Japan Geoscience Union Meeting 2013
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二成分混合ガウジの大変位摩擦実験に伴う ”弱い断層 ”の形成
Formation of weak faults during large shear deformation experiments of bimineral mixtures

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内陸活断層やプレート境界断層などの成熟した大断層は，短・長期的に弱い強度を持つことが熱流量や応力方位，熱異常の測定などから示唆されている (e.g., Lachenbruch & Sass, 1980, Zoback, 2000, Kano et al., 2006)．このような“ 弱い断層 ”を作る一つの説明として，一般的な造岩鉱物よりも強度の低い物質が潤滑剤として機能しているという考えがあり，その検証のために低強度物質を混ぜた二成分混合ガウジの摩擦実験が数多くなされてきた (e.g., Moore & Lockner, 2011)．しかしながら既存の実験の多くは変位量（歪量）が小さく，天然の大断層に相当する大歪条件下での研究例は少ない．一方で，成熟した天然の断層帯では特定の鉱物の配列・濃集したすべり面がしばしば観察され，このような組織が断層岩の強度低下に影響を及ぼすことが指摘されている (Collettini et al., 2009)．そのため，組織発達のメカニズムとそれに伴う強度変遷の理解には，低歪から大歪条件まで連続的に力学特性と組織を対比させることが重要である．そこで著者らは剪断歪を無限大に与えられる回転剪断式摩擦試験機を用いて二成分混合ガウジの変形実験を様々な変位速度条件下で行い，剪断歪量-微細組織-摩擦強度の関係性に関する研究を行っている．本発表では，乾燥（大気）条件下で行ったグラファイト-石英混合ガウジと，乾燥・水飽和条件で行ったスメクタイト（Na-bentonite）-石英混合ガウジの 2 種類についてこれまでの結果を報告する．

乾燥条件で実験を行ったグラファイト-石英混合ガウジは，動的弱化の起こらない低速領域を含め実験を行ったすべての速度域において数 m のすべり距離で明瞭な強度弱化を示した．低・中速領域では，量比 10-30 vol %の混合ガウジは剪断歪み量 (γ) = 200 程度までは純粋石英に相当する高い摩擦係数 (u = 0.5-0.7) であったのに対し，さらなるすべりに伴い急激に強度が低下し，γ = 2000-10000 で約半分の摩擦強度 (u = 0.2-0.5) にまで低下した．組織観察によると，すべり弱化は粉砕の著しい変形集中帯の形成と，その内部に発達するグラファイトの配列した薄いすべり面（Y 面）の出現に対応する．これにより，低歪時には量比約 30 %を境に緩やかに低下していた強度-量比曲線は，大歪後には約 10 %を境に急激に減少するシグモイド曲線へと進化する．一方で水飽和条件下のスメクタイト混合ガウジは，150 um/s 以下の低速では明瞭なすべり弱化を示さないが，実験開始直後の低歪条件から量比約 30 %を境に急激に低下するシグモイド型の強度-量比曲線を示す．また，mm/s 以上の中・高速条件下においては熱的もしくは機械的な pressurization process に起因する顕著なすべり弱化を示した（大橋・廣瀬, 2013, 本大会）．いずれの試料も断層中に著しい粉砕を伴った変形集中帯は存在しないが，円柱形母岩との縁に薄いスメクタイトの配列が認められた．大気条件下のスメクタイト混合ガウジは著しい粉砕を伴うことが一般的であり，高速 (1.3 m/s) および低速 (150 um/s) の両実験では，厚いスメクタイトの濃集層 (segregation zone) の形成が認められた．以上をまとめると，グラファイト-石英混合ガウジおよび乾燥条件下でのスメクタイト-石英混合ガウジは粉砕と弱い鉱物の濃集，再配列によってすべりが局所化し，強度の低下は歪み量に依存する．一方で水飽和条件下のスメクタイト-石英混合ガウジは大きな組織発達を伴わずに（粉砕を必要とせず）瞬時にすべりが局所化し，歪み量依存性はほとんど見られない．発表では，これらの異なる 2 つのプロセスが何に起因するのかについても検討を行う．

