Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SIT39-01 会場:416 時間:5 月 2 日 09:00-09:15

マックスウェル粘弾性体の力学方程式の新しい定式化
A new form of the dynamics equation of Maxwellian visco-elastic 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固体であるにもかかわらず、長い時間スケールでは流動することが知られている。そして、マントル対流などに対しては粘性流体とみなして Navier-Stokes 方程式を基に数値シミュレ-ションが行われている。氷床流動に関しても氷は粘性流体として扱われ、ただ粘性力と流れの関係が非ニュートン的とされている。

一方、両方の性質を考慮しなくてはならない問題として、氷期終了後の地殻上昇の問題では、応力とひずみの関係を表す構成方程式として、Maxwell によって提唱された短い時間では弾性体、長い時間では粘性流体となるような形の式を用いて議論されてきた。しかし、この方程式を用いた議論は、伝統的に時間に関してラプラス変換して半ば解析的に扱われてきた。これを、ちょうど大気や海洋の大循環の数値シミュレーションのように、時間空間差分化して解こうとするとうまくいかない。

そのような背景のもと、マントル対流のシミュレーションで、地表近くの弾性体としてのプレートの効果を取り込むことは大変困難であり、うまくできていない。氷床流動でも、西南極大陸で岩盤を離れて海水の上に張り出した氷棚を粘性流体として扱うのには疑問がある。「正しい」粘弾性体力学を基に両方の性質を持ち、時間空間差分化した数値シミュレーションを可能とする方程式の形をさぐる。

マックスウェルの構成方程式は、ばねとダッシュポットが直列につながれた系の示す力と変位（のび）の関係をモデルとして導かれた。この系で、ダッシュポットの部分は粘性を表すと考えられ模式図にもそのように描かれる。しかし、系の力は一つだから、ばねの伸びだけできまり、ダッシュポットの部分はばねの伸び縮みの原点の位置の時間的変化を表す式と考えてもかまわない。その結果、力が等しいという関係式はばねの原点（自然長は不変）がばねの伸び縮みによって引きずられて変化する事を表す式と読み替えられる。これを連続体における力と歪の関係に置き換えると、弾性歪を定義する原点の位置（のひずみ）即ち塑性歪の時間変化が弾性歪によって生じる事を示す式となる。即ち弾性歪が時とともに塑性歪に転化すると言う事を意味する。この時定数がマックスウェル緩和時間になる。

こう考えると、日常経験的にも知られている「弾性ひずみが時とともに塑性ひずみに転化する」という事を物理の法則とし、これと弾性体に対する運動方程式とを組み合わせて基礎方程式系とする事が適切と思われる。このことは従来の「正しい」マックスウェル構成方程式と矛盾せず、差分法による数値積分を可能にする。即ち、弾性波の伝搬より十分ゆっくりの現象に対しては（静的）準弾性平衡を保ちつつ、「弾性ひずみ緩和」によって生じるゆっくりした変化を扱うのである。

マントル対流を粘性流体として扱いつつ、地球表面近くのプレートの弾性を取り入れようとする試みが、過去２０年ほど現れてきたが、著者が調べた範囲では工学のレオロジーで使われた方程式系をそのまま持ってきたもので正しいものではない。

キーワード: マックスウェル粘弾性体, 粘弾性体力学, マントル対流, プレート・マントル結合シミュレーション
Keywords: Maxwellian visco-elsatic media, visco-elastic medium dynamics, mantle convection, plate-mantle coupling simulation

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SIT39-02 会場:416 時間:5 月 2 日 09:15-09:30

斜方輝石－カンラン石間の水の分配に与える Al の効果：リソスフェアーアセノスフェア境界に関する考察

Effects of Al content on water partitioning between Opx and Ol: Implications for lithosphere-asthenosphere boundary

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Most minerals in the Earth's upper mantle contain small amounts of hydrogen (i.e. "water"), structurally bound as hydroxyl. Water has an important influence on the behavior of rock system. This small amount of water has an important influence on the behaviours of rock systems. A large viscosity contrast of more than two orders of magnitude was detected at depths of 70 km to 100 km beneath ocean and was defined as the lithosphere-asthenosphere boundary [1]. The origin of the lithosphere-asthenosphere boundary remains an enigma. The water distribution in the Earth is critical to the nature of the boundary. For example, Mierdel et al. (2007)[2] indicated that a high water solubility in aluminous orthopyroxene among mantle geotherm in the Earth's upper mantle would effectively contribute to a stiffening of the lithosphere. Therefore, precise knowledge on the distribution of water among mantle minerals is very important for understanding the Earth's dynamics. The Earth's uppermost mantle is composed mainly of olivine (Ol), orthopyroxene (Opx), clinopyroxene (Cpx), spinel, and garnet. In particular, Ol accounts for a large proportion (60 vol.%) of the Earth's uppermost mantle. In addition, Opx, which contains significantly more water than does Ol in the mantle xenolith, is the second phase of the Earth's uppermost mantle. The FeO content in mantle Ol shows very limited variation in range, whereas the Al content of Opx in the Earth's upper mantle decreases significantly with increasing pressure [3] Therefore, the variation of Al content in mantle minerals can be important for the solubility of water in mantle minerals.

To investigate the partitioning coefficient of water between Opx and Ol ($D_{(Opx/Ol)}$) under low-water concentrations (3 ~ 387 wt. ppm) similar to the Earth's mantle conditions, high-pressure experiments have been conducted at pressures of 1.5-6 GPa and a temperature of 1573 K. The experiments were performed with Kawai-type multi-anvil and piston-cylinder apparatus by using starting materials of natural Ol and synthetic Opx with various Al contents. The water contents were obtained with a vacuum type Fourier transform infrared spectrometer (*Jasco*: FT-IR6100, IRT5000). Water content of minerals was calculated based on Paterson's calibration [4]. IR-spectra of Ol and Al-bearing Opx in this study are similar to those obtained by high-pressure experiments [5] and natural rocks [6], respectively. It is believed that broad bands in IR spectra of natural Opx are due to effect of crystal distortion by large Al substitution. On the contrary, IR-spectra of Al-free Opx are not consistent with those reported by Rauch and Keppler (2002) [7] likely because of the large difference of water fugacity. $D_{(Al-freeOpx/Ol)}$ is ~ 1 at all pressure conditions. However, the water contents of Al-bearing Opx are significantly larger than those of Ol at the same conditions. In addition, the effect of Al concentration in Opx on $D_{(Opx/Ol)}$ becomes larger with increasing pressure. The high Al content in Opx significantly increases $D_{(Opx/Ol)}$ and the trend increases with increasing pressure. $D_{(Opx/Ol)}$ drops sharply at the pressure at which the Al concentration of Opx becomes nearly 0 in the Earth's mantle conditions.

