identified a clear arrival with an arrival time and slowness between the S and ScS waves, indicating a reflected S wave from the D” discontinuity.

キーワード: D” 不連続面, LLSVP, 最下部マントル, ScS 波, アレイ解析, 北西太平洋
Keywords: D” discontinuity, LLSVP, lowermost mantle, ScS-wave, array analysis, Northwest Pacific

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地震波形分析から示唆される中央太平洋下マントル 最下部における超低速度領域の存在
Seismic Evidence for Existence of an Ultra-low Velocity Zone in the Lowermost Mantle Beneath the Central Pacific

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We consider waveform data for nine events in Papua New Guinea recorded at stations in North America that sample the lowermost mantle beneath the central Pacific. Two of these events have high-quality waveforms. We interpret the waveforms for these two events using forward full-waveform modeling and derive 1-D models appropriate for the study region. We show that a strong later phase (also noted by previous workers) about 25 s after the S arrival at epicentral distances from about 90 to 110 degrees and azimuths from about 50 to 65 degrees can be explained as an ScS phase (or diffracted ScS phase) produced by a low velocity zone (LVZ) with a thickness of about 120 km and a velocity decrease of about 5% underlain by an ultra-low velocity zone (ULVZ) with a thickness of about 50 km and a velocity decrease of about 30%. These low velocities imply the presence of a significant amount of iron.

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高伝導度鉄と地球核の熱史
The high conductivity of iron and thermal evolution of the Earth's core

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Earth's magnetic field is re-generated by dynamo action via convection currents in the liquid metal outer core, which are in turn driven by a combination of thermal buoyancy associated with secular cooling (along with possible radioactive heating) and buoyant release of incompatible light alloying components upon inner core solidification. Prior to the crystallization of an inner core, the energy for maintaining a geodynamo must be supplied in excess of the heat conducted down the isentropic gradient that develops in the presence of convection, placing tight constraints upon the core's thermal evolution. Here we present new measurements and calculations of the electrical resistivity of iron to 1 Mbar pressure, combined with a model accounting for saturation resistivity of core metal, to show that the thermal conductivity of the uppermost core is greater than 90 W/m/K. These values are significantly higher than previous estimates, implying rapid secular core cooling, an inner core younger than 1 Ga, and ubiquitous melting of the lowermost mantle during early Earth. An enhanced conductivity with depth suppresses convection in the deep core, such that its center was stably stratified prior to the onset of inner core crystallization.

キーワード: 高圧実験, 第一原理計算, 抵抗率の飽和, 核の伝導度, 熱史
Keywords: high pressure experiments, first-principles calculations, resistivity saturation, core conductivity, thermal evolution

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地球磁場の生成に関する実験的考察―三重水槽を用いたモデル実験を基にして―
Consideration about generation of the Earth's magnetic field - Based on the model experiment of three fold water tank -

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１．目的　　地球磁場は、第 1 次近似としては地球の中心部に 1 個の棒磁石が存在するとしてよいが、そのためには地球の自転方向とは逆向きに赤道に沿った円形電流が流れていなければならない。そのことを仮説に、気象学で良く知られている三重水槽の回転実験をヒントに発想の逆転で実験を行い検証してみようとする。

２．方法　　（１）回転する三重水槽を用い、中心部に熱湯（「内核」）、その外に常温の水（流体である「外核」）、最外部に氷（マントル・地殻）を満たし、電動回転台に載せ、回転（自転）させてアルミニウム粉末を蒔いた水面の模様の変化を、様々に条件を変えてどのような流れの変化や特性が現れるか観察する。
（２）次に、水の流体部（外核）をファンデグラーフ高圧静電発生装置により実際に帯電（実験の都合上、負電荷）させ、実験（１）を再度行い、三重水槽の周囲に生ずる磁場の特性を市販の磁場測定器（測定精度 0.01[m T] 程度）を用いて調べ、1 個の磁気双極子（地球に見立てた棒磁石）が周囲につくる磁場を規準磁場として両者の特性を比較検討する。