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キーワード: 断層弱化, グラファイト, スメクタイト, 断層ガウジ, 摩擦実験
Keywords: Fault weakening, Graphite, Smectite, Fault gouge, Friction experiment

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SIT38-02 会場:304 時間:5 月 23 日 11:15-11:30

高速剪断される厚い粉体層の緩和過程
Relaxation processes of a thick granular layer at seismic slip rates

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We report on laboratory experiments designed to explore transient responses of a thick granular layer following a step change in slip velocity at seismic slip rates. Experiments were performed at constant normal stresses of 10-30kPa using a ring shear apparatus with inner/outer diameters of 15mm/25mm. We measure the friction coefficient and thickness of glass beads layer at sliding velocities between 0.5 and 3 m/s. Experimental results show that the friction coefficient and layer thickness suddenly increases/decrease as sudden increase/decrease of sliding velocity and then exponentially decay to new steady state with characteristic slip length. We found that characteristic slip length is of the order of 10m when the surface of sliding wall is rough. The response to a velocity step decreases simply symmetric to that to a velocity step increase. In this presentation, we discuss the effect of sliding velocity, normal stress, and surface roughness of the sliding wall on characteristic slip length.

キーワード: high-velocity friction, granular matter, rheology
Keywords: high-velocity friction, granular matter, rheology

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ウルトラカタクラスティック脈に記録された地震すべり: 有馬ー高槻構造線六甲活断層を例に
Repeated seismic slips recorded in ultracataclastic veins along active faults of the Arima-Takatsuki Tectonic Line

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It is well known that direct evidence of earthquakes within fault zones is limited to the presence of pseudotachylyte (e.g., Lin, 2008). In addition to pseudotachylyte, previous studies have shown that the meso- and microstructural features of cataclastic veins that lack the primary cohesion of the host rocks, including crush-origin pseudotachylyte, fault gouge, fault breccia and some calcite veins, may represent primary evidence of brittle deformation caused by recurrent seismic slip within seismogenic fault zones (e.g., Lin et al., 2012, 2013a,b). It has also been reported that during the 2008 Mw 7.8 Wenchuan earthquake, ultracataclastic veins were produced along the seismic slip plane and injected into fractures within the seismogenic fault zone (Lin, 2011). Therefore, studies on cataclastic veins would provide new insights into the deformation process of seismic slip recorded in seismogenic fault zones.

In this study, we report on the structural mode of typical ultracataclastic veins including crush-origin pseudotachylyte and fault gouge veins that formed repeatedly as simple veins and complex networks within a fault zone along active faults of the Arima-Takatsuki Tectonic Line (ATTL), southwest Japan. We also discuss the formation mechanisms of such veins and their tectonic significance in terms of seismic faulting events.

Field investigations, combined with meso- and microstructural analyses, reveal that numerous ultracataclastic veins are widely developed within a fault zone (<150 m wide) as simple veins, complex lenses, and networks, along active faults of the ATTL, southwest Japan. These veins comprise mainly crush-origin pseudotachylyte vein and weakly consolidated to unconsolidated fault gouge that is black, dark-brown, brown, gray, and brownish-red in color. Meso- and microstructural features show that these pseudotachylyte and fault gouge veins and networks formed during multiple stages, as earlier veins are generally cut and overprinted by younger veins, indicating that the vein-forming events occurred repeatedly and that ultracataclastic material was injected into networks of faults and fractures in the fault zone. The pseudotachylyte and fault gouge veins are characterized by an ultrafine- to fine-grained matrix and angular to subangular fragments of host granitic rocks of various sizes, ranging from submicron to millimeters. SEM-EDS and powder X-ray diffraction analyses show that all the ultracataclastic veins are characterized by crystalline materials composed mainly of quartz and feldspar, similar to the host granitic rocks.