These results imply that viscosity of the upper mantle decreases sharply at depths deeper than those in which orthopyroxene contains no Al. The dramatic change of $D_{(Opx/Ol)}$ may explain the lithosphere-asthenosphere boundary beneath oceans and continents.

[1] D.L. Anderson, (1989) Blackwell Scientific, Boston [2] K. Mierdel et al. (2007) Science, 315, 364-368 [3] M. Obata, (1976) Am. Mineral., 61, 804-816 [4] M. S. Paterson, (1982) Bull. Mineral., 105, 20-19 [5] Q. Bai and D.L. Kohlsted, (1993) Phys. Chem. Minerals, 19, 460-471 [6] K. Grant et al., (2007) Contrib Mineral Petrol, 154, 15-34 [7] M. Rauch, H. Keppler, (2002) Contrib. Mineral. Petrol., 143, 525-536

キーワード: 水の分配係数, カンラン石, 斜方輝石, 粘性, FT-IR, リソスフェアーアセノスフェア境界
Keywords: water partitioning coefficient, olivine, orthopyroxene, viscosity, FT-IR, lithosphereasthenosphere

Japan Geoscience Union Meeting 2014
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SIT39-03 会場:416 時間:5 月 2 日 09:30-09:45

Brillouin 散乱分光法に基づく高圧力条件下での非晶質 MgGeO3 の構造変化の研究
Acoustic velocities of MgGeO3 gel at high pressure by Brillouin scattering

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Properties of silicate melts are essential for understanding evolution and dynamic behavior of the Earth and terrestrial planets. In the shallow mantle melting processes the density contrast between melts and crystals is well studied, but studies on the deep melting near the core-mantle boundary are still limited due to technical difficulties. The studies of amorphous material, analogs of melt, at high pressure can provide valuable insights about melts in the deep mantle. The Brillouin scattering method is suitable for velocity measurements of amorphous materials. It has been suggested that the change in coordination in the melt or glass structure reflects to the change in acoustic velocity. Thus we conducted sound velocity measurement using the Brillouin scattering method in diamond anvil cell at high pressure. We report in situ high-pressure acoustic velocity measurements of $MgGeO_3$ gel, an analogue of the $MgSiO_3$ melt, revealing the gradual coordination change of Ge from four- to six at least up to 80 GPa. We will conduct experiments at higher pressure in order to confirm the possible Ge coordination change in the gel expected to exist in the terrestrial and extraterrestrial planets.
Keywords: sound velocity measurement, high-pressure experiment, mantle dynamics, silicate melts, super-Earth

Japan Geoscience Union Meeting 2014
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SIT39-04 会場:416 時間:5 月 2 日 09:45-10:00

海洋多重反射波補正した広帯域海底地震計間 P 波相対走時測定
Measurement of differential P-wave travel time between two BBOBSs with Correction for crustal reverberation

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マントル３次元地震波速度構造の推定において海洋での観測が全球的に解像するのに欠かせない。しかしながら、海底での地震観測は一般的に周期５秒以下でノイズレベルが高いため、相の立ち上がりを読むことは困難である。そこで、約 10 秒またはそれ以上の周期帯で波形相関をとり、２観測点間の相対的な走時を測定することが行われている（例えば、Toomey et al. 1998, Tanaka et al., 2009）。

一方、P 波マントルトモグラフィーにおいて、P 波走時の分散を有限波長理論を用いてインバージョンに取り入れることは、分解能の向上に有効であり（例えば Obayashi et al. 2013 JpGU meeting）、観測点の少ない海洋下では特に大きな効果が期待される。Obayashi et al.（2004）は PP 波が反射点下の（海洋を含む）地殻多重反射波の影響で分散が生じることを示した。直達 P 波でも観測点下の地殻多重反射の影響はあり、特に海洋の多重反射の影響は無視できない。大林ら (2012) は地球深部構造由来の分散を広帯域海底地震計で測定すべく、堆積層を含む海洋多重反射の影響を補正する方法を提案した。それはまず堆積層を含む地殻構造および水深から Haskell のマトリックス法を用いて、観測点下の多重反射の応答を計算し、多重反射応答を互いの観測波形に畳み込み積分し、波形相関により相対走時を測定するというものであった。その際に堆積層の構造が多重反射波の波形に大きな影響を与えるため、堆積層構造の推定が重要であることを報告した。しかしながら、その後の検討の結果、堆積層が 1 km 未満と比較的薄い場合には、走時の測定においては構造の多少の違いはほとんど影響がないことが判明した。

そこで、我々はフレンチポリネシアに展開した広帯域海底地震計に上記測定法を適用した。BBOBS と島の観測点間の波形は補正を施すことでたがいに似るようになり、補正法有効であることを示している。観測された分散の特徴と分散データを取り入れたトモグラフィーの初期結果を報告する。

キーワード: 地殻多重反射, 広帯域海底地震計, トモグラフィー
Keywords: crustal reverberation, broadband ocean bottom seismometer, tomography

Japan Geoscience Union Meeting 2014
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SIT39-05 会場:416 時間:5 月 2 日 10:00-10:15

