

高压下の純粹剪断変形場におけるアンチゴライトの脱水反応と AE 挙動 Flow behaviors and AE activities during syndeformational antigorite dehydration at high pressures

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Intermediate-depth earthquakes are seismic activities in Wadati-Benioff zone at depths from 60 km to 300 km, where subducting plates deform plastically rather than brittle failure. To understand the shear instability mechanisms above ~2 GPa, there have been some acoustic emission (AE) measurements with multi-anvil apparatus (e.g., Jung et al., 2009; Gasc et al., 2011). However in previous studies, the relationships among dehydration, plastic flow and shear instability were unclear because quantitative flow data, reaction kinetics, and AE activities could not be obtained simultaneously. To conduct quantitative and simultaneous measurements of these processes, we have carried out syndeformational antigorite dehydration experiments at high pressure.

High-pressure deformation experiments were conducted at 1-8 GPa, 300-1050 K, and strain rates of $3.4-7.4 \times 10^{-5}$ s⁻¹ in pure shear using a 1500-ton uniaxial press (SPEED Mk. II) with a D-DIA type guide block installed at BL-04B1, SPring-8. 50 keV monochromatic X-ray were used to measure reaction kinetics and stress-strain data. To monitor shear instabilities by detecting AEs, six piezoelectric devices were positioned between first and second stage anvils of MA 6-6 type system. AE waveforms were recorded in trigger mode using six-channel 8-bit digital oscilloscopes at a sampling rate of 50 MHz, and were analyzed to determine 3D AE source location and AE magnitude. We used three kinds of starting materials (1.7 mm in diameter and 2.7 mm in length) of polycrystalline antigorite (Atg), fine-grained forsterite (Fo) polycrystal, and two-phase mixtures of Atg and San Carlos olivine (10%, 30%, and 50% Atg). The starting sample was first compressed at room temperature, then heated at constant load, and finally deformed with constant strain-rate mode. In some experiments, dehydration occurred during heating or deformation. Microstructures of recovered samples were preliminarily observed by optical microscopy.

Many AE events of relatively large amplitude were observed from Fo sample during cold compression stage at lower than 2 GPa. In contrast, almost no AEs were observed from Atg and 10-50% Atg samples during cold compression and heating stages. Optical microscopic observations of recovered Atg samples from each stage revealed that some faults are generated during cold compression stage, and fault slipping occurred during the heating stage. Creep behaviors of Atg samples during the deformation stage indicate that flow stress reached steady state at the sample strain of more than 10%, and no stress drops were observed until the final strain of 30-40%. These flow behaviors and flow strengths are almost similar to the previous study (Hilaret et al., 2007). Few AEs were recorded and additional faults were not observed from recovered sample during the deformation stage. We observed dehydration of Atg and 10-50% Atg samples when increasing temperature from 673K to 1000K during deformation, however we did not observe AEs during the syndeformational dehydration stage. Faults were absent in fully dehydrated samples. Although more detailed microstructural observations are needed, these results suggest that syndeformational dehydration do not enhance shear instability of antigorite in pure shear at high pressure.

多結晶体の非弾性の実験的研究と上部マントル地震波構造への応用 Experimental study on polycrystal anelasticity with implications for upper mantle seismic structure

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Rock anelasticity causes dispersion and attenuation of seismic waves. Therefore, for the quantitative interpretation of seismic low velocity and/or low Q regions in the upper mantle, understanding of rock anelasticity is necessary. Recent experimental studies have shown that anelasticity of polycrystalline materials is subject to the Maxwell frequency f_M scaling: $Q^{-1}(f/f_M)$. However, the applicability of this scaling to the seismic waves has not been guaranteed because experimental frequencies normalized to f_M of the laboratory samples are usually much lower than the seismic frequencies normalized to f_M in the upper mantle ($10^6 \leq f/f_M \leq 10^9$). In this study, by using polycrystalline organic borneol as an analogue to mantle rock, we measured anelasticity up to $f/f_M \cong 10^8$ and found that the Maxwell frequency scaling is not fully applicable at $f/f_M > 10^4$. A closer examination of our data showed that each of the relaxation spectra obtained under various temperature, grain size, and chemical composition can be represented by the superposition of a background dissipation which is subject to the Maxwell frequency scaling and a peak dissipation which is always centered at $f/f_M = 10^3$. Significant increases of the peak amplitude and width with increasing temperature, grain size, and impurity (diphenylamine) content result in failure of the Maxwell frequency scaling at $f/f_M > 10^4$, where the peak dissipation dominates over the background dissipation. To quantitatively estimate the dispersion and attenuation of seismic waves, it is important to understand the behavior of the peak dissipation.

The addition of impurity (diphenylamine) to borneol significantly reduces the melting (solidus) temperature from $T_{melt} = 477$ K to $T_{melt} = 316$ K. Therefore, we have speculated that the observed variation of the peak dissipation with impurity and temperature can be scaled by the normalized temperature T/T_{melt} , such that the peak amplitude and width increase with increasing T/T_{melt} . The significant broadening of the peak observed near (but below) the solidus temperature ($T/T_{melt} = 0.93$) means that seismic velocity and Q are considerably lowered even without melt and has important implications for upper mantle seismic structure. We further investigated the detailed behavior of the peak dissipation at near solidus temperatures ($0.88 \leq T/T_{melt} \leq 1.01$), and found that the peak amplitude saturates at about $T/T_{melt} = 0.95$, but that the peak width continuously increases up to the supersolidus temperature $T/T_{melt} = 1.01$. The obtained result was formulated in terms of the two nondimensional parameters f/f_M and T/T_{melt} and preliminarily applied to the seismic waves in the upper mantle. The result shows that low V and low Q occur at near solidus temperatures even without melt. At the onset of melting, seismic wave velocity shows a discrete reduction due to the proelastic effect of melt, but the seismic attenuation does not show a discontinuous change.

