SIT04-01 会場:201B 時間:5 月 19 日 14:15-14:30

高圧下における MgO ペリクレイスの格子熱伝導率
Lattice thermal conductivity of MgO periclase at high pressure

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　核マントル境界の熱流量は地球の熱史、マントルや核の対流、ダイナモの駆動等の議論に関わる重要なパラメータである。核マントル境界直上は熱境界層であり、熱は主に熱伝導によって輸送される。そのため、核マントル境界の熱流量は最下部マントル構成鉱物の熱伝導率と温度勾配の積で表すことが出来る。しかし先行研究による熱伝導率の見積もりは 5-30 W/m/K と、大きな幅がある。高圧下における熱伝導率測定が困難であることから、測定は比較的低圧に限られている未だ最下部マントルの熱伝導率は決定されておらず、核マントル境界の熱流量に強い制約は与えられていない。そこで本研究は高圧発生装置ダイヤモンドアンビルセル（DAC）と、サーモリフレクタンス（TR）法による熱拡散時間測定を組み合わせることで、下部マントル鉱物である MgO ペリクレイスの室温高圧下 (100 GPa 以上) における格子熱拡散率測定を行い、格子熱伝導率を求めた。DAC と TR 法を組み合わせた本研究手法は、核マントル境界における高圧力条件下において格子熱拡散率測定を行う唯一の方法である。得られた MgO ペリクレイスの格子熱伝導率を用い、先行研究で報告されている格子熱伝導率の温度依存性 (e.g. Hofmeister. 1999, Science)、Mg ペロフスカイト、ポストペロフスカイトの格子熱伝導率 (Ohta et al. 2012, EPSL)、熱境界層の温度勾配 (e.g. Tateno et al. 2009, EPSL) と併せ、最下部マントルにおける格子熱伝導率、そして核マントル境界の熱流量について議論を行う。

キーワード: 格子熱伝導率, ペリクレイス, 核マントル境界熱流量, 格子熱拡散率
Keywords: thermal conductivity, periclase, core-mantle boundary heat flow, thermal diffusivity

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X線非弾性散乱法によるPbnm－CaIrO3、 Cmcm-CaIrO3、アンチゴライトの結晶弾性定数決定
Single crystal elasticity of Pbnm-CaIrO3, Cmcm-CaIrO3, and Antigorite determined by inelastic X-ray Scattering

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Akira Yoneda[1*], Fukui Hiroshi[2], Yusuke Seto[3], Tsuitsui Satoshi[4], Uchiyama Hiroshi[4], Alfred Q. R. Baron[4], Akihiko Nakatsuka[5], Yoshiasa Akira[6], Tohru Watanabe[7], kenya ono[7]

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Single crystal elasticity of Pbnm-, Cmcm- CaIrO3 and Antigorite was measured at Spring8 BL35 by using inelastic X-ray scattering method. The former two phases are well known analog of perovskite (Pv) and post perovskite (pPv) MgSiO3, respectively. The last one is important hydrous mineral in subduction slab.

キーワード: ペロブスカイト, ポストペロブスカイト, アンチゴライト, 結晶弾性, X線非弾性散乱
Keywords: Perovskite, Post-Perovskite, Antigorite, crystal elasticity, inelastic X ray scattering

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SIT04-03 会場:201B 時間:5 月 19 日 14:45-15:00

Tomographic properties from mantle convection in a 3-D spherical shell with the self-consistently calculated mineralogy

Tomographic properties from mantle convection in a 3-D spherical shell with the self-consistently calculated mineralogy

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We use numerical thermo-chemical mantle convection simulations in a 3-D spherical shell with the self-consistently calculated mineral physics to investigate various statistical properties using global tomography models (root-mean-square, cross-correlations and spectral amplitude of seismic anomalies). Four compositional models are assumed here, which has been already used in a paper published recently [Nakagawa et al., 2012]. In order to be the similar resolution to current global tomographic images, we use spherical harmonic filter technique instead of tomographic filtering technique [e.g. Davies, et al., 2012]. The truncation of spherical harmonic filter is used as degree of 16, 24, 32 and 40 to compare with the original resolution (96x288x96x2, which is equivalent to 384x192x96 or degree of 192 of spherical harmonic expansion). The statistical properties of tomographic image could be explained by thermo-chemical cases (e.g. RMS amplitude and anti-correlation in the deep mantle). However, it would be difficult to explain the ratio of Vs and Vp or Vb for thermo-chemical origin of mantle heterogeneities, which is similar profiles to isochemical cases. On the other hand, the ratio of Vs and density could explain the mineral physics constraint [e.g. Karato and Karki, 2001] with thermo-chemical origin of mantle heterogeneity. In conclusion, in order to assess global tomographic image as a consequence of mantle convection, RMS amplitude, cross-correlation and the ratio of Vs and Vb ratio might have useful information to understand what happens in a convecting mantle inferred from tomographic images in the deep mantle.

キーワード: マントル対流, 鉱物相平衡図, 地震波トモグラフィー, 球面調和関数フィルタリング, 統計量解析
Keywords: Mantle convection, Self-consistently calculated mineralogy, Seismic tomography, Spherical harmonic filtering, statistical analysis

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マントル物性の空間変化が対流パターンに与える影響に関する数値流体力学的研究
Numerical investigations of effects of spatial variations in physical properties on the mantle convection patterns

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1. Introduction

There exist large differences in temperature and pressure within the mantle of terrestrial planets. In the Earth 's mantle, for example, a pressure increases by about 135GPa with increasing depth, while a temperature does by about 3500K. These large differences in temperature and pressure are expected to yield substantial variations in the physical properties of mantle materials and, hence, significantly affect the dynamic behaviors in the mantle. Indeed, as had been inferred by several earlier studies, the spatial variations in mineral properties play an important role in the internal structures observed in the mantle of the Earth and terrestrial planets. We will study how the spatial variation of physical properties of mantle materials affects the flow patterns of thermal convection.

2. Model and Procedure of numerical experiments

We carried out numerical experiments of thermal convection in highly viscous and incompressible fluids, in order to study the influences of the spatial variations in physical properties of fluids (viscosity, thermal conductivity and thermal expansivity) on the convecting flow patterns in the mantle of terrestrial planets. We present the results of a series of numerical calculations using (1) a linear stability analysis on the onset of thermal convection in fluids confined in planar layers, and (2) a nonlinear (finite-amplitude) time-dependent thermal convection in a two-dimensional Cartesian box of aspect ratio (width/height) of 6, with systematically varying the magnitude of (i) decrease in viscosity with temperature, (ii) increase in thermal conductivity with pressure (or depth), and (iii) decrease in thermal expansivity with pressure. By comparing the results with those in the presence of their spatial variations, we will discuss the changes on the critical conditions, dominant vertical flow structures, and the convection regimes caused by their spatial variations.