立方晶カルシウムペロブスカイトの小さな剛性率
Small shear modulus of cubic CaSiO3 perovskite

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Ca-perovskite (CaPv) is considered to be one of the most abundant minerals in the Earth's lower mantle (LM) and was suggested to have distinctly larger shear modulus than MgPv from static calculations and mean-field theory (Karki and Stixrude 1999; Stixrude et al. 2007). In this study the elasticity of cubic CaPv is reinvestigated using density functional constant-temperature first principles molecular dynamics simulations with strict calculation conditions. First, we computed the stable structure of CaPv and found that the cubic phase is more stable than the tetragonal and orthorhombic in the LM P,T condition. The thermal equation of state of CaPv was analyzed using the MD data set, which indicates its thermal properties including Gruneisen parameter quite similar to those of MgPv. Along the adiabatic temperature, CaPv was found to have higher density than the PREM and 12.5% iron-bearing MgPv. Next, we calculated elastic constants of cubic CaPv. Our new results clearly demonstrate that cubic CaPv does not have anomalously large shear modulus suggested by previous calculations with a small computation cell. This is because the cell applied in the previous studies is too small to allow the rotational phonon motion of SiO6 octahedra related to the zone boundary optic phonon instability. Acoustic wave velocities were finally determined from the elastic moduli, indicating no significant differences in velocities between CaPv and iron-bearing MgPv.

キーワード: Ca ペロブスカイト, 弾性率, 下部マントル, 第一原理計算
Keywords: Ca-perovskite, elasticity, lower mantle, first principles

Japan Geoscience Union Meeting 2014
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SIT39-06 会場:416 時間:5 月 2 日 10:15-10:30

Seismic Constraints on an Enstatite Chondrite Earth
Seismic Constraints on an Enstatite Chondrite Earth

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Recently, Javoy et al., EPSL, 2010 suggested the possibility that Earth had an initial enstatite chondrite composition due to their similar oxygen isotopes. Currently, the calculations of the bulk silicate Earth (BSE) are based on the assumption that the initial Earth began with a composition very close to that of a carbonaceous chondrite. Thus, it is necessary to evaluate whether the 1D seismic properties of the Earth are more consistent with an initial enstatite or chondritic composition. The BSE of an enstatite chondrite Earth (ECE) is different from that of a carbonaceous chondrite since the magnesium/silicon ratio is much lower for the former, resulting in a lower mantle that is almost devoid of Mg. Hence, the primitive lower mantle of an ECE consists mostly of iron-rich perovskite and pure silica. The seismic velocities of these phases are much slower than Mg-perovskite which, by itself, is faster than PREM (the slower MgO phase is necessary to match PREM velocities). However, the present-day lower mantle would be a mix of the primitive upper mantle (ie. pyrolite) and the Mg-depleted lower mantle. The latest mineral physics results are used to calculate possible 1-D seismic profiles of the Earth associated with these two scenarios and to compare with those observed for the Earth today.

Japan Geoscience Union Meeting 2014
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SIT39-07 会場:416 時間:5 月 2 日 10:30-10:45

核マントル境界の熱特性モデリング
Thermal property modeling of the core-mantle boundary

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Lattice thermal conductivity of minerals under pressure and temperature is a key property to understanding dynamics and evolution of the Earth's interior. We recently established an efficient ab initio technique for calculating the thermal conductivity of silicate minerals with complex structure and chemistry (Dekura, Tsuchiya, Tsuchiya, PRL, 2013). Calculated lattice thermal conductivity of MgSiO3 perovskite agreed satisfactorily with experimental values at room temperature, and post-perovskite was found to have thermal conductivity quite different from perovskite's, indicating that the D" discontinuity is not only the phase transition boundary but also the conductivity boundary. Using the obtained results, we determine the effective conductivity of the lower mantle and estimate the energy flow across the core-mantle boundary (CMB). Our results demonstrate that the CMB heat flux could change significantly from place to place by reflecting temperature heterogeneity located atop the core. A large CMB heat flow recently suggested from the outer core side can be reconciled only by considering polycrystalline assemblages yielding high-thermal conductivity.

キーワード: 第一原理計算, 格子熱伝導率, CMB 熱流量
Keywords: First principles computation, Thermal conductivity, CMB heat flow

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SIT39-08 会場:416 時間:5 月 2 日 11:00-11:15

西太平洋下のD”領域内部の３次元S波速度構造
Waveform inversion for localized 3-D seismic velocity structure in the lowermost mantle beneath the Western Pacific

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We infer 3-D localized shear velocity structure in the lowermost 400 km of the mantle at the western edge of the Pacific large low shear velocity province (LLSVP) by applying waveform inversion to transverse component body-wave waveforms from the F-net seismic array in Japan. Our dataset consists of relatively long period (12.5-200 s) broad-band seismic waveforms of Tonga-Fiji deep focus and intermediate deep earthquakes. We conduct several tests to confirm the robustness of the inversion results. We find two low velocity zones at the bottom of the target region, with a high velocity zone in the middle, and a low velocity zone above the high velocity zone and contiguous with the two deeper low velocity zones at a depth of 200-300 km above the CMB. This supports the idea that the Pacific LLSVP may be an aggregation of small upwelling plumes rather than a single large thermochemical pile.

キーワード: 波形インバージョン, 西太平洋, マントル対流, 最下部マントル, プルームクラスター
Keywords: Waveform inversion, Western Pacific, Mantle convection, Lowermost mantle, Plume cluster

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SIT39-09 会場:416 時間:5 月 2 日 11:15-11:30

核条件下での hcp-Fe の音速・密度測定
Compressional sound velocity and density measurements of hcp-Fe under core conditions

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SAKAMAKI, Tatsuya[1*] ; OHTANI, Eiji[1] ; FUKUI, Hiroshi[2] ; KAMADA, Seiji[1] ; TAKAHASHI, Suguru[1] ; SAKAIRI, Takanori[1] ; TAKAHATA, Akihiro[1] ; SAKAI, Takeshi[4] ; TSUTSUI, Satoshi[5] ; BARON, Alfred[3]

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Sound velocity measurements of Fe and Fe-alloy at high temperature and high pressure are necessary to understand the Earth's inner core. Despite seismological observations providing density-sound velocity data of Earth's core, there are few experimental reports about sound velocity of hcp-Fe at ultrahigh pressure and temperature conditions. In order to push forward with research, we have developed a portable laser-heating system for diamond anvil cell, which is called COMPAT (Fukui et al., 2013). We have succeeded in measuring the sound velocity of hcp-iron up to 160 GPa and 3000 K by inelastic X-ray scattering measurements combining with a laser-heated diamond anvil cell. The obtained pressure and temperature dependence of the sound velocity suggest that compressional sound velocity of hcp-Fe at inner core boundary (330 GPa and 5500 K) is higher than that of Earth's inner core. Thus, we can conclude that the light elements or combination of the light elements and nickel in the inner core decreases both density and compressional sound velocity of hcp-Fe simultaneously under the inner core conditions.