３　結果　＜実験１＞　気象学とは逆発想の三重水槽モデル実験による地磁気発生の成因を探る実験
―　現在の向きの磁場が発生することが確認できた！―
アルミニウム粉末を蒔いた水面に回転台とは逆向き（時計回り）に進む蛇行する流れ（定常波のような形態）が中心の高温部（内核）に隣接する側から発生・生長する様子が確認できた。
これにより、外核はプラスの鉄（Ｆｅ）イオンの流体であることが判明しているので、したがって、赤道に沿うように外核の中心側（内核に近い側）に時計回りの蛇行する電流が流れていることになる。したがって、右ねじの法則により現在の地磁気と同じ向きの磁気双極子による磁場が生ずることが理解できる。
＜実験２＞　磁場の「逆転」が起きるメカニズムについての新たな知見・手掛かりを探る実験
―　外核（水）の内核側とマントル側との温度差ΔＴが減少していくと磁極の逆転が起こることを発見！―
蛇行する逆行流が、高温部側（中心の内核に接する側）から生ずるのであるが、時間経過と共に三重水槽の中心部（内核）の高温部が温度下降し最外部の氷も解け出して温度差ΔＴが小さくなるにつれ、逆行流は弱くなり縮小していくのが確認できる。つまり、外核中では回転台の向きと同じ向きの流れと逆行流とがせめぎ合っていて、その勢力関係の大小によって一歩の側の磁場が強めあったり弱めあったりする。また、勢力が拮抗すると、磁場が消滅すると考えられる。
温度差ΔＴがある値以下になると、遂には回転台とほぼ同じ速度で一緒の方向に運動するようになる。これは、地磁気が逆転したことを意味している。

４．考察
（１）「地球磁場」生成を支配する主な要因は、　外核の内側（内核）と外側（マントル及び地殻）間の温度差ΔＴと、地球自転に伴う転向力、の２つであることをモデル実験から明らかに出来た。
（２）地磁気は現在のように、北極側に棒磁石のＳ極が向いている時期の方がどちらかといえば正常な時期であり基本（ベース）となっていると考えられる。
（３）地磁気の「逆転」は何かが劇的に変化することで起きるのではなく、意外にも外核の温度差ΔＴが連続的に減少する過程で起きる現象であるが分かった（【新説】の提案）。
外核中の逆行流が温度差ΔＴの現象と共に弱まり、回転台の向きの流れと磁力的に拮抗する時点で地球磁場が見掛け上相殺し合って消滅し、さらに温度差ΔＴが連続的に減少していくと流れの大勢が回転台の向きになびくようになり地磁気が逆転する。
温度差ΔＴが減少する原因については、最近の地球科学の成果である「プルームテクトニクス理論」が明らかにしているところのマントル内の数億年周期の対流現象が大いに関係していると考えられる。すなわち、マントル対流による熱輸送循環が外核の内外層部の温度差を緩和あるいは拡大する働きをするために起きると考えれば説明がつく。

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六方晶鉄の圧力-温度-体積の状態方程式
P-V-T equation of state of hcp-Fe

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It is essential to realize high pressure and high temperature conditions in the laboratory by means of high pres-sure experiments to measure the physical properties of high pressure minerals for understanding the structure and dynamics in the earth's interior. In this study, we tried to expand the pressure range in a Kawai-type mul-tianvil apparatus equipped with sintered diamond anvil by optimization of assembly size and materials for cell assembly, and then measured P-V-T relationship of hcp-iron to discuss the dynamics of the inner core because. the hcp-iron is though to be dominant phase in the inner core based on recent diamond anvil experiments (Tateno et al., 2010).

We used synchrotron radiation facility, SPring-8, to conduct in situ X-ray observation at high pressure and temperature to determine P-V-T relation. Kawai-type cell assemblies were squeezed by high pressure press (SPEED-mk.II Madonna at BL04B1) using sintered diamond cubes with 14 mm edge length and 1.0 mm trun-cation edge length. Cr-doped MgO was used as pressure medium and TiB2+hBN was used as heating material. Preheated pyrophyllite was used as preformed gasket.

In the present study, pressure and temperature range were up to ˜83 GPa and 1300K. In the experiments, X-ray diffraction data were collected at every 200 K step during cooling cycle with pressure interval of 5-10 GPa. Pressure was estimated from the volume of gold by using equation of state of gold proposed by Tsuchiya (2003).