キーワード: 非弾性, 地震波減衰, 上部マントル

Keywords: anelasticity, seismic attenuation, upper mantle

Rheological transition during large strain deformation of melting and crystallizing metapelites

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Torsion experiments (strain-rate = $3 \times 10^{-4} \text{s}^{-1}$) were performed to investigate the large strain ($\gamma = 15$) rheology on quartz-muscovite aggregate as analogue to pelitic rocks undergoing melting and crystallization during deformation at 300 MPa confining pressure and 750 °C temperature. Microstructures reveal four distinct but gradational stages of crystal-melt interactions during deformation ; (a) solid state deformation, (b) initiation and domination of partial melting, (c) simultaneous partial melting and crystallization, and (d) domination of crystallization. The microstructural stages are linked to the rheology of the deforming samples. Partial melting starts at relatively low finite shear strains ($\gamma=1$ to 3) showing approximately 60% strain softening. At $\gamma=4$ to 10 the partially molten bulk material shows a steady state flow at low stress. Further crystallization of new crystals at the expense of melt between $\gamma = 10$ and 15 causes weak strain hardening until the material fails by developing brittle fractures. The stress exponent (n), calculated at $\gamma = 1, 5$, and 10, increases from ~ 3 to ~ 43 , indicating a transition from power to power law breakdown or exponential flow of the bulk system. Hydrostatic experiments for equivalent times and conditions of the torsion experiments were also conducted to evaluate the reaction kinetics and microstructures under static conditions. The new experimental data establish that partially molten rock does not flow according to a constant strain rate-dependent power law (steady state) rheology. The rheological transition from strain rate sensitive to strain rate insensitive flow is interpreted as a function of melt-crystal ratio, their mutual interactions, and the evolution of microstructures in the partially molten rock. EBSD measurements reveal weak crystal preferred orientations, which are different for each mineral.

キーワード: Rheology, Deformation, Melting, Crystallization, Crystal preferred orientation, Localization

Keywords: Rheology, Deformation, Melting, Crystallization, Crystal preferred orientation, Localization

海洋プレート最上部マントル構造はマントルダイヤピルで形成される The uppermost mantle structure in the oceanic plate induced by mantle diapir

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This study presents results of microstructural analyses and crystallographic preferred orientations (CPOs) in order to clarify characteristics of harzburgite in the Samail and Hilti mantle sections. The Samail peridotites of seven samples were collected in the Maqsad area across the mantle diapir. The Hilti peridotites of thirteen samples were collected in the zone of the high-T deformation near the paleo-Moho in the mantle section. Thus, we studied twenty samples in Oman ophiolite. Olivine CPOs in the Samail samples are characterized by slightly strong point maximum of [010] and weak girdle distributions of [100] and [001]. Olivine CPOs in the Hilti samples are characterized by two types of the distributions: one type shows slightly strong point maximum of [010] and weak girdle distributions of [100] and [001], and the other type is slightly strong point maximum of [010] and weak point distributions of [100] and [001]. The olivine fabrics have been used to be represented by fabric intensities of each axis such as pfJ so far. However, pfJ does not necessarily reflect olivine fabrics of their whole axes and it strongly depends on a stereographic distribution. Moreover, AG-type has various patterns of distributions in both a-axis and c-axis, so that it is difficult to classify AG-type by any previous methods. In this study, we prefer to classify olivine CPO patterns using Vp-Flinn diagram. It shows that both Samail and Hilti samples are almost identical each other and in the VP-Flinn diagram that olivine fabrics could be classified into three types: 1) A-type like fabric, 2) AG-type like fabric and 3) low Vp anisotropy AG-type like fabric. Grain boundaries have different characteristics between them; the Samail samples showed regular grain boundaries, whereas the Hilti samples showed irregular grain boundaries. It is likely that the temperature in the Oman ophiolite would have been the highest in the mantle diapir beneath the ridge axis and therefore its solidus line could be deeper as moving away from the ridge axis. Therefore, the difference of grain boundary geometries may result from a temperature change in the vicinity of the mantle diapir from vertical flow to subhorizontal flow. The olivine grain sizes are almost constant regardless of their CPO patterns and are in the same range between 0.6 and 2.1 mm in both the Samail and the Hilti samples. It shows that the Hilti samples may have experienced only a small horizontal strain that is not enough to change olivine CPOs except a weak grain size reduction due to dynamic recrystallization. As a consequence, the olivine CPOs could have been formed in the mantle diapir and preserved even in the horizontal structure away from the mantle diapir. The olivine fabric could have been formed by melt effects like MORB in the mantle diapir or diffusion creep.

Keywords: olivine fabrics, lithosphere, uppermost mantle, mantle diapir

島弧の沈み込み量の推定

Supply rate of continental materials by subduction of island arcs

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Evolution of life on the Earth is strongly related to the oceans and the continents, both of which are unique to the Earth. Continental materials contain a large amount of incompatible and radiogenic elements, which may affect terrestrial thermal history and chemical evolution, as well as the Earth's surface environment. Geological studies have revealed that continental materials subduct from the Earth's surface via the following three mechanisms: tectonic erosion, sediment subduction, and direct subduction of immature oceanic arcs, which are found, for example, in the western Pacific. In the first two processes, the continental materials are conveyed through subduction channels of thickness of 2-3km just above the subducting slabs. Here, in order to estimate the supply rate of continental materials of oceanic arcs to the deep mantle, we have conducted numerical simulations of subduction of arcs based on the finite element method, using relevant rheology models. The results show that the subduction rate highly depends on temperature profiles of the subducting slabs and the size of the arcs.

キーワード: 大陸地殻, 島弧, マントル, 沈み込み, レオロジー

Keywords: continental crust, island arc, mantle, subduction, rheology

Anisotropic viscosity of olivine aggregates: A laboratory, field, and numerical approach

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Shearing of mantle rocks within Earth's lithosphere and asthenosphere causes mantle minerals, particularly olivine, to develop crystallographic textures that can be detected seismically. In laboratory studies, such crystallographic textures have also been associated with dependence of the viscosity of a mineral on the orientation of an applied stress. This anisotropic viscosity may affect tectonic plate motions and the stability of the lithospheric base, but it is highly dependent on 1) the rate of fabric development and 2) the poorly constrained viscosity tensor, which relates the stress applied to an olivine crystal of known orientation to the resulting strain-rate.

Here we constrain the importance of viscous anisotropy in the upper mantle using deformation experiments conducted in a gas-medium apparatus. Olivine aggregates were deformed at a temperature of 1200 °C and a confining pressure of 300 MPa. One set of samples was initially deformed in torsion and subsequently deformed in tension. A second set of samples was initially deformed in tension and subsequently deformed in torsion. Torsion experiments reached a maximum shear strain of ~20. This combination of strain paths allowed us to quantify the effect of evolving crystallographic texture on multiple components of the viscosity tensor.