3. Results

From the changes in flow patterns with increasing the amplitudes of temperature dependence of viscosity, we successfully identified the transition into the " stagnant lid " (ST) regime, where the convection occurs only beneath a thick and stagnant lid of cold fluid at the top surface. We also found by both linear and nonlinear numerical calculations, that the transition takes place regardless of the spatial variations in thermal conductivity and/or expansivity. However, detailed analysis of the numerical results showed a quantitative difference in the critical condition for the onset of ST convection due to the presence of spatial variations in thermal conductivity and expansivity. Especially we focused on the horizontal wave number of perturbation which is largely decreased by the introduction of spatial variations in these properties. We further developed an analytical model of convection cells which consider the thickness of stagnant lid and convective vigor beneath it. The model successfully reproduced the mechanism of increasing horizontal length scale of ST regime convection cells for each condition of spatial variations in physical properties.

4. Discussion and concluding remarks

The results of present studies indicate that, under certain conditions, the convection of fluids with strongly temperature-dependent viscosity takes place which is characterized simultaneously by (i) large horizontal length scales of convective cells and (ii) thick stiff lid of highly viscous fluid above it. This is in a stark contrast with earlier numerical studies using constant thermal conductivity and expansivity where the convection beneath stagnant lids is always associated with cells with small horizontal length scales. Our findings therefore highlight the essential roles of the spatial variation of the thermal conductivity and thermal expansivity on the convection patterns in the mantle of terrestrial planets.

キーワード: マントル対流, 粘性率, 熱伝導率, 熱膨張率, スタグナントリッド
Keywords: mantle convection, viscosity, thermal conductivity, thermal expansivity, stagnant-lid convection

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FeCr2O4 の高圧相転移と新規ポストスピネル相の結晶構造
High-pressure transitions in FeCr2O4 and crystal structures of new post-spinel phases

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Introduction

$FeCr_2O_4$ chromite has the spinel (Sp) structure, and forms the solid solution with $MgAl_2O_4$ and $MgCr_2O_4$ which occurs in the Earth's mantle. The chromitite composed of mostly $FeCr_2O_4$-rich spinel includes high-pressure minerals such as diamond and coesite, which suggest possible indicators of material cycles in the deep mantle (Arai, 2010; Yamamoto et al., 2009). Chen et al. (2003) reported occurrence of the high-pressure polymorphs of $FeCr_2O_4$-rich composition in Suizhou meteorite and synthesized them with diamond anvil cell. They demostrated that the natural chromite spinel transforms to calcium ferrite (CF)-type at 12.5 GPa and to calcium titanate (CT)-type above 20 GPa. High-pressure transiton study of pure $FeCr_2O_4$ end-member demonstrated that cubic spinel of $FeCr_2O_4$ transforms to tetragonal at high-pressure and room temperature (Kyono et al., 2012). In this sudy, we report experimental results on the phase relations in $FeCr_2O_4$ at high pressure and high temperature and the crystal structure analyses of new post-spinel phases.

Experimantal methods

$FeCr_2O_4$ spinel was synthesized from a mixture of Fe_2O_3 and Cr_2O_3 with a 1:2 molar ratio by heating at 1200C for 24 h in a controlled oxygen fugacity using a mixture of H_2, CO_2 and Ar with volume ratios of 1:1:2. High-pressure experiments were made by quenching method at 12-28 GPa and 800-1600C with a Kawai-type 6-8 multianvil high-pressure apparatus at Gakushuin University. Phase identification of each recovered sample was made with powder and microfocus X-ray diffractometers, and compositional analysis was made with a SEM-EDS. The recovered $FeCr_2O_4$ sample was observed by a TEM at Geodynamics Research Center of Ehime University. Angle-dispersive synchrotron X-ray diffraction measurements of some recovered samples were made at ambient conditions using the beam line BL02-B2 at SPring-8 for Rietveld analysis with the RIETAN-FP software (Izumi and Momma, 2007).

Results and discussion

Sp-type $FeCr_2O_4$ first dissociates into a mixture of $Fe_2Cr_2O_5$ + Cr_2O_3 at about 15 GPa, and further transforms to a CF-like phase at lower temperature than 1300C and CT-type $FeCr_2O_4$ at higher temperature at around 20 GPa. Although the CF-like phase had the same space group as the CF-type structure from the result of TEM observation, the X-ray diffraction pattern was somewhat different from that of the CF-type structure. Rietveld refinement confirmed that the $FeCr_2O_4$ synthesized above about 20 GPa at higher temperature than 1300C has the CT-type structure and that $Fe_2Cr_2O_5$ phase is isostructural to the high-pressure $Mg_2Al_2O_5$ phase (Enomoto et al., 2009). The CT-type phase with pure $FeCr_2O_4$ composition and the $Mg_2Al_2O_5$-type $Fe_2Cr_2O_5$ were synthesized for the first time, and the structure analyses of the phases were carried out.

キーワード: ポストスピネル, 高圧, リートベルト解析, クロマイト, FeCr2O4, TEM 観察
Keywords: post-spinel, high-pressure, Rietveld analysis, chromite, FeCr2O4, TEM observation

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SIT04-06 会場:201B 時間:5 月 19 日 15:30-15:45

熱力学的性質が及ぼす沈み込むスラブ形状への影響
Effects of Thermodynamic Properties on the Geometrical Evolution of Subducting Slabs

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In this study, we perform a series of numerical experiments to investigate the effects of thermodynamic properties on the geometrical evolution of subducting slabs. We calculate density, thermal expansivity, and heat capacity of mantle mineral assemblages of a lherzolite composition over a range of pressure and temperature (PT) conditions applicable to the Earth's mantle, using the thermodynamic database of Stixrude and Lithgow-Bertelloni (2011) and the thermodynamic calculation code Perple_X (Connolly, 2009). Following Nakagawa et al. (2009), we assume that thermal diffusivity follows a theoretical power-law relationship with density and derive thermal conductivity from the calculated density, expansivity, and diffusivity. The calculations show that density, expansivity, and conductivity varies significantly with depth; for example, the ranges of their values for a typical mantle geotherm are 3300-5100 km/m^3, 1.5-3.5 10^{-5}/K, and 3-18 W/m K, respectively. The change in heat capacity is relatively small ($<$ 5%). We incorporate the effects of these thermodynamic properties into a 2-D finite element code with compressible convection formulations under the anelastic liquid approximation (Lee and King, 2009) and develop a thermodynamically consistent dynamic subduction model with kinematic boundary conditions. In the model, we use a composite mantle rheology that accounts for both diffusion and dislocation creep for the upper mantle with rheological parameterization for wet olivine (Hirth and Kohlstedt, 2003). For the lower mantle, following Billen and Hirth (2007) and Lee and King (2011), we adjust the rheological parameter values for wet olivine diffusion creep to test the effects of viscosity contrast between the upper and lower mantle on slab evolution. In models with PT-dependent density, lithostatic pressure in the lower mantle at a given depth is higher than a case with a constant density (by ~800 kg/m^3 at the core-mantle boundary). The higher pressure leads to stronger mantle due to the pressure dependence of the mantle viscosity, leading to a different viscosity structure from the case with a constant density. This change in the viscosity structure due to PT-dependent density alone can have a significant effect on the simulation of slab evolution; for example, for a given set of rheological parameters, a model with PT-dependent density predicts buckling of the slab in the lower mantle while a model with constant density shows no buckling. To focus on the effects of thermodynamic properties, we remove this rheological effect of density variation by adjusting the rheological parameters for the lower mantle to maintain a similar viscosity structure for each set of experiments. When no viscosity contrast is imposed between the upper and the lower mantle, the model predicts that the slab sinks vertically into the lower mantle without experiencing much resistance regardless of the effects of thermodynamic properties. When viscosity contrast of~10-100 is imposed, the model with constant thermodynamic properties predicts the buckling of the slab immediately below the transition zone. In contrast, the thermodynamically consistent model with the same viscosity structure predicts that the slab sinks sub-vertically into the lower mantle, and slab buckling tends to occur in the bottom half of the lower mantle. When large viscosity contrast ($>$100) is imposed, however, slab buckling occurs immediately below the transition zone even in a thermodynamically consistent model. These modeling results indicate that in numerical simulations, particularly those with viscosity contrast of $<$~100, noticeably different slab geometry can evolve, depending on the treatment of thermodynamic properties.
Keywords: Dynamic slab model, Thermodynamic properties, Mantle viscosity, Slab geometry, Slab buckling