We fitted our data to third-order Birch-Murnaghan equation of state and Mie-Gruneisen thermal equation of state. As a result, thermoelastic parameters of the isothermal bulk modulus, its pressure derivative, Debye temperature, Gruneisen parameter at ambient pressure and volume dependence of the Gruneisen parameter were determined to be 151.1 (4.8) GPa, 5.6 (0.2), 1110 (87) K, 2.92 (0.24) and 0.99 (0.42), respectively. In addition to present analysis, we need to re-analyze by taking into account the electric pressure term in equation of state.

Our thermoelastic data indicate that the density of the inner core is 4-5 % heavier than observations by seis-mology (e.g., PREM). This result is consistent with previous study (Dubrovinsky et al., 2000) and indicates the existence of light elements in the inner core.

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南極域の内核境界近傍の地震学的構造
Seismic structure near the inner core boundary in the south polar region

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Good spatial coverage of seismic data points is important for better understanding physical processes occurring in the Earth's core. Although fine seismic structure near the inner core boundary (ICB) has been examined using body waves by many researchers, the core structure of the polar region, especially the south polar region, still has been poorly resolved. Investigating the seismic structure in the polar region has a geophysical importance associated with the tangent cylinder in the outer core. The tangent cylinder acts as a barrier to the convective mixing and can create a reservoir of compositional anomalies. The polar region of the Earth's outer core can then be characterized by low density and high temperature. Investigating the polar regions is also important for increasing constrains on the nature of hemispherical variation in properties of the inner core observed in seismological studies. Based on such seismic models anisotropic growth possibly associated with the outer core convection has been suggested. It however remains under discussion whether lower velocities would reflect either a low growth rate or a fast growth rate. The preferential equatorial solidification in the Earth's core leads to slower inner-core growth in the polar region. Thus the comparison of the structure near the ICB between in the polar region and in the rest can provide a test for solidification scenarios.

Seismic rays from South America to Indonesia pass beneath Antarctica. These rays are invaluable because they sample the region near the ICB beneath the south polar region. We analyzed core phases on vertical-component broadband seismograms of JISNET, OHP and IRIS stations in and near Indonesia for earthquakes in South America from January 1998 to September 2002. We selected waveforms including PKIKP whose turning point or one of its intersections at the ICB is located south of 60 S. The total number of selected waveforms is 118 for the 37 earthquakes. The observed waveforms were band-pass filtered between 1 and 20 s. Synthetic seismograms are computed up to the frequency of 2 Hz using the Direct Solution Method (DSM). The PREM model is used as the reference. We analyzed differential traveltimes and amplitude ratios between core phases (PKIKP, PKiKP, PKPbc, and PKPc-diff). The model we obtained (SPR) is described relative to PREM as follows: a 0.05 km/s lower Vp value at the top of the inner core, a 1.5 times steeper Vp gradient in the upper 300 km of the inner core, a smaller Qp (300) in the upper 300 km of the inner core, and a 0.04 km/s lower Vp at the bottom of the outer core.

Our velocity structure in the lowermost outer core lies in between the two global reference models PREM and AK135. Previous models for the western hemisphere are close to SPR for the base of the outer core. The Vp value of SPR at the base of the outer core is larger than that of AK135 by 0.2%, suggesting that the outer core inside the tangent cylinder is not distinctive from the rest of the outer core. As regards the Vp structure in the upper inner core, SPR has smaller Vp values compared to PREM and AK135, and is close to that of previous models for the western hemisphere, although most of our data sample the eastern hemisphere of the inner core. Our results thus indicate that the inner core does not have a simple hemispherical variation as usually supposed. An eyeball-shaped high-Vp anomaly, such that higher Vp than the global reference models is rather concentrated to smaller region beneath eastern Asia, could be consistent with our results. If the same relationship between slow inner core growth and low inner core Vp applies to near the equatorial region, the western-hemisphere would also have a low growth rate of the inner core.

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Fe-Ni-S 系の 15GPa における溶融関係
Melting relationships of the Fe-Ni-S system at 15GPa

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The planetary core consists of iron-nickel alloy and lightening elements, such as sulfur and silicon. Study of melting relations of iron alloys is of important to understand formation, evolution, and the present state of the planetary core. An addition of nickel to iron affects significantly the phase relations of iron alloys. Here, we report the results of quenching experiments on the Fe-Ni-S system at 15GPa.