We developed a micromechanical model that allows estimation of the complete viscosity tensor based on a measured texture and a single-crystal viscosity tensor. We then used the laboratory-derived mechanical data in conjunction with this model to invert for the values of the single-crystal viscosity tensor. We developed a second, independent model of olivine textural development that takes into account the strength of individual slip systems yet is stable to high strains. We calibrate this texture model through comparison to the strengths and shapes of measured textures in experimental samples. Together, these two calibrated models allow us to constrain both the rate of texture development in an arbitrary deformation geometry and also the resulting macroscopic viscosity tensor. Our results indicate that olivine textural development can yield viscosities that vary by over an order of magnitude depending on the orientation of the applied stress relative to the dominant crystallographic texture.

We tested our mechanical and textural evolution model through comparison to natural peridotite shear zones exposed in the Josephine Peridotite. We find that (1) the natural textural development is well approximated by our numerical model and (2) a significant portion of the strain localization can be attributed to the development of viscous anisotropy.

キーワード: rheology, olivine, crystallographic preferred orientation, viscosity, rock deformation, shear zones
Keywords: rheology, olivine, crystallographic preferred orientation, viscosity, rock deformation, shear zones

含水かんらん石多結晶体の変形と組織発達
Evolution of the rheological and microstructural properties of olivine aggregates during dislocation creep under hydrous

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Since hydrogen plays an important role in dynamic processes in the mantle, we conducted high-strain torsion experiments on Fe-bearing olivine aggregates under hydrous conditions. Most of the samples deformed homogeneously to total shear strains of up to $\gamma \approx 5$. We deformed samples to high enough strain that a steady-state microstructure was achieved, in order to investigate the evolution of the rheological and microstructural properties. The stress exponent of $n \approx 3$ and the grain size exponent of $p \approx 0$ determined from the fitting of strain rate, stress, and grain size data indicates that these samples deformed by dislocation creep. Fourier transform infrared (FTIR) measurements of an imbedded olivine single crystal demonstrated that our samples were saturated with hydrogen during the deformation experiments. The crystallographic preferred orientation (CPO) of the olivine aggregates changed as a function of strain due to competition among the three slip systems (010)[100], (100)[001], and (001)[100]. The observed strain weakening that occurs early in each experiment is to geometrical softening associated with development of a CPO, which reduces the stress by 36% in constant strain rate experiments. The evolution of the rheological and microstructural properties observed in our experiments is important for understanding dynamic evolution of Earth's mantle under hydrous conditions.

Keywords: olivine, deformation, high-strain torsion experiment, hydrous conditions, mantle

オリビン多結晶体の合成と高温クリープ実験 Synthesis and deformation experiments on polycrystalline olivine

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マントル対流やアセノスフェアの成因を理解する上で、上部マントルの流動特性を決定することは非常に重要である。これまで、天然で産出したオリビンから作製されたオリビン多結晶体を用いて高温変形実験により、オリビン多結晶体の流動特性に対する温度、粒径、応力依存性や水やメルトによる効果が調べられ、上部マントルの理解が進んできた (Karato et al 1986, Hirth and Kohlstedt 1995, Hirth and Kohlstedt 2003)。しかしながら、Faul and Jackson (2007) が、試薬からゾル・ゲル法で人工的に合成したオリビン多結晶体が天然由来のオリビンよりも粘性率にして1~2桁固いことを報告し、オリビン多結晶体の流動則が確立されていないことが明らかになった。そこで、本研究では第三の手法を用いてオリビン多結晶体の合成を行い、変形実験によってその流動特性を調べた。また、先行研究の固さの違いの原因と推測される、微量な不純物を含んだオリビン多結晶体の合成と変形実験を行い、添加物が流動特性に与える影響を調べた。

試料作製には、高純度かつ細粒 (<100 nm) の試薬を用いて細粒な鉱物粉末を合成し、それを真空中で焼結するという手法を用いた (Koizumi et al 2010)。その中で、鉄源としての原料粉の種類最適化と、酸素分圧制御手法の開発をおこなった。添加物を含まない試料と、0.1wt%の Al₂O₃、CaO、NiO、TiO₂ をそれぞれ含む試料を作製した。それぞれについて変形実験を行ったところ、拡散クリープ条件下では添加物による大きな流動特性の変化は見られなかった。また、本研究の試料の固さは Faul and Jackson (2007) の人工的に合成されたオリビン多結晶体の固さと一致した。したがって、本研究で添加した不純物以外にオリビン多結晶体の流動特性を大きく変化させる化学種が存在することが示唆される。

キーワード: オリビン多結晶体の合成, 高温変形実験

Keywords: Synthesis of polycrystalline olivine, High-temperature deformation experiments

In situ deformation of eclogite at high pressure and temperature In situ deformation of eclogite at high pressure and temperature

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Little is known about the physical behaviour of heterogeneous, rheological contrasting rocks in the Earth's mantle and their impact on mantle processes. Understanding of the stress/strain partitioning, microstructural evolution, and seismic signatures in bimineralic eclogites provide crucial information for transport modeling of these dense materials into and out of the deep Earth. For example, heterogeneity in the peridotite-dominated mantle may develop via a variety of processes such as entrainment and mixing of discrete eclogite bodies from subducted slabs or from detachment of deep continental roots into the convecting mantle. Exhumed eclogitic bodies are characterized by intense foliation and strain localization and strong shape- and crystallographic preferred orientations. In this preliminary study we used synchrotron X-ray diffraction at the ID06 beamline at ESRF to estimate the stresses *in situ* on a deforming bimineralic eclogite (~40% garnet and ~60% clinopyroxene) and a dunite (100% olivine) at 5 GPa and a range of temperatures (1473 - 1673 K), i.e. at subsolidus conditions. The starting material was prepared as a residual eclogite after extraction of ~46 wt% melt from GA2 eclogite (Spandler *et al.*, 2008, *J Petrology* 49, 771-795) and was pre-sintered at 5 GPa and 1673 K using a multi anvil apparatus. The run products yield well-equilibrated sub-/euhedral crystals of garnet and tabular crystals of clinopyroxene with average grain sizes of <30 μm . Coesite was present only as multiple small, rounded inclusions in garnet. The compressive deformation experiments were carried out at constant strain rates of 10^{-6} to 10^{-5} s^{-1} to axial strains of 5 to 30% on a stack comprising the pre-sintered bimineralic eclogite sample above a pure San Carlos olivine sample (as a reference). The cylindrical samples have dimensions of 1.2 mm in diameter by 1.5 mm in length and are separated by metal foils (e.g. Re) acting as strain markers visible in radiographic images. The deviatoric stresses are transmitted via hard alumina pistons above and below the sample stack. Furthermore, the samples are surrounded by a boron nitride sleeve and graphite resistance heater and the cubic pressure medium is made of boron epoxy, which is transparent to synchrotron X-rays. We expect results on the strength partitioning between garnet and pyroxene in a residual bimineralic eclogite and between the eclogite and the dunite deformed under conditions applicable to the upper mantle. Complementary information on crystallographic preferred orientation development of garnet and clinopyroxene in eclogite, and of olivine in dunite will give insight into the deformation mechanisms and interpretation of fast seismic wave propagation directions and anisotropy relative to the prevalent stress direction. The data will be compared against natural field and seismic observations and offer insight into deep crustal seismic reflectors seen in regions of intense deformation.