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SIT04-07 会場:201B 時間:5 月 19 日 16:15-16:30

Sound velocities of CaSiO3 perovskite
Sound velocities of CaSiO3 perovskite

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Calcium silicate perovskite (CPv) is the most significant Ca-bearing mineral of the mantle transition zone and the third most abundant phase of the lower mantle within the pyrolite assumption (ONeill and Jeanloz, 1990; Ringwood, 1976). In addition, it is believed that subducted materials such as Mid-Ocean Ridge Basalts (MORB) may involve substantial amount of CPv. Thus the high-pressure and high-temperature structural and elastic behaviours of CPv have been extensively studied for their importance in understanding the internal structure of the Earth mantle. However, and besides reports by theoretical calculations, high-pressure experimental measurements of sound velocities of CPv are few (Li et al., 2004; Kudo et al., 2012).

Here, we examinated the sound velocities of $CaSiO_3$ perovskite in situ at high-pressure and high-temperature up to 23 GPa and 1700 K using a combination of ultrasonic interferometry and synchrotron X-ray diffraction techniques within a DIA-type multi-anvil press apparatus at BL04B1 in SPring-8. The velocities of P- and S-wave appeared to behave quasi-linearly within the P and T range studied. Linear fitting for the tetragonal structure of CPv at 300 K yielded $V_P(0)$ = 10.171 km/s and $V_S(0)$ = 5.285 km/s. Generally our results agreed with Kudo et al. (2012), with V_S being slower than previous estimates by theoretical and experimental methods. In addition we present new high P and T data for the cubic structure of CPv, which displayed velocities about ˜5% faster than the tetragonal structure at $T > 500$ K.

This new results suggested that V_P and V_S of CPv are high compared to surrounding mantle in the uppermost part of the mantle transition region (MTR). In the lowermost part of the MTR, CPv would have velocities comparable to PREM velocities, which make this phase barely detectable in this region. On the other hand, velocities of CPv would be significantly slower than lower mantle.

キーワード: CaSiO3 perovskite, high-pressure, high-temperature, ultrasonic interferometry, X-ray diffraction
Keywords: CaSiO3 perovskite, high-pressure, high-temperature, ultrasonic interferometry, X-ray diffraction

SIT04-08 会場:201B 時間:5 月 19 日 16:30-16:45

スティショバイトの電気伝導度：Al と水の影響について
Electrical conductivity of stishovite: effects of Al2O3 and water

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Stishovite is one of the major constituent minerals in subducted oceanic crust. At pressures above 25 GPa, the post-garnet assembly transformed from garnetite originated from eclogite contains up to 25 vol.% stishovite. On the other hand, if Archean continental crust mainly consisteing of tonalite-trondhjemite-granodiorite (TTG) was destructed and subucted into the deep mantle, its assembly contains more than 80 vol.% stishovite. In this case, stishovite should be considered as a main controling phase for the electrical conductivity structure of the mantle. Electrical conductivity of stishovite is expected to be very low because migration of Si and O vacancies is quite slow even high temperature. However, electrical conductivity of stishovite may drastically increase because of their fast mobility as a charge carrier when stishovite crystals contain small amounts of Al and H.

In the present study, effects of Al and H components on electrical conductivity of stishovite was investigated to consider as a cause of the high conductivity anomaly observed in the mantle transition zone. The starting materials were prepared from SiO2 powder with various amounts of Al(OH)3. Stishovite aggregates were synthesized at 12 GPa and 1673 K. Chemical composition of the run products was SiO2 with various amounts of Al2O3 (0, 1, 5 wt.%) and water. The electrical conductivity measurements were performed at 12 GPa and various temperature conditions to detect effect of water. Relatively dry conditions were accomplished by annealing at 1900 K, proton conduction can be detected under relatively lower temperature conditions less than 1100 K. The conductivity of stishovite increases with increasing H2O and Al2O3 contents. This trend implies that the charge carrier in stishovite is probably interstitial alkali ion in association with substitutional Al in Si site. At low temperatures, the Al-related defect occupied by proton in Si site could be a main charge carrier. Because activation enthalpy for proton conduction is lower than that for Al3+-M+ pair and its dissociation products, proton conduction could be dominant conduction mechanism below 1100 K.

Electrical conductivity of Al-bearing stishovite (more than 1 wt.% Al2O3) is more than one order of magnitude higher than those of wadsleyite and ringwoodite. The high conductivity values observed in the mantle transition zone can be explained by a presence of aluminous stishovite derived from subduction of Archean continental crust.

キーワード: スティショバイト, 電気伝導度, マントル遷移層
Keywords: stishovite, electrical conductivity, mantle transition zone

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第一原理計算による新しい高圧含水ケイ酸塩相の予測
First principles prediction of a new dense hydrous magnesium silicate

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The global circulation of water in the earth is important to investigate the evolution history and dynamics of the earth, since the physical properties (e.g. atomic diffusivity, melting temperature, electrical conductivity and seismic velocities) of the constituent minerals are considerably changed by the presence of water. It has been reported that water is carried into the deep Earth's interior by hydrous minerals such as the dense hydrous magnesium silicates (DHMSs) in the descending cold plate. However, high pressure behavior of DHMSs, especially the stability of phase D which is the highest pressure phase of DHMSs has not been clarified so far. In this study, I explored the possibility of further phase transition and dissociation of phase D into the hydrous or anhydrous minerals. As a result, the new phase which has lower enthalpy than phase D has been found above about 40 GPa. Therefore, there is a possibility that this new phase in subducting slab takes over water and carries into the deeper part of earth's lower mantle. The detail of the structure and the high pressure-temperature phase boundary determined by quasi-harmonic approximation will be shown and the possible geophysical implications will also be discussed at the presentation.

