SIT35-01 会場:106 時間:5 月 26 日 14:15-14:30

Hcp 鉄の高温高圧弾性特性
High-P,T elasticity of hcp iron

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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.

Kawai and Tsuchiya, Geophys. Res. Lett. (2015) under review; Ichikawa et al., J. Geophys. Res., 119, 240 (2014); Martorell et al., Science 342, 466 (2013); Sha and Cohen, Phys. Rev. B 81, 094105 (2010a); Sha and Cohen, Geophys. Res. Lett. 37, L10302 (2010b); Vocadlo et al., Earth Planet. Sci. Lett. 288, 534 (2009)

キーワード: 第一原理計算法, Hcp 鉄, 弾性特性, 地球内核
Keywords: Ab initio calculation method, Hcp iron, Elasticity, Earth's inner core

SIT35-02　　会場:106　　時間:5 月 26 日 14:30-14:45

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られており (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細密充填構造（dhcp 構造）から六方細密充填構造（hcp 構造）、さらに面心立方構造（fcc 構造）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 hcp 構造から 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提唱されてきた dhcp 構造ではなく、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

SIT35-03 会場:106 時間:5 月 26 日 14:45-15:00

地球核条件下にレーザー衝撃圧縮された Fe-Si 合金の音速
Sound velocities of liquid Fe-Si alloys at Earth's core pressures by laser-shock compression

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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 seismological Earth model (PREM: Preliminary Reference Earth 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 GEKKO-XII laser irradiation facility [10] at the Institute of Laser Engineering, Osaka University. The samples are Fe-Si alloys ($Fe_{95}Si_5$, $Fe_{90}Si_{10}$, $Fe_{80}Si_{20}$ and $Fe_{66}Si_{34}$ in weight percent). The sound velocities and densities of shock-compressed Fe-Si alloys using the high-power laser were measured by x-ray radiography [7, 11, 12] at pressures up to 960 GPa. The linear relation between the sound velocity and the density for FeSi alloy well follows Birch's law [4] up to 960 GPa along the Hugoniot. The extrapolated sound velocity of FeSi alloy was about 40% faster than that of PREM at inner core boundary pressure. The outer core is composed of 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.

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キーワード: 音速, レーザー, 衝撃波, Fe-Si 合金, 地球核, 実験
Keywords: sound velocity, laser, shock wave, Fe-Si alloys, Earth's core, experiment

SIT35-04 会場:106 時間:5 月 26 日 15:00-15:15

液体 Fe-Ni-S 合金の弾性波速度
Sound velocity of liquid Fe-Ni-S alloy at high pressure: Sulfur in the core?

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BARON. Q.R. Alfred[2]
IMADA, Saori[1*] ; NAKAJIMA, Yoichi[2] ; HIROSE, Kei[1] ; KOMABAYASHI, Tetsuya[4] ; OZAWA, Haruka[3] ;
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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 $(Fe,Ni)_3S$ 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 sucessfully determined the sound velocity of liquid $(Fe,Ni)_3S$ 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.

キーワード: 弾性波速度, 液体鉄合金, 硫黄, 外核, 火星核
Keywords: Sound velocity, liquid iron alloy, sulfur, outer core, Martian core

Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)

SIT35-05 会場:106 時間:5 月 26 日 15:15-15:30

鉄合金液体の第一原理熱弾性計算による地球外核組成の制約
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

SIT35-06 会場:106 時間:5 月 26 日 15:30-15:45

外核最下部にとくに敏感な波を用いた速度構造の推定
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 Yu 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.

キーワード: 外核最下部 P 波速度, F 層, PKPbc 波走時の分散, PKPbc と PKiKP との走時差
Keywords: P-wave velocity in the lowermost outer core, F-layer, Traveltime dispersion of PKPbc, differential traveltimes between PKiKP and PKPbc

SIT35-07 会場:106 時間:5 月 26 日 16:15-16:30

生命居住惑星とプレートテクトニクスの役割
Role of Plate Tectonics for Habitable Planet

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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 CO_2 and H_2O, (2) Role of tectonic erosion, (3) Production of nutrients-source rocks at subduction zone, (4) Driving force of Earth's magnetic filed, (5) The buffer of Earth's system, and (6) The controller of thermal history of the Earth.

Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)

SIT35-08 会場:106 時間:5 月 26 日 16:30-16:45

地球内部の東西半球構造とグローバルダイナミクス
East-west hemispherical structures in the Earth and their implications for global dynamics

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IWAMORI, Hikaru[1*] ; NAKAMURA, Hitomi[1] ; YOSHIDA, Masaki[1] ; TANAKA, Satoru[1] ; NAKAGAWA, Takashi[1] ; NAKAKUKI, Tomoeki[2]

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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

SIT35-09 会場:106 時間:5 月 26 日 16:45-17:00

下部マントルに沈み込むスラブの運動と水の輸送
Slab dynamics and water transport in the lower mantle

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地表から固く冷たいスラブがマントルへ沈み込むことは、地球マントル対流を特徴づける要因のひとつであると考えられている。最近の研究では、660-km 相境界を超えたスラブは急に太くなっていることを示しているが、分解能の限界により下部マントルでのスラブの運動や変形を定量的に議論することは困難である。一方、LLSVPs の形状や親水元素の分布などにより、スラブの沈み込みとマントル最下層構造との間には関連性が示されている。本研究では、人為的な力を与えることなく対流を再現できる数値モデルを用い、下部マントルへ沈み込むスラブの運動と最下層構造のより自然的な相互作用を調べる。

2 次元のマントル対流モデルによってプレートの運動と水輸送を数値シミュレーションにより解く。さらに、実験に基づく含水鉱物の相図 (Iwamori, 2004, 2007) と水の輸送を組み込む。マントル最深部には、周囲のマントルより重い層と post-perovskite (PPV) への相変化を導入する。今回は、粘性率と熱膨張率の深さプロファイル、スラブの降伏強度を変化させて計算を行う。

今回の結果では、スラブ強度が低い時は (200 MPa) 下部マントルの粘性率にかかわらずスラブは座屈する。スラブの座屈の太さや降下速度は、下部マントルの粘性率の深さ変化の影響を受ける。さらに、熱膨張率が深さ依存性を持つ時は、スラブが硬い時（300 MPa）でも座屈は生じる。これは、熱膨張率によりマントル深部ではスラブが持つ下向きの浮力が減少する効果で説明できる。さらにこの場合、マントル浅部では、逆に海洋リソスフェアの沈み込みが促進されるために、表面プレートは下部マントルのスラブの影響を受けにくくなり、観測によるプレート運動と調和的になる。
スラブの形状の違いは下部マントルでの水が移動と最下層での高密度物質の構造に変化をもたらす。座屈したスラブは、褶曲の間に水を含むために、水は沈み込み帯前後面に広がる。一方、スラブがまっすぐに沈み込むとコア-マントル境界での接触領域の粘性が低くなり、スラブ直上に形成される含水層がスラブから剥がれるために、沈み込み帯前面に多く分布するようになる。このような水が前面に多く分布する特徴は、PPV 相のスラブの粘性率が大きく低下するときにも起こる。各物理パラメータがマントル対流に与える影響を調べた今回の研究から、下部マントルスラブ構造および CMB 近傍の物質構造には降伏強度または熱膨張率が、さらに水の分布には PPV の粘性降下が重要な役割を果たしている可能性があると考えられる。

キーワード: 自由対流, スラブの沈み込み, スラブの座屈, 最下部構造, 水輸送
Keywords: free convection, subducting slab, slab buckling, lower mantle structure, water transport

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SIT35-10 会場:106 時間:5 月 26 日 17:00-17:15

表面波の位相及び振幅を用いた北米大陸の高精度マッピング
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

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アセノスフェア熱イベントの検出：マントルゼノリスからのアプローチ
Detection of an asthoenospheric 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, soid-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.

キーワード: アセノスフェア, リソスフェア, 熱イベント, マントルゼノリス, 鉱物累帯構造
Keywords: asthenosphere, lithosphere, thermal event, mantle xenolith, mineral zoning

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マックスウェル粘弾性体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」とみなされ、その動きを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、氷期終了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なるような小論”The viscosity of the mantle(1967, Geophys. J. roy. astr. Soc. 14, p.297)”の冒頭で次のように述べている。

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基礎として、固体物理や材料工学で知られているクリープ現象、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。上の文は、この応力—歪（速度）関係を流体力学方程式の内部応力として採用する、と言っているととれる。

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力の効果は「運動量拡散」を表すことは数学的・物理的に明らかだが、この小論や固体地球科学で想定される大きな粘性率、たとえば 10**21Pa・sec を使うなら、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、おかしいと言ったりしていない。）

上記の英語でも、日本語でも、“応力—歪（速度）関係”という時、どちらが原因でどちらが結果か明白でない。「固体の流動」から思い浮かぶようにクリープ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ープ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。この混同が考え違いの原因であろう。

このような間違いを起こさない「新しい定式化」を昨年の学会で発表したが、若手から碩学に至るまで、固体地球物理学者は釈然としないようであった。今回は定式化の概略を繰り返すとともに上記観点や、弾性力と粘性力という「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」など基本的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略を箇条書きすると次の通り (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を基に展開された粘弾性体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。

・新しい視点で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 の構成側 (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される。

・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。

・非発散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。

・発散のある圧縮性弾性体では、相変化がおこらない限り、塑性変位に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じにはならない。

・発散を含む一般の場合、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。

キーワード: プレート・マントル結合系力学, マントル対流, マックスウェル粘弾性体, 粘弾性体力学, 弾塑性体力学
Keywords: plate-mantle coupled system dynamics, mantle convection, Maxwellian viscoelastic medium, viscoelastic medium dynamics, elastico-plastic medium dynamics