キーワード: two-phase deformation, eclogite rheology, in situ X-ray diffraction, mantle heterogeneity

Keywords: two-phase deformation, eclogite rheology, in situ X-ray diffraction, mantle heterogeneity

上部マントルの流動を支配する粒界すべり

Grain boundary sliding as the major deformation mechanism of olivine in Earth's upper mantle

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Anisotropic propagation of seismic waves have been observed in the Earth's upper mantle, which is attributed to the crystallographic preferred orientation of olivine associated with mantle dynamics. The most likely deformation mechanism of olivine that explains the observed seismic anisotropy has been considered to be dislocation creep (e.g., Karato et al, 1986). Diffusion creep may also partly contribute to the deformation of olivine in the upper mantle, while another possible mechanism, grain boundary sliding, has been thought to play only minor roles in some limited circumstances such as in melt-bearing rocks or fine-grained rocks (Hirth and Kohlstedt, 1995; Hiraga et al., 2010). Hansen et al. (2011) proposed that the dislocation-accommodated grain boundary sliding (DisGBS) may dominate the upper mantle flow, based on deformation experiments for olivine at a pressure of 0.3 GPa and temperatures to 1523 K. Development of crystallographic preferred orientation (CPO) of olivine through DisGBS-controlled creep is so significant (Hansen et al., 2012) that this would be a potentially important deformation mechanism controlling the upper mantle flow. Nevertheless, most of experimental investigations on the deformation mechanism of olivine have been limited to the pressures below 0.5 GPa, which are lower than those in the actual upper mantle.

We conducted uniaxial deformation experiments on olivine aggregates with a composition of $Mg_{1.8}Fe_{0.2}SiO_4$ at pressures 1.5-6.7 GPa and at temperatures 1273-1473 K with strain rates of $0.3-7.2 \times 10^{-5} \text{ s}^{-1}$ using a deformation-DIA apparatus. The averaged values of stress exponent, activation energy, and activation volume were obtained to be 3.0, 423 kJ/mol, and $17.7 \text{ cm}^3/\text{mol}$, respectively. The obtained parameters supports the deformation of water-poor olivine controlled by DisGBS. A significant water-fugacity dependency of creep strength of olivine on water fugacity was observed, and the water fugacity exponent was obtained to be 1.25. The dependency of creep strength of olivine controlled by DisGBS on pressure is weak due to competing the pressure-hardening effect of activation volume and the pressure-softening effect of water fugacity. Because creep strength of olivine controlled by the grain boundary sliding is insensitive to pressure, the estimated viscosity of water-poor olivine is independent of depth and is in a range of $10^{20}-10^{21.5} \text{ Pa s}$ throughout the upper mantle, which is consistent with geophysically observed viscosity profiles. Viscosity of the deep upper mantle would be overestimated by $\sim 10-10^4$ times if we assume the conventional dislocation creep mechanism for water-poor olivine.

Keywords: grain boundary sliding, olivine, upper mantle, pressure, water, viscosity

拡散クリープにおける1粒子スケールから複数粒子スケールでの変形
Observations of grain- to multi-grain-scale deformation of mineral aggregates deformed
by diffusion creep

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We deformed cylindrical polycrystalline samples of synthesized forsterite + diopside and anorthite mineral aggregates at its diffusion creep regime. We polished the lateral side of the sample where we imposed grooves parallel to the compression axis of the sample using a focused ion beam. These marker lines allow us to observe fine-scale deformation of the sample. After the high temperature one atmosphere compression creep experiment, we observed the sample surface with marker lines under scanning electron microscope.

Strains of bulk sample and of the marker line exhibited the similar values indicating that the similar deformation proceeded both at bulk and surface regions of the samples. Grain rotation, which was identified by misfits of the markers at grain boundaries and rotation of intra-granular markers, were frequently observed in all the samples. No distortion of the markers within the grains was found indicating the absence of intragranular deformation process such as a glide of dislocations; however, in the samples deformed at high stress (~300 MPa), curved intra-granular markers were observed, which is consistent with dislocation activity at high stress condition. The changes in grain configuration were also observed elsewhere in the samples demonstrating significant operation of grain boundary sliding which produced grain switching. Grain rotations were controlled by the orientation of long flat crystallography-controlled grain boundaries with respect to the compressional direction. Such grain rotation resulted in a significant development of crystallographic preferred orientation in the samples.

キーワード: 拡散クリープ, 鉱物

Keywords: diffusion creep, mineral

高圧下でのフォルステライト反応帯の組織と成長カインेटィクス Microstructure and growth-kinetics of forsterite reaction rim under high pressure

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Since many transport properties, such as rheology, highly depend on grain-size of the constituent materials, knowledge of grain-growth is important for accurate understanding of dynamics in the Earth's mantle. Tasaka and Hiraga (2013) showed that grain-growth in forsterite-enstatite two-phase system is rate-limited by growth of secondary phase through Mg-O grain-boundary diffusion in primary phase. In this study, we have experimentally studied growth-kinetics of forsterite (Mg_2SiO_4) reaction rim at deep upper mantle conditions which is controlled by Mg-O grain-boundary diffusion in forsterite. Based on the experimental results, depth dependence of grain-growth in the upper mantle is discussed.