キーワード: 高圧含水マグネシウムケイ酸塩, 第一原理計算, 含水鉱物, 高圧
Keywords: DHMS, first principles calculation, hydrous mineral, high pressure

SIT04-10 会場:201B 時間:5 月 19 日 17:00-17:15

CO_2 レーザー加熱 DAC 技術を用いた水の融解温度計測
Melting temperature measurements of water using a laser-heated diamond anvil cell technique with CO_2 laser

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Tomoaki Kimura[1*], Yasuhiro Kuwayama[1]

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The phase relations and physical properties of water at high pressures and temperatures are important to physical, geophysical, and planetary problems. For example, recent molecular dynamics calculations suggest that water is superionic at high densities relevant to planets such as Uranus and Neptune, and this predicted property plays a key role in dynamo models to explain the unusual non-dipolar magnetic field structure of these planets. The advances in combining techniques such as synchrotron x-ray diffraction or in situ optical Raman spectroscopy with diamond anvil cell (DAC) technologies allow us to measure the melting temperature of water to within a few percent for pressures up to 35 GPa. However, at pressures above 35 GPa, recently reported values of melting temperature exhibit significant differences with each other. This discrepancy should be caused by a chemical reaction occurred between the metal absorber contained in the DAC and the dissociated water. By using CO_2 laser for sample heating, the metal is not necessary because water has significant absorption in the wavelength range of CO_2 laser (10.6 micron). We report the melting temperature of water in a diamond anvil cell more than 35 GPa using CO_2 laser heating system.

We performed the experiments using a DAC with diamonds having flats of 300 micron diameter. Third distilled H_2O was loaded into a ˜100 micron diameter and ˜50 micron thick sample chamber in a DAC. A rhenium gasket was used to contain the sample. The samples were first compressed to a required pressure at room temperature and then heated by two CO_2 lasers with a both-sided heating technique reducing the axial temperature gradient in the sample. The incident angle of radiation of the CO_2 lasers (Synrad 100 W) is about 20 degree. The laser beams were focused by ZnSe lens onto the sample in a DAC. The heated area, which corresponds to about ˜30 micron, is imaged from both sides of sample on the slit of the entrance of the spectrometer and the two charge coupled device (CCD) detectors, respectively. The temperature was measured by the spectro-radiometric method. The uncertainty in temperature within the 30 micron area was less than approximately 7 % stemming from radial temperature gradients.

Melting was determined by plotting the laser power / sample temperature function and looking for the thermal anomaly associated with melting. We found a temperature plateau arising from the melting of water at each pressure. This temperature was determined as the melting point. Another heating experiment of water including a small amount of Ir powder (<10 micron) was performed for cross-check of the melting temperature determined from the relation between the power and the temperature. The temperature when the powder moves was in good agreement with that of the plateau at each pressure. This fact supports that the temperature of the plateau corresponds to the melting point.

The melting temperatures determined in this experiment are much lower than those of the planetary isentropes of Neptune and Uranus. Therefore, at least, solid water might not exist in the interiors of Uranus and Neptune at 100 GPa.

キーワード: 水, レーザー加熱 DAC 技術, 高圧
Keywords: water, laser-heated DAC technique, high pressure

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SIT04-11 会場:201B 時間:5 月 19 日 17:15-17:30

オントンジャワ海台下の上部マントル減衰構造の推定
Seismic attenuation in the upper mantle beneath the Ontong Java plateau

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We investigate attenuation structure in the upper mantle beneath the Ontong Java plateau (OJP) to identify the origin of this largest LIPs (Large Igneous Provinces) in the globe. Previous studies have shown that S-wave velocities in the upper mantle beneath the OJP are slower than those in the surrounding regions (Richardson et al., 2000). On the other hand, only a few studies have been performed on the attenuation beneath the OJP. Gomer and Okal (2003) showed that ScS-waves traveling beneath the OJP exhibit weaker attenuation than those traveling in the surrounding regions, from which they suggested that the slow velocities in the upper mantle beneath the OJP are not of thermal origin. However, the attenuation of the ScS waves represents average attenuation in the entire mantle beneath the OJP, not in the upper mantle. We need to determine the attenuation in the upper mantle to compare with the slow velocity anomalies in the upper mantle beneath the OJP.

We analyzed teleseismic broadband waveforms of transverse component from deep earthquakes beneath the Solomon Islands subduction zone. Spectral ratios of the sS and S waves were computed to extract information of the attenuation in the upper mantle beneath the OJP. We made correction for crustal structure in and around the OJP, since the sS waveforms are sensitive to the crustal structure at the surface bounce points. Qs values were estimated to be 30-50 for the sS waves of which bounce points are located in the OJP and 40-100 for the sS waves traveling out of the OJP. The Qs values beneath the OJP are well lower than those estimated in other back-arc regions (70-90; Flanagan and Wiens, 1994). The Qs values outside the OJP are close to those in back-arc region. Differential travel time residuals of sS-S are also measured. The differential residuals are well correlated with attenuation pattern: sS waves bouncing at the OJP travel slower by 3 sec than those outside the OJP, which is consistent with the previous studies (e.g., Richardson et al., 2000). These results suggest that the slow velocity anomalies in the upper mantle beneath the OJP are caused mainly by thermal effects.

キーワード: オントンジャワ海台, 地震波減衰
Keywords: Ontong Java plateau, Seismic attenuation

SIT04-12 会場:201B 時間:5 月 19 日 17:30-17:45

二段階進化する地球のマントルの熱史
The thermal history of the Earth's mantle that evolves in two stages

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The thermal history of the mantle calculated from numerical models of a coupled magmatism-mantle convection system is compared with that of the Earth. Both magmatism and mantle convection with tectonic plates are self-consistently reproduced in a two-dimensional rectangular box. The mantle evolves in two stages in these models. On the earlier stage that continues for 1-2 Gyr, heat producing elements (HPEs) and heat flux from the core (HFC) strongly heat the deep mantle, and frequently let hot materials there ascend to the surface as bursts. The mantle-bursts cause vigorous magmatism, stir the mantle efficiently, and make plates move chaotically. As HPEs and HFC decay, however, mantle-bursts stop. On the later stage, subducted basaltic crusts accumulate on the core mantle boundary to form compositionally dense basaltic piles, and plate motion becomes more stable. The average temperature in the entire mantle Tw steadily decreases with time owing to heat extraction by magmatism and mantle convection. The cooling rate is 80-130 K/Gyr on average depending on the internal heating rate. The thermal history of the upper mantle is, however, quite different from this: The average temperature in the upper mantle Tu drops to about 1800 K within the first 100 Myr, and remains almost constant at 1700-1800 K for the subsequent 3 Gyr or even longer regardless of the internal and basal heating rate as well as the initial temperature; Tu gradually decreases to around 1600 K only after that. The thermostat effect of magmatism keeps Tu below 1800 K on the earlier stage no matter how strongly the mantle is heated or how high the initial temperature is. Tu does not decrease on the later stage till 3 Gyr because subducted slabs stagnate on the CMB and do not return back to cool the upper mantle till that time; the steady decrease in Tw during this period is due to the cooling of the lower mantle. The delayed cooling of the upper mantle makes the heat flux at the surface remain almost constant throughout the 4.5 Gyr history of the mantle. At 4.5 Gyr, the Urey ratio is as low as 0.4-0.5 depending on the internal heating rate, and the lower mantle is significantly colder than expected from adiabatic extrapolation from the upper mantle.