Reference
Fukui et al., 2013. A compact system for generating extreme pressures and temperatures: An application of laser-heated diamond anvil cell to inelastic X-ray scattering. Review of Scientific Instruments 84, 113902; doi: 10.1063/1.4826497.

キーワード: 地球核, 音速, 密度, 高温高圧, X 線非弾性散乱, レーザー加熱式ダイヤモンドアンビルセル
Keywords: Earth's core, sound velocity, density, high pressure and high temperature, inelastic X-ray scattering, laser-heated diamond anvil cell

Japan Geoscience Union Meeting 2014
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SIT39-10 会場:416 時間:5 月 2 日 11:30-11:45

第一原理分子動力学法による鉄・軽元素系液体合金の状態方程式の決定
The P-V-T equation of state of liquid pure Fe and Fe-light elements alloys by ab initio molecular dynamics simulations

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The equation of state (EoS) of pure Fe and Fe-light elements alloy liquids were calculated by means of ab initio molecular dynamics simulations at the outer core *P*-*T* conditions. In the outer core, many light elements, such as carbon, nitrogen, oxygen, hydrogen, sulfur, and silicon, have been proposed as possible constituents. The concentrations of these elements have been strongly debated for years. In this study, internally consistent thermodynamic and elastic properties of pure Fe and Fe-light elements alloys, in particular density, adiabatic bulk modulus, and P-wave velocity were analyzed in order to clarify the effect of light elements incorporation on seismically observable data. Then the results were compared with the seismological data of the Earth's outer core to confine the plausible compositions of the outer core. The new EoS model of liquid iron alloys as a function of pressure, temperature and fraction of light elements may serve as fundamental data for the composition model of the Earth's core.

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SIT39-11 会場:416 時間:5 月 2 日 11:45-12:00

X 線吸収法と超音波法を併用した高圧下における Fe-C 融体の密度-弾性波同時測定
Simultaneous measurement of liquid Fe-C density and sound velocity at high pressure

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水星や火星、月といった地球型惑星および衛星の液体核は軽元素を含有した鉄合金融体で構成されていると考えられており、これら天体核の組成を解明する為には高温高圧下における鉄融体の密度や体積弾性率に対する軽元素の影響を定量的に評価することが必要となる。このような密度の情報に加え核中の軽元素を特定するためには、地震波速度データと直接比較できる弾性波速度の情報が不可欠である。本研究では弾性波速度測定の手法を SPring-8 BL22XU の装置に新たに導入し、高圧下における鉄合金融体の弾性波速度ー密度の同時測定を行った。

高温高圧実験は BL22XU 設置の 180ton キュービックマルチアンビルプレスを用いた。弾性波測定は超音波法 (Higo et al., 2009)、密度測定は X 線密度吸収法 (Katayama et al., 1993) を用いた。圧力と温度の測定は試料部に封入した MgO と h-BN 混合粉末の X 線回折パターンから格子体積を求め、2 つの圧力マーカーより圧力ー温度条件を算出した。

今回の測定では Fe-3.5wt%C 組成での測定を行った。圧力・温度条件は 2.9 GPa, 1850 K までの測定を行った。その結果、X 線吸収法により求めた密度の値は 1.2 GPa, 1675 K では 7.01 g/cm^3, 2.9 GPa, 1700 K では 7.15 g/cm^3 となり圧力とともに密度の上昇が観察された。この結果はこれまで我々が得ている X 線吸収密度法の結果 (Shimoyama et al., 2013) と調和的な結果であった。また超音波法による測定では試料の前面、背面からの反射波をはっきり観察することができ、得られた Fe-C 融体の縦波速度 V_P は、圧力と共に増加する傾向が見られた

キーワード: 密度, 弾性波速度, Fe-C 融体
Keywords: Density, Sound velocity, liquid Fe-C

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SIT39-12 会場:416 時間:5 月 2 日 12:00-12:15

レーザー衝撃圧縮による液体状態での FeSi の音速密度測定
Sound velocity and density measurement of liquid FeSi alloy by laser-shock compression

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The internal structure of the earth is estimated by observing seismic wave. Comparing seismic wave observations and experimental data of sound velocity of iron(Fe), the composition of the Earth's core is not pure Fe. Several light elements (hydrogen, carbon, oxygen, silicon, sulphur, etc.) have been considered as the candidate of the composition of the Earth's core, but its composition is still unclear. In order to constrain the core composition, it is important to measure the sound velocity of iron alloys because it can be directly compared with the seismic wave. Silicon (Si) has been proposed as a major light element in the inner core [Mao et al., 2012]. So we measured the sound velocity of laser-shocked FeSi alloy in order to investigate the effect of Si for sound velocity of liquid Fe in the outer core condition.

The starting sample was prepared by synthesizing from mixture of Fe (99.98% purity) and Si (99.9% purity) slugs at arc furnace. The compositions of Fe and Si are 66.5 wt.% and 33.5 wt.%, respectively. We measured sound velocities and densities of FeSi at high pressure and high temperature conditions at the large laser facility in Institute of Laser Engineering, Osaka University. The sound velocities were measured by the x-ray radiography [Shigemori et al., 2012].

We obtained the sound velocity and density of FeSi at pressures around 700 GPa. It is seen that Si has the effect of increasing the sound velocity of liquid Fe. Comparing our experimental results and PREM model [Dziewonski and Anderson, 1981], Si may be contained up to 13.1 wt.% at 135 GPa, and up to 5.5 wt.% at 330 GPa in the outer core.