Experiments were carried out using multi-anvil apparatus installed at GRC, Ehime University, Japan. The starting materials, MgO (single crystal) and $MgSiO_3$ (powder or aggregate), were packed in Pt capsule. The annealing experiments were conducted at pressure of 3.0-11.1 GPa and temperature of 1473-1873 K for duration of 0-780 min. Recovered samples were analyzed by SEM or FE-SEM for microstructural observation and by FT-IR to examine water content.

Water content in MgO single crystal in the recovered samples was relatively low and 6.9 wt ppm H_2O at the maximum. The Pt marker, which was originally placed at MgO- $MgSiO_3$ boundary, was always on MgO- Mg_2SiO_4 boundary indicating that Mg-O diffusion in Mg_2SiO_4 is the rate-limiting process in the rim growth. $MgSiO_3$ inclusions were found in Mg_2SiO_4 grains suggesting the grain-boundary diffusion is rate-limiting. Based on the analysis using equation for reaction-rim growth rate-limited by grain-boundary diffusion (Gardes and Heinrich, 2011), the activation energy and the activation volume were determined to be 375 kJ/mol and $-2.1 \text{ cm}^3/\text{mol}$, respectively. Although reason for the small negative value of the activation volume is not quite clear, this may be due to successive structural change of grain-boundary. The results suggest that the grain-growth in the Earth's upper mantle is faster at deeper part.

キーワード: 上部マントル, 原子拡散, カンラン石, フォルステライト, 粒成長, レオロジー

Keywords: Upper mantle, Element diffusion, Olivine, Forsterite, Grain-growth, Rheology

In situ creep strength measurement on ringwoodite up to 1700 K at 17-18 GPa using a deformation-DIA apparatus

In situ creep strength measurement on ringwoodite up to 1700 K at 17-18 GPa using a deformation-DIA apparatus

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Deformation experiments on polycrystalline $(\text{Mg}_{0.9}\text{Fe}_{0.1})_2\text{SiO}_4$ ringwoodite have been conducted in uniaxial geometry up to strains of 15.5 % at 17.3-17.9 GPa, 1500-1700 K and strain rates of $3.46\text{-}3.59 \times 10^{-5} \text{ s}^{-1}$ using a deformation-DIA apparatus at the synchrotron facility SPring-8. Stress magnitude was measured from azimuthal dependence of three diffraction peaks of ringwoodite (220, 311 and 400) by two-dimensional X-ray diffraction. Strain was calculated from X-ray radiographs of strain markers. Stress magnitude of ringwoodite at steady-state deformation, i.e. creep strength, was 400 MPa at 1500 K. The creep strength decreased to 130 MPa with increasing temperature to 1700 K. The creep strengths of this study are lower than those (4-6 GPa) observed at 3-10 GPa and room temperature using a deformation-DIA apparatus (Nishiyama et al., 2005) and those (1.7-2.8 GPa) determined at 21-23 GPa and 1800 K using a rotational Drickamer apparatus (Hustoft et al., 2013; Miyagi et al., 2014). Further deformation experiments and subsequent sample analyses should be performed to determine flow laws of ringwoodite and in turn to discuss viscosity at the lower part of the mantle transition zone.

キーワード: ringwoodite, creep strength, stress, strain, deformation-DIA apparatus, synchrotron X-ray
Keywords: ringwoodite, creep strength, stress, strain, deformation-DIA apparatus, synchrotron X-ray

Si and O self-diffusion in stishovite Si and O self-diffusion in stishovite

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Seismological studies revealed the seismic reflectors in the lower mantle at the depth from 900 to 1850 km (e.g., Kaneshima and Hellfrich, 1999; Niu et al., 2001; Castle and Creager, 1999). These reflectors are interpreted as pieces of subducted ancient oceanic crust (Kaneshima and Hellfrich, 1999), indicating the high viscous oceanic crust to inhibit the deformation during subduction and further mixing with the lower mantle. At lower mantle depth, stishovite is as much as 20 % in the basaltic composition and 40 % in the sedimental rocks (Irfune and Ringwood, 1993; Ono et al., 2001; Irfune et al., 1994). Therefore, the viscosity of stishovite may be one of the key parameter to constrain the viscosity of the ancient oceanic crust in the lower mantle. Viscosity of solid is thought to be controlled by diffusion of the constituting elements. To know the viscosity of stishovite, thus, diffusivity of Si and O was studied by means of high pressure experiments in this study.

Single crystals of stishovite (~500 μm in size) were synthesized at 12 GPa in a Kawai-type high pressure apparatus by slow-cooling method (Shatskiy et al., 2010). The polished {110} surfaces were coated with ~150 nm ²⁹Si and ¹⁸O enriched SiO₂ layer in a high-vacuum thermal evaporator. The coated crystals were again compressed at 14-21.5 GPa and 1673-2073 K in the Kawai-type apparatus for diffusion. The recovered samples were measured by secondary ion mass spectroscopy (SIMS) to obtain diffusion profiles by the depth profile method. The obtained profiles were fitted to semi-infinite diffusion model and the fitting results were ΔE , ΔV and $\log D_0$ to be 178.6 ± 4.4 kJ/mol, 6.0 ± 0.2 cm³/mol and -12.9 ± 0.14 m²/s, respectively, for Si diffusion, and 262.7 kJ/mol, 5.0 ± 1.6 cm³/mol and -10.1 m²/s, respectively, for O diffusion, where ΔE , ΔV and D_0 are the activation enthalpy, activation volume and pre-exponential factor, respectively.

Our results show that Si diffusion in stishovite is slower than O under mantle conditions and hence the deformation of stishovite is controlled by Si diffusion. The diffusivity of Si in stishovite is ~3 orders of magnitude smaller than that in wadsleyite and garnet (Shimojuku et al., 2009, 2013), ~4 orders of magnitude smaller than that in ringwoodite (Shimojuku et al., 2009) and perovskite (Yamazaki et al., 2000). We can conclude that stishovite is the hardest mineral among the main mantle minerals. The survival of the subducted slab observed as seismic reflector at the lower mantle might be supported by the significantly high viscous stishovite.

キーワード: stishovite, diffusion, viscosity, subducted oceanic crust

Keywords: stishovite, diffusion, viscosity, subducted oceanic crust

Development of a rotational Drickamer apparatus (RDA) Development of a rotational Drickamer apparatus (RDA)

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Many major developments in the study of deformation of Earth materials occurred based on the developments of new techniques. They include the contributions from UCLA lab (Griggs) based on the development of a solid-medium deformation apparatus, and the contributions from ANU lab (Paterson) based on the development of a high-resolution (but low pressure) deformation apparatus. Surprisingly (or embarrassingly), there was a large hiatus in the development of new technology between ~1980 and ~2000 and until very recently reliable experimental results on rheological properties were limited to ~0.3 GPa (~10 km).