The present results support the existing hypothesis that ultrafine- to fine-grained materials formed by comminution can be fluidized and injected rapidly into fracture networks located far from the source fault plane in a solid-fluid-gas system during seismic slip; therefore, such materials provide a record of paleoseismic faulting events that occurred repeatedly within the seismogenic fault zone.

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キーワード: 有馬ー高槻構造線活断層帯, ルトラカタクラスティック脈, シュードタキライト, 断層ガウジ, 細粒破砕物質, 流動化作用
Keywords: Arima-Takatsuki Tectonic Line active fault zone, ultracataclastic vein, pseudotachylyte, fault gouge, fine-grained katerial, fluidization

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フラクタル性を考慮した粉体摩擦の理論
Friction of granular matter with a wide dispersity

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本講演では、粉体摩擦係数と空隙率の間に成り立つ定量的関係式を導出し、空隙率が高いと摩擦係数が強くなるという結果を報告する。これは「粒子再配置イベント一回あたりの粒子変位」が空隙率とともに増加し、散逸率が上昇するためである。対応する粒子シミュレーションの結果も併せて紹介し、 ガウジの摩擦では (離散的な) 粒子再配置イベントの繰り返しに依ってバルク変形が実現されていることを見る。粒度分布がフラクタル的な場合とそうでない場合の違いについても論じる。

キーワード: 断層ガウジ, 粉砕過程
Keywords: fault gouge, comminution

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アノーサイト多結晶体の拡散クリープ実験
Diffusion creep experiments on polyctystalline anorthite

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下部地殻の粘性変形が内陸地震発生に重要な役割を果たしていると考えられている。したがって、下部地殻のレオロジーを知ることは非常に重要なことである。本研究では、下部地殻を代表する鉱物としてアノーサイトを選び、その流動動性について調べた。

これまでの研究より、様々な含水率を持つアノーサイト多結晶体の流動則が得られている。その結果、下部地殻の条件（温度 400〜700 ℃、及びマイロナイトで見られる粒径数十μm 程度）では拡散クリープで変形すると考えられている。しかし、先行研究で用いられた試料には、多結晶体合成法に起因する水やガラス相が含まれており、結晶のみからなる試料のクリープ則は未だ得られていない。そこで我々は水やガラス相を全く含まない試料を作製し、高温変形実験を行うことで流動則のパラメータを求めた。変形実験の温度は 1150〜1380 ℃、応力は 10〜120 MPa、歪速度は 5×10^{-7} 〜2×10^{-3} s^{-1}、大気圧下で行った。時間に依存せず、一定の歪速度になったところで応力-歪速度を読み取った。実験終了前後の走査型電子顕微鏡観察で、試料の粒径は 1 μm、変形実験中の粒子成長は見られないことがわかった。応力-歪速度を対数プロットしたところ、両者に線形関係が見られた。その傾きから、応力指数 n =1 がえられ、拡散クリープで変形したと推定された。活性化エネルギーQ=490 ± 30 kJ、比例定数A=$10^{10.7}$ MPa^{-1} μ m^3 s^{-1} であった。先行研究と比較すると、実験室の温度領域では 2 ケタ固かったが、活性化エネルギーに大きな違いはなかった。この違いは水やガラス相の影響によるものと考えられる。

本研究で得られた流動則を低温領域に適用した。これより、下部地殻が完全なドライ及び粒径が 10 μm とすると、アノーサイト多結晶体はオリビン多結晶体が転位クリープで変形した際に比べて、大きな粘性率を持つことがわかった。

キーワード: アノーサイト多結晶体, 拡散クリープ, 下部地殻
Keywords: polycrystalline anorthite, diffusion creep, the lower crust

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人工アノーサイト多結晶体中の水の不均質分布と歪の局所化
Heterogeneous distribution of water and strain localization of polycrystalline synthetic anorthite