キーワード: マントル進化, プレートテクトニクス, 火成活動, 数値シミュレーション, 熱史
Keywords: mantle evolution, plate tectonics, magmatism, numerical simulation, thermal history

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Origin of life: Mechanism of leaking Earth; Fate of cooling Earth
Origin of life: Mechanism of leaking Earth; Fate of cooling Earth

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Supply of nutrients is essential to bear life. To enable a nutrient supply, a landmass must appear above sea level, because continental crust (landmass) is nutrient-enriched. Through weathering, erosion, and transportation of nutrient-enriched rocks, particles are eventually fined to a sufficient size for life to ingest. The emergence of a landmass is caused by a drop in sea level. Here, the cause of sea level change through time is discussed.

Mechanism of change of ocean thickness through time

In the early 2 Ga, after the birth of the ocean, the surface ocean thickness increased through the degassing of a water-rich magma generated from a primordial mantle,. This is a theoretical speculation based on the geologic constraints. From the Archean to the Proterozoic Earth, mantle potential temperature was 200-150K higher than that of today. The subduction-zone geotherm, as documented by P-T conditions of regional metamorphic belts, prohibits water transportation into the mantle through the subduction of hydrated slabs.

Since the Archean, OIBs, such as komatiites and picrites, are enriched in H2O and CO2, as well as MORBs with minor water and CO2, all of which tend to increase the ocean volume through time. On the other hand, the volume of the ocean never reaches sufficient size to bury all of the continents in the Precambrian. Presumably, the maximum thickness of the ocean would have been less than 1km.

Subduction of ocean water and hydrated oceanic slabs began at the onset of the Phanerozoic, as discussed below. About 700-600 Ma ago, the ocean thickness started to decrease, with the reduction of about 600 m until now through the fluctuations in the balance between output versus input of water into the mantle.

Phase diagrams of MORB + H2O and peridotite + H2O indicate that the ocean level would decrease though subduction of hydrated oceanic slabs if the top of the descending slab changes to temperatures lower than 600oC at Moho depth of 30km through time from hot Archean mantle to the present. The subduction zone geotherm along the surface of the descending slab turns to generate blueschist-facies rocks if it crosses the high-temperature corner of the blueschist facies in a P-T space defining the subduction zone geotherm and passing to the point at 10kb, 600oC. A plot of the P-T conditions of the regional metamorphic belts over the world since the Archean shows that the first appearance of blueschist was ca. 700Ma, and the subduction zone rapidly cooled at the onset of Phanerozoic. The temperature of Moho depth was higher than 600oC before 700Ma, but rapidly cooled below 600oC, thereafter, and down to 200oC at present. This suggests that the initiation of return-flow of seawater into the mantle began in the Latest Proterozoic, as estimated by the phase diagrams. The observed drop in sea-level clearly supports the idea, and the proposed sea-level-change curve shows that ca. 600m thick ocean has been removed from the surface into the mantle, at the 410-660km depth transition zone, which has a capability to store about 5 times of the total mass water of surface oceans.

The sea-level fluctuation of plus minus 300m in the Phanerozoic could be explained by the glacial/non-glacial periods, as well as the partial mantle overturn when high-temperature and fertile lower mantle materials catastrophically replaced the upper mantle, such as during the Cretaceous (120-85Ma), a major period of magmatic-driven activity. Another pulse was during the mid-Paleozoic, when huge batholith belts were formed similar to the Cretaceous pulse. If the rate of decreasing ocean volume continues over the next 1.0-1.5 b.y., the Earth will finally dry up, which will mark the end of life.

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強い圧縮性と深度依存物性をもつ流体中の温度成層の安定性: スーパー地球のマントル対流に関する考察
On the stability of thermal stratification of highly compressible fluids with depth-dependent physical properties

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近年の天文学的観測手法の進歩により、太陽系以外の惑星系の存在が数多く知られるようになってくると、そこには地球より大きな地球型惑星がいくつか含まれているらしいことも分かってきた。これらは最大で地球の 10 倍程度の質量を持っており、「スーパー地球」(super Earth) などと呼ばれている。「スーパー地球」の発見により、地球より大きな地球型惑星のマントルダイナミクスが新たな研究テーマの 1 つになってきた。しかしながら過去の研究のほとんど全てにおいて、「スーパー地球のマントル対流」が地球用モデルからの単なる「外挿」として取り扱われており、惑星の大きさの違いに起因するさまざまな効果が十分に反映されているとはいえない。そこで本研究では、スーパー地球のマントル内部に存在する大きな圧力 (〜TPa) 条件下で重要になると期待される、マントル物質の (i) 断熱的圧力変化、および (ii) 熱膨張率と熱伝導率の深さ変化、の 2 つに注目し、これらがスーパー地球のマントル内の鉛直方向の流れに与える基本的な影響を考察した。

モデルとして、静止状態にある圧縮性流体の層を考える。流体中の重力加速度と定圧比熱は一定とするが、熱膨張率と熱伝導率は深さとともに指数関数的に変化 (前者は減少、後者は増加) するものとした。流体層の上面と下面での温度は一定とし、流体層内部の温度分布は鉛直方向の定常 1 次元熱伝導状態によって与えられるものとする。本研究では、この流体中の温度成層構造の安定性を「パーセル法」により検討する。具体的には、ある深さにある流体塊 (パーセル) を鉛直方向に断熱的に (微小) 変位させたときに、流体塊がそのまま動き続ける (静力学的不安定) か、あるいは元の位置に戻ろうとする (静力学的安定) かのどちらかを調べる。特にここでは、流体の熱膨張率・熱伝導率の深度依存性、及び流体の圧縮性の効果の強さをさまざまに変化させたときに、流体層中で静力学的不安定となる深度の範囲がどう変化するかを調べた。

本研究の結果、圧縮性の効果を取り入れた場合には、熱膨張率の深度依存性が大きいほど流体層全体が不安定になりやすいことが分かった。これは深部の熱膨張率が小さいほど断熱温度勾配が小さく、鉛直方向の変位によって熱的な浮力を失いにくいことに起因している。また地球質量 10 倍の「スーパー地球」に相当する条件では、静力学的に不安定となる深さ範囲が、流体層の置かれた条件によって大きく変わることも分かった。例えば流体層全体が静力学的に不安定となるのは、熱膨張率の深さ依存性が十分強く、かつ表面温度が十分低い場合に限られる。特にこれらの条件を満足しない「スーパー地球」のマントルの内部は、静力学的に不安定な「対流圏 (troposphere)」と安定な「成層圏 (stratosphere)」の 2 つの層に分離している可能性が示唆される。なおこれらの結果は圧縮性の効果を無視した場合とは極めて対照的であり、「スーパー地球」のマントル対流の描像や進化の過程を理解する上で、圧縮性の効果が決定的に重要であることを意味している。

さらに極端な例として、表面温度が極めて高い条件で解析を行ったところ、流体層全体が静力学に安定になる場合が検出された。これより、主星に近い軌道を公転するスーパー地球の中には、マントルが全く対流しない惑星が存在する可能性すら考えられる。

キーワード: スーパー地球, マントル対流, 断熱圧縮, 温度成層
Keywords: super-Earths, mantle convection, compressibility, thermal stratification