Recognizing this, a group of scientists in USA started a serious effort of developing new techniques of quantitative deformation experiments. The developments include the design and operation of new types of deformation apparatus and the development of synchrotron-based techniques of measuring stress and strain. In this presentation, I will review the development of RDA (rotational Drickamer apparatus) and a theory of stress measurements performed in my lab. The advantage of RDA include (i) the capability of conducting high-P (and T) deformation experiments (compared to D-DIA), and (ii) the capability of large-strain deformation experiments. A brief description of RDA deformation experiments and some recent results will be presented including the results of deformation of a mixture of bridgmanite + ferro-periclase at the lower mantle conditions.

キーワード: high pressure, deformation experiments, synchrotron facility, lower mantle, RDA
Keywords: high pressure, deformation experiments, synchrotron facility, lower mantle, RDA

Dislocation mobility in ringwoodite as a function of temperature and water content Dislocation mobility in ringwoodite as a function of temperature and water content

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Ringwoodite is the dominant mineral in the lower part of the Earth's mantle transition zone from 520 to 670 km depth. Understanding the creep properties of ringwoodite is thus essential to know the geodynamical process at this depth. Dislocation creep, which could cause seismic anisotropy and non-Newtonian viscosity, is an important creep mechanism for high temperature plastic deformation of minerals. Since the dislocation creep rate is controlled by the mobility of dislocations, we measured the dislocation mobility in ringwoodite single crystals as a function of temperature and water content under the mantle transition zone conditions.

The ringwoodite single crystals were synthesized from natural olivine at 1800 K and 22 GPa in a multi-anvil apparatus. The crystals were deformed after synthesization by increasing the load to create high density dislocations. The deformed crystals were surrounded by CsCl and annealed at 22 GPa, 1600-2000 K for dislocation recovery. The water contents in the crystals were measured by Fourier transform infrared, the dislocation densities before and after recovery were determined by transmission electron microscopy, and the dislocation mobility were calculated from the dislocation densities and annealing durations.

The activation enthalpy for dislocation mobility is 360 ± 90 kJ/mol. This value is much lower than that for Si diffusion (480 ± 90 kJ/mol), but similar to that for O diffusion (370 ± 80 kJ/mol) (Shimojuku et al., 2009). It is probably because the dislocation movement in ringwoodite is controlled by both Si and O due to their similar diffusion rates (less than 0.5 orders of magnitude difference, Shimojuku et al., 2009). Temporary results suggest that the water content exponent for the dislocation mobility in ringwoodite is about $1.1(\pm 0.9)$. Namely, in contrast with olivine (Fei et al., 2013; 2014), water may have large effect on ringwoodite rheology. But more experimental data are required for precise determination of the water content exponent.

Shimojuku et al. (2009), *EPSL* **284**, 103-112.

Fei et al. (2013), *Nature* **498**, 213-215.

Fei et al. (2014), *JGR* **119**, 7598-7606.

キーワード: ringwoodite, dislocation mobility, recovery, water content

Keywords: ringwoodite, dislocation mobility, recovery, water content

ブリッジマナイトのその場応力-歪同時測定のための予備的変形実験 Preliminary deformation experiments for in-situ stress-strain measurements of bridgmanite

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In order to discuss mantle dynamics in the Earth's interior, knowledge of viscosity of the Earth's lower mantle, which is the highest of the whole mantle, is important. Viscosity models of the Earth's lower mantle were reported by geophysical observations. However, observation values of viscosity have large variety (2~3 order magnitude). Although determination of viscosity of lower mantle minerals by high pressure experiments is needed to understand mantle dynamics, stress-strain relationship for bridgmanite, which are principal minerals of the Earth's lower mantle, are not reported due to difficulty of high pressure deformation experiments. In this study, we tried in-situ stress-strain measurements of Mg-Pv at 27 GPa.

In-situ uniaxial deformation experiments were conducted using MADONNA, which is D-DIA apparatus, as Kawai-type apparatus at SPring-8 BL04B1. Experimental conditions are 27.3 GPa, 1473 K estimated by equation of state on bridgmanite (Katsura et al., 2009). WC anvils with slit or corn (5°) to take tomography and 2D X-ray diffraction, was used along X-ray path. Two-dimensional X-ray diffraction patterns were taken for 300 s using CCD detector. To calculate the stress magnitude from the X-ray diffraction data, we used a model of stress-lattice strain relationship (Singh et al. 1998),

$$d_{hkl}(\psi) = d_{0hkl} [1 + (1 - 3\cos^2\psi) \sigma / 6 G_{hkl}] \quad (1)$$

where d_{hkl} is the d-spacing measured as a function of azimuth angle ψ , d_{0hkl} is the d-spacing under the hydrostatic pressure, G_{hkl} is the appropriate shear modulus for a given hkl, and σ is the uniaxial stress. Pressure and stress were estimated using bridgmanite (111) diffraction peak at deformation experiments. X-ray radiographies of the strain markers was taken using an imaging system composed of a YAG crystal and a CCD camera with an exposure time of 10 s.

Uniaxial tension stress and strain of Mg-Pv at 27.3 GPa, 1473 K were estimated as ~1.3 GPa and ~4 % during deformation by differential ram. We confirmed deformation experiments at the lower mantle pressure conditions can be conducted by WC anvils. We will perform additional deformation experiments with large strain.

キーワード: ブリッジマナイト, その場観察, 変形実験, 下部マントル

Keywords: Bridgmanite, In-situ measurements, deformation experiments, The Earth's lower mantle

天然で変形したオリビンの転位芯に認められる鉄の濃集 Iron concentration around dislocation in naturally deformed olivine

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The concentration of specific atom on dislocation core can be caused by pipe diffusion and Cottrell atmosphere. Both the phenomena are important for the property of materials including rocks and minerals. As an example of the former, Fe concentration has been reported in the naturally deformed olivine (e.g. Plumper et al., 2011). Pipe diffusion is important for atomic migration during various reactions in the Earth, such as metasomatism and serpentinization. On the other hand, Kitamura et al. (1986) and Ando et al. (2001) have reported Fe concentration in the mantle-derived olivine caused by Cottrell atmosphere. The Cottrell atmosphere strongly influences plasticity of materials in the low strain rate regime. Therefore, the discovery of Cottrell atmosphere from the mantle-derived olivine indicates that the effect on the plasticity of olivine is important to understand mantle dynamics under very low strain rate condition. However, the possibility of pipe diffusion cannot be neglected completely to explain the observations of Kitamura et al. (1986) and Ando et al. (2001). Here, we carried out more detailed chemical composition analysis of the mantle-derived olivine to assess whether the Fe concentration on dislocation core is a common phenomenon, and to clarify the exact mechanism of the Fe concentration, *i.e.* Cottrell atmosphere or not.