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SIT39-P01 会場:3 階ポスター会場 時間:5 月 2 日 14:00-15:15

水が沈み込むスラブの挙動に与える効果
Effects of hydrous rocks on behaviors of subducting slabs

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はじめに　深部マントルに数十から数百 ppm 含まれるとされる水は，プレートテクトニクスの発生と活性化・沈み込み帯火山・内陸および深発地震・親水元素の大規模輸送などの地球固有のダイナミクスを引き起こすと考えられている．その重要性から，マントル内部の水輸送の数値シミュレーションが行われてきたが，それらのモデルではプレートの速度や形状が人為的に与えられてきた．本研究では，一切の外力を与えないマントル全域に亘る数値モデルにより，地球深部への水輸送，およびそれに伴って水がどのようにスラブの自発的な挙動を変化させるかを同時に調べる．

手　　法　２次元流体力学シミュレーション (Tagawa *et al*., 2007, *EPS*) に基づき，固相の運動を解く．含水した岩石の移流は粒子法により解き，脱水・再含水反応は，実験に基づく含水玄武岩および含水かんらん岩の相平衡図 (Iwamori, 2007, *Chem. Geol*.) により評価した．含水した岩石の構成方程式 (*e.g*. Karato and Wu, 1993, *Science*) と状態方程式を導入することで，水輸送と固相のダイナミクスとが相互に作用するようになっている．構成方程式中のr (= 0, 0.7, 1.0, 1.93; 含水化による粘性低下の大きさ) と状態方程式中のβ (= 0. 1.0, 2.0; 含水化による密度低下の大きさ) の２者のみを変化させ，その他の設定は統一して計算を行った．

結果と議論　計算結果で，スラブ上面の岩石の反応経路（p-T経路）はいずれも西南日本のものと同一のものとなり (Iwamori, 2007)，200 km 以深で含水かんらん岩の層がスラブ上に形成された (NAMs 中に 2000 ppmH_2O 程度)．背弧拡大には含水域が軟らかくなることが必要のようである．スラブ沈み込みにより上盤プレート内部に引張応力が生ずるのに伴い，含水した低粘性域に変形が集中するからである．計算結果同士を比較すると，rが大きくなるにつれ，海洋プレート速度が速くなる．これは，スラブ上面の含水層が粘性抵抗を減らす効果で説明できる．一方，βが大きくなるにつれ，海洋プレート速度は遅くなる．これは，含水岩石がスラブの負の浮力を部分的に相殺する効果で説明できる．沈み込み速度は，マントルウェッジ内のコーナー流れの速さを決める最も重要なパラメータである．コーナー流れが速い場合，スラブ表面にかかる吸い上げの力が大きくなり，沈み込み角度は浅くなる．速いコーナー流れはまた，マントル深部から表面への移流による熱輸送を活性化させ，急速で継続的な背弧の拡大に寄与する．このような解析的な議論によって，rとβを変化させた場合の計算結果の違いを説明できる．東アジアでは，スタグナントスラブと背弧とが広域に分布するが，その両者を実現するためには，大きなrと小さなβが必要である．両者の生成には強いコーナー流れが必要だが，βはそれを妨げる力を生むからである．このように，スラブの形状や背弧拡大の寿命などから，マントルウェッジ内に働く含水化に伴う浮力の大きさと粘性低下の大きさを制約できる可能性がある．

キーワード: 水輸送, 自由対流, 沈み込みのダイナミクス, プレート速度, 大マントルウェッジ
Keywords: water transportation, free convection, subduction dynamics, plate velocity, big mantle wedge

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SIT39-P02 会場:3 階ポスター会場 時間:5 月 2 日 14:00-15:15

Hi-net で計測される日本列島における splitting intensity の空間的変化について II
Regional scale variation of splitting intensity observed in Japanese islands by Hi-net II

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To systematically investigate the spatial variation of seismic anisotropy around the Japanese islands, we measured the splitting intensity (SI) of teleseismic SKS and SKKS phases by Hi-net (Ogawa et al., 2013, SSJ). SI is first introduced by Chevrot (2000) as a method of measuring seismic anisotropy; it is based on cross-correlation of polarized waveforms, and can be modeled like the delay time of seismic tomography considering the effect of finite frequency (e.g., Favier and Chevrot, 2003). In this study, we extend our previous work by measuring SI for a large number of dataset recorded by the dense seismic station network, Hi-net. We use data from tilt-meters of Hi-net from October in 2000 to September in 2013. We have selected the recordings of SKS phases for epicentral distances between 90 and 135 degrees and SKKS beyond 105 degrees, and Mw larger than 6.0, resulting in a total number of events to be 189 that is much larger than the previous case. For the actual analysis, we apply a band-pass filter between 0.05 and 0.125 Hz, and the measurement error of each SI will be carefully estimated using a new formulation, as there appears an error in the Chevrot (2000)'s original treatment. The preliminary analysis indicates regional scale variations of SI patterns that apparently depend on the back azimuth of seismic event, which may be influenced by the subducting slabs.

キーワード: 地震波異方性
Keywords: seismic anisotropy, splitting intensity

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SIT39-P03 会場:3 階ポスター会場 時間:5 月 2 日 14:00-15:15

660km 不連続面付近におけるパイロライト、MORB、ハルツバージャイトの相関係の比較：マルチセル法を用いた精密実験
Comparison of phase relations in pyrolite, MORB and harzburgite across 660-km discontinuity

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Pyrolite is the model rock which composes the average upper mantle. It is accepted that 660-km seismic discontinuity is formed by post-spinel transition of pyrolite. MORB (mid-ocean ridge basalt) and harzburgite in slabs subduct to 660-km seismic discontinuity due to their higher densities than pyrolitic average mantle. It has been considered that the density cross-over between pyrolite and slab materials occurs due to post-spinel transition in pyrolite at the 660-km discontinuity, and MORB and harzburgite are trapped around the depth (e.g. Ringwood and Irifune, 1988). Therefore, the phase transition pressures of these mantle rocks are the important parameters to elucidate the dynamics around 660-km seismic discontinuity. We investigated detailed phase relations of pyrolite, MORB and harzburgite with multi-sample cell technique.