SIT04-P02 会場:コンベンションホール 時間:5 月 19 日 18:15-19:30

月の潮汐散逸の周波数依存性：最下部マントルの低粘性領域の効果
Frequency-dependence of the tidal dissipation on the Moon: Effect of the low-viscosity zone at the lowermost mantle

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一般に固体天体の潮汐エネルギー散逸は重要な地球物理学的現象の一つである．先ず潮汐散逸は内部構造，特に粘性構造に依存するから，その制約条件と成り得る．更に天体内部の潮汐発熱や粘性分布は熱的状態や軌道状態と関連するから，延いては熱進化や軌道進化に対しても制約を与えられる可能性がある．それは月も例外でない．

月の潮汐散逸の内部構造依存性に関するモデル計算は過去に幾つか行なわれているが，それらは何れも依然として，測地学的観測から得られた実際の潮汐散逸の周波数依存性を説明出来ているとは言い難い．特に長年の月レーザー測距から得られたクオリティファクターは弱い周波数依存性を示している．しかし従来のモデル計算では，観測された周波数依存性を完全に説明していないか，或いはそもそも周波数依存性を無視している．

上述の周波数依存性の問題を解決する事は月の科学の観点で有意義である．少なくとも周波数依存性と調和的な内部構造を見出すという事は，内部構造に対して新たな制約条件を課す事と同義である．それに加えて熱進化や軌道進化といった歴史を復元する為の示唆を与える事さえも出来るかもしれない．

ここで周波数依存性を説明する為に特に着目すべき事はマントルの低粘性層の影響である．既に月震の観測から，月のマントルの底には地震波の減衰の大きな領域が存在する，という事が知られている．この高減衰領域の存在は，マントルの最下部の粘性が上部と比べて低い事を暗示する．もしそうであれば，最下部領域が潮汐散逸に及ぼす影響を考慮すれば周波数依存性を説明可能かもしれないが，先行研究では検討されていなかった．

そこで本研究では，月の潮汐散逸の周波数依存性に及ぼす最下部マントルの低粘性領域の効果を定量的に見積もる為，一箇月周期と一年周期に関する粘弾性潮汐変形のモデル計算を実行した．ここで密度構造と弾性構造に関しては月震に基づく内部構造に従った．一方，粘性構造に関しては低粘性層と共にリソスフェアとアセノスフェアの存在も考慮するが，低粘性層の粘性のみ調整して残りの二層の粘性は均一かつ一定とした．又，この計算における力学的構成関係はマクスウェル物体のレオロジー則に従った．そして計算結果を既存の観測結果と比較する事によって内部構造，特にこの特殊な領域の粘性を決定した．

本計算の結果，低粘性層の影響を加味する事によって潮汐散逸に関する測地学的観測量と矛盾の無い粘性構造を得る事が出来た．より具体的には，一箇月と一年の各周期における月レーザー測距のクオリティファクターを共に満足する粘性率が得られた．その粘性値は極めて低く，そのマクスウェル緩和時間は潮汐周期に近かった．しかもクオリティファクターにより制限された粘性構造に対応する複素潮汐ラブ数の理論値は，過去の月周回衛星の精密軌道決定に基づく観測値とも概ね調和的であった．

この結果は，低粘性層の存在さえ仮定すれば，単純な線形のレオロジーを想定しても月の潮汐散逸の周波数依存性は容易に説明され得る，という事を明示した．或る先行例では，マクスウェルモデルのみならずバーガースモデルのような複雑なレオロジーモデルに従っても，観測された潮汐散逸の周波数依存性は説明不可能と指摘されていた．しかしそれと異なる示唆が低粘性層という単純かつ自然な前提条件によって導かれた．

本結果から得られる結論は，月マントル最下部には低粘性層が確かに存在し，かつそれによって非常に効率的な潮汐エネルギー散逸が励起されている，という事である．本研究が明らかにした最も重要な知見は，地震波の高減衰領域が低粘性領域にも相当する点である．即ち月の場合でも地球と同様に核マントル境界付近に極めて粘性の低い領域が存在すると考えられる．そしてこの超低粘性領域の緩和時間が潮汐周期に近いという事実は，上記の計算の中で定義された内部構造の範囲内において潮汐発熱がほぼ最大であるという事を意味する．又，従来指摘されていたように深部で部分溶融が起こっている可能性がある．若しかしたら多量のメルトを含んでおり，レオロジー的臨界状態にあるかもしれない．

本結論は月の熱進化や軌道進化に対しても更なる示唆を与え得る．中でも潮汐散逸が低粘性層に局在化している事は特筆に値する．換言すれば，低粘性層は核の冷却に対して毛布の如く振る舞うと予想される．従ってこの層は，放射性核種に富むチタン鉄鉱集積層と類似の影響を有する筈である．又，このような低粘性層内の潮汐発熱は，マントルの対流，及び部分溶融状態ならメルトの分離も含む熱輸送と平衡しているのかもしれない．かつ熱的平衡を保つ最適な粘性が自己調節的に選択されていると考えられる．このような熱史は月の軌道進化に支配される．潮汐進化によってポテンシャルの周期や振幅が遷移すれば，それに応じてマントルの粘性や温度も変化する．

キーワード: 月, 潮汐散逸, マントル, 粘性
Keywords: the Moon, tidal dissipation, mantle, viscosity

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高圧下の輝石の熱拡散率・熱伝導率と沈み込むスラブの熱的状態
Thermal diffusivity and thermal conductivity of pyroxenes under pressure and the thermal state of subducting slabs

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Pyroxene is an important constituent next to olivine in the upper part of the Earth's mantle. Therefore, its thermal properties are indispensable for investigation of the thermal state of the mantle. Moreover, alike olivine, pyroxene reveals anisotropy in thermal conduction. Magnesium-iron bearing pyroxene has the most significance, however, measurements of thermal diffusivity or thermal conductivity of single crystal pyroxene mineral, such as enstatite, are hard to perform under pressure because obtaining sufficient size of sample is a hurdle. So using polycrystalline sample is the next best thing. We measured thermal diffusivity and thermal conductivity of jadeite as a pyroxene analogue material. In addition, we conducted measurements on omphacite and diopside. Omphacite, mostly composed of a solid solution of jadeite and diopside, is the main component of eclogite, a major rock in deep subduction zone and lowermost crust of thickened continents.

Jadeite sample was a natural aggregate of which source was Itoigawa, central Japan. Omphacite and diopside samples were prepared from fused glass of reagent mixture to sintered polycrystals. The synthesis and sintering were carried out using the Kawai-type apparatus at ISEI. The sample cell was installed in a magnesia pressure medium of 25 mm edge-length. The cell assembly was compressed by anvils with a trancation length of 15mm. The synthetic conditions were 5 GPa, 1100 ^{o}C and 120 minutes for omphacite and 5 GPa, 1200 ^{o}C and 120 for diopside. The recovered samples were confirmed by X-ray diffraction and EPMA analysis, and were seen to have small porosity by SEM observations.