We studied two types of peridotites, which are xenolith-type in basalt (Takashima, Megata, Kurose and Salt Lake) and alpine-type (Uenzaru and Horoman) by using EPMA and ATEM techniques. EPMA and ATEM analyses show Fe concentration at dislocations in all the studied samples, which suggests that it is a common phenomenon in mantle peridotites. Fe-enrichment at the rim of olivine grains and other major element concentration on dislocations, which are general features of pipe diffusion, cannot be observed. Therefore, the mechanism of Fe concentration on dislocation core in olivine grains is possibly derived by Cottrell atmosphere, not pipe diffusion.

Ando et al. (2001) *Nature*, 414, 893; Kitamura et al. (1986) *Proc. Japan Acad.*, 62, 149; Plumper et al. (2011), *Contributions to Mineralogy and Petrology*, 163, 701.

Keywords: Cottrell atmosphere, olivine, dislocation

強磁場印加コロイドプロセスを用いた細粒緻密配向性オリビン多結晶体の創製 Fabrication of textured Fe-free and Fe-bearing olivine aggregates using colloidal process- ing under high magnetic field

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Crystallographic preferred orientation (CPO) of minerals is considered to be widely produced in the Earth's interior. Due to the presence of anisotropic physical properties such as elasticity, plasticity, electron conductivity and etc... of single crystal minerals, their bulk rock properties can significantly be affected by the presence of CPO. To measure CPO effect on the bulk rock properties by room experiments, it is required to prepare polycrystalline materials with ideally controlled CPO.

Magnetic field was applied to fine-grained (~120 nm) equigranular Fe-free and Fe-bearing olivine particles, which were dispersed in ethanol (solvent) with dispersant (polyethyleneimin). We expected the particles to align with respect to magnetic direction due to their magnetic anisotropy. The aligned particles were gradually deposited on a solid-liquid separation filter during ethanol drainage. The directions of magnetic field and particle deposition were parallel. The dried particles were then densified isostatically at 200 MPa for 10 min and sintered using the alumina tube furnace with vacuum pump.

Highly dense (density of $\geq 99\%$) and fine grained ($\sim 1 \mu\text{m}$) samples with a-axis alignment for Fe-free and c-axis alignment for Fe-bearing olivine to the magnetic direction were obtained. Such synthesized aggregates will allow us to measure CPO effect on the physical properties of olivine aggregate.

キーワード: 結晶方位, オリビン

Keywords: crystallographic orientation, olivine

ローソナイトの高温高压変形実験による結晶方位定向配列の観察：沈み込むスラブに見られる地震波の低速度異常層の解釈
High pressure and high temperature deformation on lawsonite: Implication for low velocity layers in subduction zones

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Low-velocity layers (LVLs) located in the upper portions of subducting slabs, are regions of lower seismic wave velocities than those in the surrounding mantles. LVLs apparently persist to depths of 100-250 km [1,2]. Hydrated mafic rocks provide a plausible explanation for the origin of LVLs and trench-parallel/normal S-wave fast polarization. Lawsonite ($\text{CaAl}_2\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$), which is stable at depths greater than serpentine minerals, is considered to be one of the prime candidate hydrous minerals that can be present deep in the cold subduction zones [3,4]. Single crystals of lawsonite have a high elastic anisotropy, suggesting that the development of the crystallographic preferred orientations (CPOs) when it deformed might strongly affect the seismic properties [5].

This study reports deformation experiments on lawsonite aggregates that were conducted at high pressure and high temperature corresponding to 150 km depth in the subduction zone, to investigate the development of CPOs and the seismic properties of lawsonite. Experiments were performed using a multi-anvil apparatus with six independently acting rams installed at Bayerisches Geoinstitut, Bayreuth University. The starting material consisted of fine-grained ($<25 \mu\text{m}$) natural lawsonite powder, which was loaded in a Pt capsule and annealed for >20 h at 5 GPa, between 500 and 800 °C. The samples were then deformed using pure or simple shear geometry at strain rates of 10^{-4} - 10^{-6} s^{-1} and a finite strain of 0.3-1.0. Recovered samples were analyzed using a scanning electron microscope (SEM) coupled with an electron backscatter diffraction (EBSD) detector and a transmission electron microscope (TEM).

The deformed lawsonite aggregates display a porphyroclastic texture characterized by a bimodal grain size distribution. The microstructures with dynamically recrystallized grains imply the evidence for the deformation through grain-boundary sliding accommodated by diffusion creep due to the grain size reduction, whereas the porphyroclasts (20-50 μm in size) have undulose extinction, deformation lamellae, irregular grain boundaries, and many sub-grain boundaries. The porphyroclasts also display a CPO characterized by a girdle distribution of the [100] axes in the shear plane with a maximum concentration close to the shear direction. The [010] axes form a maximum subnormal to the shear plane. The microstructures and the occurrence of a CPO show that the dominant deformation mechanism for the porphyroclasts is dislocation creep. These results of CPOs diverge from those of previous studies of natural lawsonite rocks [e.g., 6], which might result from differences in experimental or natural conditions. TEM images show a variety of dislocations with a high density of {110} wedge-shaped mechanical twins. Lawsonite seems to have numerous potential slip systems with [100](010) appearing to be the most dominant. The calculated anisotropies of the seismic wave velocities ($AV_p = 2\%$ and $AV_s = 6\%$, respectively) are characterized by the fast propagation of P-wave is oriented subnormal to [010] maxima of the deformed lawsonite aggregates and the polarization of the fastest S-wave is perpendicular to the foliation. This indicates that lawsonite can contribute to the LVL observations and trench-normal S-wave splitting observed at depth of >150 km in the cold subducting slab of northeastern Japan [7].