The starting materials were prepared from the oxide mixtures of pyrolite, MORB and harzburgite composition after McDonugh and Sun (1995) (excluding MnO, K_2O and P_2O_5), Melson et al. (1976) (P_2O_5) and Michael and Bonatti (1975), respectively. High-pressure and high-temperature experiments by quench method were performed at about 20-28 GPa and 1600-2200C for 2-10 hours using a Kawai-type 6-8 multianvil high-pressure apparatus at Gakushuin University. These samples were packed with pressure calibrants ($MgSiO_3$ or pyrope) in a Re multi-sample capsule with four holes. Temperature was controlled with a LaCrO3 heater and measured with a W5%Re-W26%Re thermocouple inserted in a Cr_2O_3-doped MgO pressure medium. Phases of recovered samples were identified with microfocus-Xray diffractometer and SEM-EDS.

In pyrolite at 1600-2200C, the mineral assemblage of $MgSiO_3$-rich perovskite (Mpv) + magnesiowustite (Mw) + garnet (Gt) + $CaSiO_3$-perovskite (Cpv) is stable at pressure range of 22-24 GPa, and changes to that of Mpv + Mw + Cpv above 24 GPa. The mineral assemblage of ringwoodite (Rw) + Gt + Cpv at 1600C transforms to that of Rw + Mw + Gt + Cpv due to transition of Rw to Gt + Mw at 1800-2000C, and Rw disappears perfectly above 2200C. In MORB, the mineral assemblage of Gt + stishovite (St) + Cpv changes to that of Mpv + St + Al-rich phase + Cpv with continuous post-garnet transition. In harzburgite at 1600C, the mineral assemblage of akimotoite (Ak) + Rw + Gt changes to that of Mpv + Mw by post-spinel transition after the Ak to Mpv transition. Above 1800C, no Ak was observed.

At 1600C, post-spinel transition in pyrolite occurred by about 0.5 GPa and 2 GPa lower pressure than that of harzburgite and post-garnet transition in MORB, respectively. The Clapeyron slope of post-spinel transition in harzburgite is larger than that of pyrolite, and both boundaries intersect at 2000C. From the comparisons of density profiles at 1600C, MORB and harzburgite have lower densities than pyrolite by post-spinel transition in pyrolite.

キーワード: ポストスピネル転移, ポストガーネット転移, 660-km 地震波不連続面, パイロライト, MORB, ハルツバージャイト
Keywords: post-spinel transition, post-garnet transition, 660-km discontinuity, pyrolite, MORB, harzburgite

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SIT39-P04 会場:3 階ポスター会場 時間:5 月 2 日 14:00-15:15

ミッシングキセノン問題に対する鉄キセノン系の融解実験
Melting experiments in the system Fe-Xe and Earth's missing xenon

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The abundances of noble gases in the Earth's atmosphere should be consistent with those in CI chondrite. However, xenon in the atmosphere is depleted relative to chondritic abundance, while lighter rare gases, Ne,Ar, and Kr, are less depleted. This is the so-called "missing xenon" problem and its reservoir has been discussed for a long time. Since xenon is too heavy to escape toward outer space, the missing xenon (Xe) might be hidden in the deep Earth.

The potential reservoirs are the mantle and core because xenon has a good reactivity under high pressure. Although extensive studies on the reactions of Xe and various mantle materials have been performed, none of those found a Xe reservoir (e.g., Sanloup et al., 2005; 2011; Brock et al., 2011). On the other hand, the alloying of iron with xenon has been expected based on the fact that Xe becomes metallic above 130 GPa (e.g., Eremets et al., 2000). While first-principle calculations suggested that the solubility of xenon in hcp iron is 0.8 mol% at Earth's core conditions (Lee et al., 2006), experimental study showed that the solid Fe-Xe reaction did not occur at least up to 155 GPa and 3000 K (Nishio-Hamane et al., 2010). Here we performed melting experiments in the Fe-Xe system to 86 GPa and 6450 K.

High pressure and temperature (P-T) conditions were generated in a laser-heated diamond-anvil cell. We used pure iron foil as a starting material. Xe was loaded cryogenically. Angle-dispersive X-ray diffraction (XRD) measurements in-situ at high P-T were conducted at BL10XU, SPring-8. The textural and chemical characterizations of recovered samples were made by using a field-emission-type scannning electron-microprobe (FE-SEM) equipped with energy dispersive x-ray spectrometry (EDS). Both cross section and surface of a sample were carefully examined by combining a focused Ga ion beam (FIB) with FE-SEM.

Any evidence for the reaction was not observed at least up to 83 GPa and 3810 K based on both XRD measurements and chemical analyses. On the other hand, chemical analysis on the sample recovered from 86 GPa and 6450 K, the highest P-T condition achieved in this study, showed Fe alloyed with up to ˜1.6 wt.% Xe as tiny grains. This sample had a difference in the texture between heated and unheated regions. We calculated the concentration of Xe in the entire molten area by assuming the heated region and the small grains of Fe-Xe alloy as a cylinder and spheres, respectively. The xenon content was estimated to be 0.02 wt. % for the heated area which is high enough to account for the missing xenon problem (10^{-10} wt.% Xe in the core). The present results could be a clue to solve the "missing xenon" paradox. Since the temperature of the present Earth's core is most likely lower than 6000 K, xenon might be incorporated into the core during Earth's early history at higher temperature.