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近年のトモグラフィーによる地殻の断層帯付近の観測から，下部地殻領域に低地震波速度領域や高電気伝導度領域が観測されている．このような領域は高温，高圧の流体に富んだ領域であると推定されている．そこでは岩体中に発達した割れ目を通じて導入された水が，その領域で広がることによって，塑性変形が促進されていると考えられている（例えば Wannamaker et al. 2009）．

下部地殻の主要構成鉱物である長石に関して，これまでの水の効果を検証した変形実験では，多結晶体の粒界や，結晶粒内部で水が平衡に存在した状態で実験が行われてきた．このような実験条件では，上述したトモグラフィーによる観測と対応して，非平衡の系で水が導入され，水の効果による脆性変形から塑性変形の遷移過程や塑性変形の促進過程について評価することはできない．

そこで本研究では無水の人工アノーサイト多結晶体に外部から水を導入させることで，試料内部で水の不均質な分布を再現させながら剪断変形実験を行った．実験に用いたアノーサイト多結晶体は，平均粒径 3 μ m で 5 vol%のシリカリッチなメルトを含む．6.2 mm φの試料を 1 mm 厚，45 °にカットし，厚みと直交方向の試料内部に Ni 箔歪マーカーをセットした．そして試料を上下から 45 °にカットしたアルミナ剪断ピストンで挟んだ．固体圧 (Griggs 型) 変形試験機を用いて，900 ℃，封圧 1.0 GPa，剪断歪速度を $10^{-3.5,-4.0,-4.5}$/sec，剪断歪を 2 までの中で実験を行った．試料に対して 0 から 0.5 wt%の水が発生するように，パイロフィライト粉末をピストン周囲に添加した．これが高温，高圧下で脱水することによって水の供給源となる．

応力-歪曲線は 0.5 wt%の水を加えたときのみ，実験を行った全ての剪断歪速度において弱化した．例えば，$10^{-4.5}$/sec の剪断歪速度の実験で，0.5 wt%の水を加えた実験では差応力 50 MPa 以下で弱化を示した．一方，同じ剪断歪速度で 0.5 wt%より少ない水を加えた実験では，ドライで行った実験と同様に，最大差応力が 1000 MPa まで到達した後，弱化した．回収試料を偏光顕微鏡で観察すると，添加した水が少ないほど破砕流動が卓越していた．0.5 wt%の水を添加した試料では塑性変形が卓越しており，力学データから求められるバルクの歪が 2 であることに対して，薄片では局所的に歪マーカーが剪断歪 5 を示す領域も認められた．

赤外分光法面分析を実施し，含水量分布について測定したところ，0.1 wt%の水を加えて破砕流動が卓越した試料の含水量は少なく，最大でも 130 ppm H_2O であり，水は分子状の水として含まれていた．一方，0.5 wt%の水を添加し，$10^{-4.0}$/sec の剪断歪速度で行った実験では，剪断歪が局所化している領域では最大 550 ppm H_2O の水が含まれていた．こちらも水は分子状の水として存在していることが分かった．このような水はおそらく粒界に含まれていると考えられる．同試料内でも破砕している領域が見られ，この領域での含水量は 250 ppm H_2O 程度であった．このように，微小試料内においても，含水量の不均質性によって，脆性変形から塑性流動までの変形機構の遷移が認められた．以上の実験結果より，実際の天然のマクロの場合においても，水が周囲の岩体に水が導入され，非平衡状態，かつ不均質に分布した中で，水に富んだ領域で塑性変形が局所的に促進されていると推察できる．本発表ではこのような添加した水の量の違いによる応力-歪曲線の変化に加えて，微細組織の発達，そして試料内部での含水量測定から水の存在状態を考察すると共に，その不均質分布と変形との関連性について議論する．

キーワード: Griggs 型変形試験機, 剪断変形実験, 水の導入, 塑性変形の促進, 赤外分光法
Keywords: Griggs deformation apparatus, Shear deformation experiment, Water introduction, Enhancement of plastic deformation, IR spectroscopy