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キーワード: ローソナイト, 結晶方位定向配列, 変形組織, 変形実験, 沈込み帯, 地震波速度異常

Keywords: lawsonite, deformation, crystallographic preferred orientation, high pressure, subduction zone, low velocity layer

Griggs 型高温高压変形試験機の応力測定値の較正 Calibration for stress measurement of Griggs-type high temperature and high pressure deformation apparatus

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1. はじめに

岩石のレオロジー特性を定量的に明らかにするためには、地球内部に相当する温度・圧力下で変形実験を行う必要がある。岩石変形試験機には、使用する圧媒体の違いから固体圧変形試験機、油圧変形試験機、ガス圧変形試験機がある(例えば、Tullis and Tullis, 1986)。油圧試験機は高温での油の変質を防ぐため、500 °C以下に実験が制限される。ガス圧試験機は荷重計測器が圧力容器内にあるため、力学データの精度が最も高いが、国内では高压ガスの規制法規のため封圧 200 MPa 以下に制限されている。固体圧試験機は柔らかい固体の圧媒体を用いているため、比較的容易で長期間安定的に高封圧 (~2 GPa, 下部大陸地殻 70km に相当) を得られる。しかし、圧媒体と試料や載荷ピストンの間に生じる摩擦を主な原因として、実際の試料の強度よりも高い応力値が測定されてしまう(例えば、Tullis and Tullis, 1986)。

近年、固体圧試験機とガス圧試験機の応力測定値の比較から、固体圧試験機の較正則が示されている(Holyoke and Kronenberg, 2010)。この較正則によって、固体圧試験機を用いて定常領域の差応力を±30 MPa の誤差で求めることができるようになった。しかし、この較正則は定常領域に当たる歪5%における応力値を比較することで求めているため、弾性領域や遷移領域、降伏後の歪硬化や歪軟化といった挙動を再現することはできない。また、ガス圧試験機の実験結果と比較可能な低封圧 (~300 MPa) の実験結果がほとんどであるため、固体圧試験機の長所である高封圧下での応力測定値の精度に関してよく分かっていない。地殻深部・最上部マントル及び沈み込み帯深部を構成する岩石の詳細なレオロジー特性を明らかにするために、高压を長期間安定的に発生できる固体圧試験機において、広範な変形挙動を再現可能な較正則が必要である。本研究では、マスターカーブ法を用いて固体圧試験機における応力測定値の較正則の導出を行った。

2. 軸圧縮実験とマスターカーブ作成

本研究では、東北大学所有の Griggs 型固体圧変形試験機(固体塩アセンブリを採用)を用いて、ニッケルやモリブデンといった金属試料に対して軸圧縮実験を行った。実験は、様々な温度・封圧・歪速度条件下(封圧: ~300 MPa, ~1200 MPa, ~1500 MPa。温度: 600 °C, 700 °C, 800 °C, 歪速度: 2×10^{-4} /s, 2×10^{-5} /s, 2×10^{-6} /s)で行った。低封圧の応力測定結果は、先行実験(Holyoke and Kronenberg, 2010)の同条件での結果とよく一致していた。しかし、高封圧の実験ほど、応力測定値が大きくなる傾向があった。今回の封圧範囲内では、定常状態における応力測定値の対数は封圧とほぼ線形の関係を持つことが示唆された。得られた力学データを嶋本(1987)において示されている粘弾性構成則に基づいて解析し、様々な温度・歪・封圧の異なる力学データを規格化したマスターカーブを得た。Holyoke and Kronenberg (2010)のガス圧試験機による力学データについても同様の解析を行い、マスターカーブを得た。

3. 較正則の導出と適用

固体圧試験機とガス圧試験機の実験には同じ金属試料を用いて、温度・歪・封圧を規格化しているため、両者のマスターカーブの差はそれぞれの試験機システムを構成する様々なレオロジー要素の差異に由来するものと考えられる。二つのマスターカーブの差から固体圧試験機の応力測定値の較正則を導出した。本研究で導出された較正則を固体圧試験機によって得られた金属の応力測定値に適用したところ、ガス圧試験機による応力測定値を定常領域だけでなく、弾性領域や遷移領域も±30 MPa 程度の誤差で再現することができた。降伏後の挙動も以前の較正則よりよく再現することができた。また、1500 MPa までの高封圧の実験結果も較正することが可能となった。炭酸塩岩の応力測定値にも較正則を適用したところ、比較的大きな誤差 (~70 MPa) があったが、弾性変形領域から降伏後の挙動まで再現することができた。

キーワード: レオロジー, 岩石変形実験, 固体圧変形試験機

Keywords: rheology, rock deformation experiment, solid medium deformation apparatus

Weak-beam dark-field TEM characterization of dislocations in wadsleyite deformed in simple shear at 18 GPa and 1800 K
Weak-beam dark-field TEM characterization of dislocations in wadsleyite deformed in simple shear at 18 GPa and 1800 K

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Characterization of dislocations in textured wadsleyite is important in understanding crystallographic preferred orientation (CPO) of wadsleyite and in turn seismic anisotropy at the mantle transition zone. A [001](010)-textured wadsleyite was recently obtained by deformation experiments on wadsleyite in simple shear at 15-18 GPa and 1770-1870 K with a deformation-DIA apparatus (Kawazoe et al., 2013; Ohuchi et al., 2014). However, [001] dislocations have been rarely reported in wadsleyite in the literature (cf. Cordier, 2002). To reconcile the wadsleyite CPO pattern with its slip systems, dislocation microstructures of the [001](010)-textured wadsleyite have been investigated in weak-beam dark-field imaging in a transmission electron microscope. $1/2\langle 101 \rangle$ partial dislocations on the (010) plane are characterized with [100] dislocations on the (001) plane and $1/2\langle 111 \rangle$ dislocations forming {011} slip bands. The former partial dislocations are extended on the (010) stacking fault as a glide configuration (i.e. Shockley-type stacking faults with $1/2\langle 101 \rangle$ displacement vector). The [001] slip on the (010) plane occurs by glide of the dissociated dislocations on a sub-oxygen close packing plane, which can play an important role to generate the crystallographic preferred orientation patterns reported in water-poor deformation conditions (e.g., Kawazoe et al. 2013, Ohuchi et al. 2014).

キーワード: wadsleyite, crystallographic preferred orientation, dislocation, seismic anisotropy, transmission electron microscopy, deformation-DIA apparatus

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