キーワード: ミッシングキセノン, 高温高圧, 融解実験, コア
Keywords: Missing Xe, melting experiments, High pressure and temperature, core

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SIT39-P05 会場:3 階ポスター会場 時間:5 月 2 日 14:00-15:15

全マントル P 波鉛直異方性トモグラフィー
Whole-mantle P-wave radial anisotropy tomography

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1. はじめに

地震波の異方性を研究する際には，ほとんどの場合において六方対称の異方性（即ち，transverse isotropy）が仮定される．その対称軸は，水平面内（即ち，方位異方性）又は鉛直方向（即ち，radial anisotropy）にとることが多い．

マントル内の地震波の異方性は，かんらん石などの造岩鉱物のもつ結晶方位異方性，及び応力のかかることによるそれらの選択配向（lattice preferred orientation, LPO）によるものと考えられる (e.g., Zhang & Karato, 1995; Tommasi et al., 2000; Kaminski & Ribe, 2001)．地震波の異方性と地球内部物質の状態との関係が分かれば，異方性を観測することで地球内部の構造とダイナミクスを解き明かすことができる (Silver, 1996)．地震波の方位異方性に関する研究は数多く行われている．一方, 異方性は鉛直方向のみに存在すると仮定した鉛直異方性に関する研究は, P 波走時データを用いて Wang & Zhao (2013) により東北地方と九州地方で行われた．

本研究では全マントルの鉛直異方性を考慮に入れたグローバルトモグラフィーを実施し, マントルダイナミクスの研究を試みた．

2. データ・手法

国際地震センター (ISC) の EHB カタログから山本・趙 (2010) によって選択された 6765 点の観測点で観測された 12,657 個の地震を解析に用いた．約 140 万個の P, pP, PP, PcP と Pdiff 波の走時データをインバージョンに使用した．

解析に用いた手法は, Wang & Zhao (2013) の鉛直異方性トモグラフィーの手法を Zhao et al. (2013) によるグローバルトモグラフィーの手法に組み込んだものである．三次元等方速度構造を表す格子点の間隔は２度 (約 220 km) であり, 三次元異方性構造を表す格子点の間隔は１０度 (約 1100 km) である．

3. 結果

鉛直異方性を考慮に入れたトモグラフィーを実施した結果, 等方成分のみを考慮したモデルに比べて最終的な root-mean-square (RMS) 走時残差は減少した．　上部マントルには環太平洋に低速度異常が, 安定大陸の下には著しい高速度異常が見られた．また, 南太平洋とアフリカの下には核―マントル境界 (CMB) から地表まで連続した低速度異常が見られるなど等方成分については先行研究で行われた等方トモグラフィーの結果と非常に調和的であった．異方性成分は, 太平洋スーパープルームなどでは鉛直方向の速度が水平方向より卓越している領域が見られ, マントル中の鉛直方向の運動を表していると考えられる．

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キーワード: トモグラフィー, マントル, 異方性トモグラフィー
Keywords: tomography, mantle, anisotropy tomography

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SIT39-P06 会場:3 階ポスター会場 時間:5 月 2 日 14:00-15:15

CO_2 レーザー両側加熱ダイヤモンドアンビルセルを用いたMgO-$MgSiO_3$ 系の溶融実験
Melting experiments on the MgO-$MgSiO_3$ system using double CO_2 lasers heated diamond anvil cell

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Seismological studies suggest the presence of ultralow-velocity zones (ULVZ) near the core mantle boundary (CMB). Partial melting of the lower mantle materials has been proposed to explain these zones, but experimental validation at the appropriate temperature and pressure regimes remains challenging. The melting curve of the lower mantle material is a key to constrain the existence of melt at the base of the mantle. A laser heated diamond anvil cell (LHDAC) provides an enabling tool for determination of melting temperatures of materials under high *P-T* conditions. Although YAG, YLF lasers (the wavelengths are about 1 μm) have been generally used for LHDAC experiments, the use of metal absorber is required to heat silicate materials. However, the thermal absorber may cause a chemical reaction and a temperature gradient in the sample. The accuracy of temperature determination is suffered from the chemical reaction and the temperature gradient. In contrast, the CO_2 laser with the wavelength of about 10 μm can directly heat silicate materials. For the minimization of temperature gradients, double-sided heating system for LHDAC was suggested by Shen *et al*. (1996). This technique using the YAG laser has been widely used to study the behavior of materials under high *P-T* conditions. However, the double CO_2 laser heating system has not been used due to the wavelength of this laser is different from that of visible light.

The requirements for the pressure medium in laser heating experiments are low thermal conductivity and chemical inertness. Ar, which is a noble gas, is one of the suitable pressure mediums. However, loading Ar into the DAC is difficult under room temperature and ambient pressure. Therefore, a simplified method to load Ar into the DAC is required. In this study, I established new experimental technique for the minimization of temperature gradients and chemical reactions and performed melting experiments of the lower mantle materials using LHDAC.

First, a double-sided heating system using CO_2 laser was developed by separating optical elements. This system consists of the heating system using two CO_2 lasers which have the high power (100 W), the observation systems and the temperature measurement system. By using lenses designed for the CO_2 laser wavelength, the laser system is separated from observation and temperature measurement system. Two dimensional images and radiation spectrums are observed by Charge Coupled Device (CCD) camera and spectrometer, respectively.

Second, a simplified method to load Ar into the DAC was developed by the cryogenic technique. In this technique, Ar is cooled using liquefied N_2 until it forms a liquid, and the liquefied Ar is loaded into the sample chamber of the DAC. Cu was used to enhance cooling efficiency.

Finally, I performed melting experiments of the lower mantle materials using the double CO_2 lasers heated diamond anvil cell and Ar as the pressure medium. I used forsterite (Mg_2SiO_4) and mixtures of MgO and $MgSiO_3$ as the starting material. After the complete pressure release, the sample was recovered from the DAC and examined by FE-SEM. From the surface texture of recovered samples, I discussed melting temperatures of the lower mantle materials under high *P-T* conditions.

The double CO_2 laser heating and loading Ar methods developed in this study could powerful tool for determination of melting temperatures of the lower mantle materials.