Thermal diffusivity and thermal conductivity were measured simultaneously using the one-dimensional pulse heating method (Osako et al., 2004). This method requires three identical sample disks. Measurements of jadeite were carried out using an 18 mm edge-length MgO octahedral pressure medium up to 10 GPa by anvils with 11 mm truncated edge. The diameter of the jadeite sample was 4.3 mm and the total thickness was 1.05 mm, whereas omphacite and diopside samples had a diameter of 3 mm and a thickness of 0.75 mm. The measurements of these minerals were performed at pressures up to 15 GPa using a 14 mm edge-length MgO octahedral pressure medium and anvils with 8 mm truncated edge.

It is remarkable that omphacite has considerable low thermal conductivity, that is 55-60 % of those of its end members, diopside and jadeite. This value is close to that of garnet. The low thermal conductivity of omphacite may come from disturbed ordering of cations in the structure. Dobson et al. (2010) showed that thermal diffusivity (and hence thermal conductivity) of eclogite was equal to that of olivine, whereas majorite has low thermal conductivity compared with those of surrounding materials (wadsleyite- or ringwoodite-rich assemblages). He suggested that this contrast in thermal conductivities yields deep earthquake activity in the deeper part of subducting slab. Whereas our measurements on thermal conductivity of omphacite (and garnet) could lead to low thermal conductivity or thermal diffusivity of eclogite compared with that of olivine. This would cause the same condition at the eclogite bearing layer in the subduction zone. Moreover, the considerable low thermal conductivity of serpentine (antigorite) would even have such potential in the shallower part (depths$<$150 km) of the subduction zone.

キーワード: 熱拡散率, 熱伝導率, 輝石, 高圧力, 沈み込み帯
Keywords: thermal diffusivity, thermal conductivity, pyroxene, high-pressure, subduction zon

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H/D interdiffusion in Wadsleyite
H/D interdiffusion in Wadsleyite

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Wadsleyite which is thought to be the dominant mineral in the upper half of the mantle transition zone, can incorporate large amount of H in its structure. Knowledge of relationship between hydrogen diffusion and proton conduction in wadsleyite is essential to accurately estimate the amount of water present in the transition zone. But so far, there is only hydrogen diffusion data obtained from polycrystalline wadsleyite (Hae et al. 2006), whose result showed one log unit higher than the hydrogen diffusion coeffcient expected from conductivity measurement data because of unavoidable grain boundary diffusion and low spatial resolution of FITR.

Shatskiy et al (2006) succeeded to synthesize big hydrous wadsleyite single crystals (>1mm and 3000ppm H2O) by Kawai-type multi-anvil press. Thus, we can currently measure the hydrogen self-diffusion and exclude the grain boundary effect. Recently, hydrogen-deuterium interdiffusion method was demonstrated in olivine to obtain more accurate hydrogen self-diffusion rate (Du Frane et al. 2006). We improved Shatskiy's method to synthetize big single crystal with different hydrogen and deuterium content (maximum 7000ppm) at 16 GPa by multi-anvil to do H/D interdiffusion experiments.

After determination of crystallographic orientation, a pair of hydrous wadsleyite and deurterium wadsleyite crystals was put together into gold capsule and fed a fine gold powder (1 micrometer) to the fill with the space. The polished surface was tightly contact each other. For every orientation, we did three diffusion experiments at different temperatures 1000K, 1200K, 1400K respectively. The preliminary results for D/H diffusion profile were obtained from micro Raman analysis using OD/OH peak ratio. The diffusion coefficient calculated by the Fick's second law indicates that single crystal experiments showed slower diffusion rates than Hae's polycrystalline results and more consistent with the electrical conductivity result. In order to obtain more accurate lattice D/H interdiffusion coefficient in wadsleyite, the diffusion profiles will be measured by SIMS. The SIMS results also will be introduced in this presentation.

キーワード: wadsleyite, mantle transition zone, hydrogen, deurterium, interdiffusion, conductivity
Keywords: wadsleyite, mantle transition zone, hydrogen, deurterium, interdiffusion, conductivity

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パイロープに富むガーネット中の Si 拡散の温度と圧力依存性
Effects of pressure and temperature on the silicon diffusivity of pyrope-rich garnet

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We determine the pressure and temperature dependencies of Si volume diffusion rates in single crystal of Pyp75Alm15Gr10 garnet at 6-25 GPa and 1673-2073 K by the ^{29}Si tracer diffusion method. High-pressure experiments are conducted by using the Kawai-type multi-anvil high-pressure apparatus. The diffusion profiles are obtained by using the secondary ion mass spectrometry in the depth-profiling mode. The Si diffusion coefficient in garnet (D_{gt}) is expressed by the Arrhenius equation: $D_{gt} = D_0 \exp(-(E + PV)/RT)$, with $\log_{10}D_0 = -7.9$ m^{2}s^{-1}, E = 330 kJmol^{-1}, and V = 4.6 cm^{3}mol^{-1}. Si diffusion seems to be the slowest in the major constituent elements and controls rates of plastic deformation under the upper mantle to the mantle transition zone conditions. The comparisons of Si diffusion rates between garnet and wadsleyite/ringwoodite suggest that garnet has almost similar or slightly higher strength (at most 4 times) compared with wadsleyite and ringwoodite at the temperature ranging from 1173 to 1573 K. Thus, the subducted oceanic crust may have plastically similar or slightly higher strength compared with the underlying peridotite layer at the mantle transition zone conditions. This result suggests that the separation of the subducted oceanic crust from the underlying peridotite layer may not occur.
Keywords: garnet, diffusion, rheology, subducted oceanic crust

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Lattice preferred orientation of stishovite in shear deformation
Lattice preferred orientation of stishovite in shear deformation

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Seismic observations reveal strong polarization anisotropy (VSV> VSH) at around 550 km depth in the lower part of mantle transition zone (Visser et al., 2008). The observed anisotropy can be caused by lattice preferred orientation (LPO) of constituting material when the material is elastically anisotropic. Majorite and ringwoodite, which are the dominant minerals in this region, are nearly isotropic (Chai et al., 1997; Weidner et al., 1984). On the other hand, stishovite, which may occur in significant amounts in this region derived from the delaminated subducting basaltic layer (Karato et al., 1997) and continental crust (Kawai et al., 2012), shows strong elastic anisotropy indicated by the acoustic velocities study (Yoneda et al., 2012) on single crystal of stishovite. Therefore, the LPO of stishovite has a high potential to interpret the seismic anisotropy in the lower part of the transition zone.

To investigate the LPO of stishovite, deformation experiments on stishovite were conducted in the simple shear geometry. We prepared starting material of polycrystalline stishovite with grain size of ˜30 micron at 12 GPa and 1723 K in a Kawai-type high-pressure apparatus. Then shear deformation experiments were carried out at 12 GPa and 1873 K by Kawai-type apparatus for triaxial deformation (KATD) with 200 micron thickness of sample. Shear strain was ˜0.8 estimated from the rotation of platinum strain maker after deformation. The microstructure and crystallographic orientation of the deformed samples were investigated by SEM with EBSD.

Recovered sample shows the recrystallization occurred during deformation, meaning that the dominant deformation mechanism is dislocation creep. Based on preliminary analysis of LPO, the dominant slip system of stishovite is considered to be [001](100). With the assumption of transverse isotropy of polycrystalline stishovite, our result is consistent with seismic observation (VSV>VSH).