Phase relations of the Fe-Ni-S system at 15 GPa were studied by using a KAWAI type high pressure apparatus at Okayama University. Recovered samples were examined by the electron microprobe JXA-8230.

At 15GPa, $(Fe,Ni)_3S_2$ and $(Fe,Ni)_3S$ are stable as intermediate compounds at subsolidus conditions. Iron solubility of $(Fe,Ni)_3S_2$ is limited to Fe/(Fe+Ni)=0.76 at 1000K, although Fei et al.(1997) reported that Fe_3S_2 is stable at 14GPa and 1125K. $(Fe,Ni)_3S$ is stable at only the Ni-rich portion. Addition of nickel depresses significantly the melting temperature of the Fe-FeS system. Ternary eutectic point locates around $Fe_{12}Ni_{55}S_{33}$ and its melting temperature is lower than 900K.

キーワード: 核, Fe-Ni-S 系, 相関係
Keywords: core, Fe-Ni-S system, phase relations

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X 線吸収法を用いた高温高圧下における Fe-O 融体の密度測定
Density measurement of liquid Fe-O at high pressure and high temperature using an X-ray absorption method

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The Earth’s outer core is thought to be composed of liquid iron alloys with a small amount of light elements, such as sulfur, oxygen and silicon. Existence of a liquid core is also suggested to other terrestrial planets (Mars and Mercury).Thus the effect of light elements on the density of liquid iron is fundamental to understand the composition and structure of the planetary cores.

The densities of liquid Fe-S, Fe-Si, and Fe-C have been reported using X-ray absorption method (Nishida et al., 2011; Sanloup et al., 2004; Terasaki et al., 2010). As a result, it was revealed that the rate of density decrease is quite different depending on the dissolving light element. Hence, it is important to figure out the effects on liquid iron by individual light elements. Although oxygen is one of the most popular candidates of the light elements in the Earth’s outer core, the effect of oxygen on the density of liquid iron has never been reported to date. In this study, we have measured the density of liquid Fe-O (O = 0.5 wt%) up to 3 GPa and 2250 K using X-ray absorption method at BL22XU, SPring-8 synchrotron facility. The obtained density of this study is 6.65(3) g/cm^3 at 3 GPa and 2005 K. Compared to the density of pure liquid iron at the present experimental condition, the density of liquid Fe-O is about 7% smaller than that of liquid iron and thermal expansion coefficient of liquid Fe-O is similar to that of liquid iron.

キーワード: 地球核, 酸素, 密度, 高温高圧, 放射光
Keywords: core, oxygen, density, high pressure and high temperature, synchrotron

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高圧下における Fe-S 融体の音速速体：地球および月核への応用
Sound velocity measurements of liquid Fe-S at high pressure: Implications for the Earth's and lunar cores

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The sound velocity of liquid Fe-S is an important physical property to understand the Earth's and lunar outer cores. We measured P-wave velocity (V_P) of liquid $Fe_{84}S_{16}$, $Fe_{60}S_{40}$, and $Fe_{50}S_{50}$ up to 5.4 GPa and 1550 ^{o}C using ultrasonic method combined with synchrotron X-ray technique. The derived VP of liquid Fe-S shows very little change with temperature. The V_P of liquid Fe-S decreases linearly with increasing S content at 2.5 GPa and 1300 ^{o}C. The V_P of liquid $Fe_{60}S_{40}$ increases almost linearly. The expected V_P of the lunar outer core range 3840-4250 m/s assuming the lunar core consists of liquid Fe-FeS outer core and solid Fe inner core. Although the V_P of liquid $Fe_{60}S_{40}$ is slower than that of pure liquid Fe up to 5.4 GPa, the V_P of liquid $Fe_{60}S_{40}$ should be exceed that of liquid Fe over 7 GPa because the pressure derivative of V_P of liquid $Fe_{60}S_{40}$ is larger than that of liquid Fe. This result suggests S is effective in increasing the V_P of liquid Fe over 7 GPa. Therefore, S is considered to be a possible light element of the Earth's outer core.

キーワード: 高圧, 音速, 核, 液体, Fe-S
Keywords: high pressure, sound velocity, core, liquid, Fe-S