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SIT39-P07 会場:3 階ポスター会場 時間:5 月 2 日 14:00-15:15

2 段式加圧方式 DAC による超高圧発生への試み
Ultra high pressure generation using the double-stage diamond anvil cell

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SAKAI, Takeshi[1*] ; YAGI, Takehiko[1] ; OHFUJI, Hiroaki[1] ; IRIFUNE, Tetsuo[1] ; OHISHI, Yasuo[3] ; HIRAO, Naohisa[3] ; SUZUKI, Yuya[4] ; KURODA, Yasushi[4] ; ASAKAWA, Takayuki[4] ; KANEMURA, Takashi[4]

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高圧物性科学にとって 1 TPa 領域は今も未開拓地である。ダイヤモンドアンビルセル (以下 DAC) による静的圧縮実験としての最高圧力は 400 GPa 程度 (Akahama and Kawamura, 2010) であった。これに対し、Dubrovinsky et al. (2012) が DAC を用いた 2 段式加圧方式により 640 GPa を発生したと報告し、静的圧縮による 1 TPa の発生は目指しうる目標として見えてきた。しかしこの報告では、1 段目に通常のダイヤモンドアンビル、2 段目に炭素から直接変換した半球状のナノ多結晶ダイヤを対向させたものが使用されており、マイクロアンビルの形状制御が困難、アンビルの位置がずれやすい、試料設置が困難等により再現性ある実験を行うことが難しいといった問題点がある。

本研究では、集束イオンビーム（FIB）加工機によるマイクロアンビルの作成を行った。この利点は、アンビルの形状制御ができる、サブミクロン精度での組み立て可能、試料も同時に作成可能、素材によらず加工が可能といった点で、種々のパラメータを制御しながら再現性良く実験を繰り返すことができる。我々はこの手法により現在最高で 340 GPa までの発生に成功しており、その詳細について報告する。

キーワード: ナノ多結晶ダイヤ, マイクロアンビル
Keywords: nano-polycrystalline diamond (NPD), microanvil

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SIT39-P08 会場:3 階ポスター会場 時間:5 月 2 日 14:00-15:15

第一原理分子動力学法による Fe-O 液体の相分離に関する研究
Ab initio molecular dynamics study on a phase separation in liquid Fe-O

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The Earth's outer core is mainly composed of liquid Fe-Ni alloy. The density of the outer core is, however, ˜10% smaller than this alloy. The density deficit indicates that substantial amount of light elements are present in the outer core [Birch, 1964]. Recent seismological observations proposed that seismic wave velocity is ˜3% slower than PREM below a few hundred kilometers of the CMB [Helffrich and Kaneshima, 2010]. The low-velocity anomaly is considered to be cause by stratification. However, mechanisms of the stratification have not been clarified yet. One possible cause is phase separation into Fe-rich and light element-rich liquid. Oxygen is one of the most important light elements, because an iron-oxygen phase separation was observed experimentally at low-pressure condition [Tsuno et al., 2007]. This immiscible behavior is, however, still unclear at the outer core pressure.

In this study, we calculated liquid Fe-O alloy at the outer core condition by means of *ab initio* molecular dynamics simulations. First, we analyzed local structures of liquid Fe-O alloy to detect signs of phase separation. Second, we evaluated its excess enthalpy. Both indicate that the liquid was well-mixed. Finally, we computed P-wave velocity in liquid Fe-O alloy. P-wave velocity was found to increase with increasing the oxygen concentration. All these results suggest that the simple enrichment process is less suitable to explain the low-velocity anomaly.

Keywords: ab initio molecular dynamics simulation, phase separation, liquid Fe-O alloy

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SIT39-P09 会場:3 階ポスター会場 時間:5 月 2 日 14:00-15:15

放射光 X 線その場観察と川井式マルチアンビル装置を用いた 30 GPa までのクロム苦土鉱の相関係の解明
In situ X-ray observations of phase transitions in MgCr2O4 to 30 GPa using Kawai-type multianvil apparatus

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Phase relations in $MgCr_2O_4$ (magnesiochromite) have been studied up to 30 GPa and 1600 ℃, using a large volume Kawai-type multianvil apparatus and in situ X-ray diffraction measurements system installed at SPring-8/BL04B1. $MgCr_2O_4$ spinel dissociates into $Mg_2Cr_2O_5$ (orthorhombic type) + Cr_2O_3 (eskolate) at 9 GPa and 1200 ℃, and then reunion to higher pressure phase ($CaTi_2O_4$ type) at 22 GPa and 1200 ℃. Moreover, another high-pressure phase was observed above $CaTi_2O_4$ type structure phase, and this phase was unquenchable to ambient condition. In addition, pressure-induced phase transition in $MgCr_2O_4$ was confirmed without decomposition under cold compression process. In this cause, Magnesiochromite is directly transformed to high-pressure phase through the mixture of spinel and high-pressure phase. In this study, $CaFe_2O_4$ type and ε-phase, which reported in earlier studies in $MgAl_2O_4$ were not observed. The Birch-Murnaghan equation of state was used for least-squares fitting of the volume data (assuming $K_0{}'$ =4). Thus, determined zero-pressure bulk modulus (K_0) of the $CaTi_2O_4$ type $MgCr_2O_4$ was 195 GPa.

In this presentation, we will discuss further details of high-pressure phase relation and physical properties of high-pressure phases in $MgCr_2O_4$ series.

Keywords: Magnesiochromite, in situ X-ray diffraction measurement, Kawai-type multianvil apparatus, phase transition

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SIT39-P10 会場:3 階ポスター会場 時間:5 月 2 日 14:00-15:15

地球核条件下にレーザー衝撃圧縮された Fe-Ni 合金の音速
Sound velocities of laser-shocked Fe-Ni alloys under Earth core conditions

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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 (1) which can yield the physical properties of the Earth's interior. Cosmochemical data and the composition of iron meteorites suggest that Earth's core contains mainly Fe-Ni alloy with 5-25 wt.% Ni. Although Lin et al. (2) and Kantor et al. (3) measured compressional sound velocities of Fe-Ni alloys at room temperature by inelastic x-ray scattering (IXS) at diamond anvil cell (DAC), the sound velocity data of liquid Fe-Ni alloys is very few (4).

We performed laser-shock experiments of liquid Fe-Ni alloys at HIPER system of Gekko-XII laser in Institute of Laser Engineering, Osaka University (5). Sound velocities were measured by side-on radiography (6, 7). We obtained sound velocities of Fe-Ni alloys at pressures up to 770 GPa. The sound velocity of Fe-Ni alloy was about 10% lower than that of liquid Fe at inner core boundary (ICB) pressure.

Part of this work was performed under the joint research project of the Institute of Laser Engineering, Osaka University.

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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