キーワード: stishovite, shear deformation, LPO
Keywords: stishovite, shear deformation, LPO

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大型氷天体内部における氷 VII 相の塑性流動
Plastic deformation of ice VII in sub-Neptune-size icy planets

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It is indispensable to construct flow laws of high-pressure ices to understand the convecting interiors of large icy moons and planets. Ice VII is stable over large pressure ranges and possibly major constituent of the icy mantle of the recently found Sub-Neptune-size icy planet (Beaulieu et al., Nature2006). Rheology of high-pressure ices has been studied by using a gas-medium deformation apparatus up to several hundreds MPa. To expand the pressure range in the interior of the large icy objects, we newly conducted a synchrotron radiation study on high-pressure ice rheology.

Plastic deformation experiments of ice VII were carried out by using a deformation-DIA (D-DIA) apparatus installed at NE7A of Photon Factory, Japan (Shiraishi et al., HPR2011). We used monochromatic X-ray (50 keV, collimated to 100-500 microns) and obtained two-dimensional X-ray diffraction (2D-XRD) patterns every 3-5 minutes using imaging plate (IP). The number of diffraction spots on IP that fulfill the Bragg condition is proportional to the grain density. We expect to observe changes of the grain size from the evolution of numbers of diffraction spots as a function of time (Kubo et al., JPCS2010). Differential stress of the sample in uniaxial compression can be measured from distortions of Debye ring on IP. X-ray radiography image is used to determine the sample strain during plastic deformation.

We first compressed water enclosed in teflon capsule using D-DIA at 300K, and synthesized relatively coarse-grained ice VII showing spotty diffraction patterns. Then, the polycrystalline ice VII was uniaxially deformed at 3-10 GPa, 300-650K, and constant strain rates of around 10-5-10-6/s. The total strain reached up to 30%. We observed that the flow stress increases from 40 MPa to about 300 MPa with the pressure from 4 GPa to 10 GPa, at the strain rate of 5x10-5/s and 300K. The flow stress of ice VII is almost comparable to that of ice VI previously reported in the gas apparatus (Durham et al., JGR1996) at around 4GPa, but the pressure dependence is smaller in ice VII. The number of diffraction spots increased with plastic strain, which may indicate dynamic recrystallization of ice VII in the dislocation creep regime. Based on the relationship between the number of spots and the grain sizes in standard samples, we estimated the grain size decreased from 30-40 micron to 10-20 micron during the plastic deformation. Although some further improvements are needed to conduct the quantitative grain-size measurement, we expect that these experimental methods based on synchrotron radiation are useful to explore both GSI and GSS creep of high-pressure ices.

The stress and the temperature dependence of the strain rate will be analysed to construct the flow law of ice VII. It has been known that the diffusion mechanism in water ice changes at high pressures from molecular to ionic migration (e.g., Katoh et al., Science2002). It has also been suggested that a plastic ice phase may appear when heating ice VII above several GPa (e.g., Takii et al., JCP2008). These changes may affect the ice VII rheology in sub-Neptune-size icy planets. Our present deformation experiments cover these conditions and quantitative analysis of the obtained creep data is indispensable to know the effects on the plastic deformation of ice VII.

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マグマ等の高粘性における流体ー粒子混相流シミュレーションコードの開発
Development of fluid-particle coupled simulation method in the Stokes flow regime: toward 3-D geodynamic magma simulatio

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A fluid-particle two-phase flow has been widely studied in geodynamics, because particle-saturated fluid layer is important for understanding the dynamics of solidifying and melting process in the magma chamber or magma ocean. In order to deal with such particle-fluid systems as the geodynamical modeling in 3-D geometry, we develop a new coupled simulation code of Finite Difference method (FDM) for fluid flow and Discrete Element method (DEM) for solid particles. Although this type of numerical method has been well developed in the engineering field to investigate the fluidized bed especially for the high Reynolds number in short time scales, the method for the low Reynolds number over long time scales has not yet been fully addressed.

In the geodynamic modeling with highly viscous fluid, the fluid motion can be treated as the Stokes flow. We employ empirically derived a coupling term between fluid flow and particle motion providing good fit with experimental data of the creeping flow. When this coupling force is directly introduced to the normal DEM equation of particles, we have to numerically solve dumped oscillation with a small time step dt ˜1/eta for high fluid viscosity eta. Thus the normal DEM does not seem to be suitable solution method for our target problems. We therefore propose to drop off the inertial term from the governing equation of DEM based on the Stokes flow approximation and solve the force balance equation as same as that for the fluid. With this approach, we can employ the large dt˜eta for the problems with highly viscos fluid.

Since our original solution algorithms for both of FDM and DEM are designed for the massively vector parallel architectures with two characteristic numerical techniques, we can solve large size of problems in 3-D geometry. 1. The geometric multi grid method of our robust Stokes flow solver is implemented with agglomeration technique to enhance the parallel efficiency in coarse grid operations. 2. Our DEM utilizes the parallel algorithms for a summation of contact force and search of particle pairs using particle labels sorted by the cell number to improve computational efficiency of the code.

We introduce details of our coupled model treatment of the granular medium and demonstrate the validation test with an analogue experiment.

キーワード: マグマ対流, DEM, Stokes 流れ, 混相流シミュレーション
Keywords: magma flow, DEM, Stokes flow, particle-fluid coupled simulation

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Expanding-Contracting Earth
Expanding-Contracting Earth

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Since the birth of the Earth by giant impact at 4.56 Ga, the Earth has been regarded to be cooled, hence shrunk over geologic time. However, if the Earth was double-layered in convection, the story must have been different with a peak of expanding during a uni-directional cooling. Using the thermal evolution model of Breuyer and Spohn (1995), we calculated expanding-contracting effect, using the First Principle Calculation. The result shows ca.60km in radius larger Earth right after the consolidation of magma-ocean on the surface shrunk 50km in radius within ca. 10 m.y., and gradually expanded 11km in radius due to radiogenic heating in the lower mantle in spite of cooling in upper mantle in the Archean. This was due to double-layered convection in the Archean with final collapse of overturn, presumably by the end of Archean. Since then, the Earth has been gradually cooled down to reduce its radius 12km up to now.

Geologic evidences support the late Archean mantle overturn ca. 2.6Ga, e.g., the global distribution of super-liquidus flood basalts on nearly all cratonic fragments >35 examples. If this is correct, the surface environment of the Earth must have suffered from extensive volcanism and emergence of local landmasses, because of thin ocean cover 3-5km thickness. Global unconformity appeared for each cratonic fragment with stromatolite back to 2.9Ga with a peak at 2.6Ga. The global magmatism brought extensive crustal melting to yield explosive felsic volcanism to transport volcanic ash into stratosphere during the catastrophic mantle overturn. This event seems to be recorded by sulfur mass-independent fractionation (SMIF) at 2.6Ga. During the mantle overturn, numbers of mantle plume penetrated into upper mantle and caused local doming ca. 2-3km upward to lead local landmasses above sea-level. This led the rapid increase of atmospheric oxygen enabling life from Prokyaryotes to Eukyarhyotes by 2.1Ga or much earlier.