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下部地殻グラニュライト中の過冷却メルト包有物とチャネル流動による急速上昇
Supercooled melt inclusions in lower-crustal granulites and rapid exhumation by channel flow

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我々は従来の想定（常識）をはるかに超える速度でグラニュライトが上昇・冷却したことを示す証拠を、太古代から顕生代までの世界各地の大陸衝突型造山帯（太古代のリンポポ帯、原生代のグレンビル帯、原生代末期 - 古生代初期のスリランカのハイランド岩体と南極のリュツォ・ホルム岩体、古生代中期のボヘミア岩体）に産出するグラニュライト中に見出した。それはザクロ石結晶中の急冷組織（球晶状、樹枝状、骸晶状の石英、長石、斜方輝石などを含む）をもつメルト包有物であり、部分融解メルトが 50 ℃以上の大過冷却度で固結したことと、固結後も再結晶・粗粒化がほとんど起こらない程度に急速に冷却したことを示す。特にスリランカでの広域的で、特定の構造的位置での産出は注目に値し、グラニュライトの上昇機構や速度に新しい視点を与えるものである。

キーワード: 珪長質メルト包有物, グラニュライトの上昇, 過冷却, チャネル流動
Keywords: felsic melt inclusions, granulite exhumation, supercooling, channel flow

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下部マントル上部に沈み込んだスラブ内でのフェロペリクレースの連結とそれに伴う粘性降下とスラブの形態
Interconnection of ferro-periclase reduces viscosity of the subducted slab at the top of lower mantle

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Subduction of cold slab is one of the most important phenomena for dynamics of the Earth and hence many studies have been performed based on geophysical observation, geodynamical simulation and mineral physics. Seismic tomography revealed that the subducting slab classified in two types from the view of shape of slab around 660 km depth discontinuity: one is the continuous penetration into the deep lower mantle and the other is stagnation around 660 km discontinuity forming horizontal layer at this depth (e.g., 1, 2). However, recent tomographic images show the trapped slabs around 1000 km depth, for example, Tonga, Java, Kermadic, Mariana and so on (3, 4). The slab shape around 660 km depth can be explained by the viscosity structure after phase transformation in which relatively low (high) viscosity with colder (warmer) slab because of small (large) grain size (5). However, for understanding the whole mantle convection, the mechanism to trap the subducting slab around 1000 km depth, related to the rheology of lower mantle rock, should be clarified.

The mineral assembly of the subducting slab in the lower mantle is approximately 80 volume % of silicate perovskite and 20 volume % of ferro-periclase. Therefore, we often approximate the bulk rheology of slab by that of silicate perovskite. This approach works well when dominant phase is weaker than secondary phase, for example, a case of the upper mantle (6). However, in the case of the lower mantle, this approximation does not work because silicate perovskite is much stronger than ferro-periclase (7). A presence of ferro-periclase may significantly reduce bulk viscosity when the interconnected layer of ferro-periclase is formed in the bulk rock (8). To estimate the bulk viscosity, we need to understand not only individual viscosities of silicate perovskite and ferro-periclase but also the connectivity of ferro-periclase in the lower mantle rock.

In the present study, we observed the electrical conductivity change of post-spinel phase just after phase transformation from ringwoodite with time at the uppermost lower mantle conditions to detect the interconnectivity of ferro-periclase. The electrical conductivity is very sensitive for the interconnection of high conductive phase of ferro-periclase in mantle composition. Based on the results of the electrical conductivity measurements by means of high pressure experiments, ferro-periclase forms the interconnected layer in the aggregates of sillicate perovskite and ferro-periclase. The interconnected microstructure can be maintained for a geological time scale (˜10 My) under the condition of the cold subuducted slab (˜800 oC), indicating the low viscous slab even at lower temperature than the surrounding mantle, because of lower viscosity of ferro-periclase than that of silicate perovskite. The low viscous slab may be prevented the penetration into the deeper lower mantle against the high viscous region at ˜1000 km depth, named ”viscosity hill”(9, 10), and therefore causes the stagnation at this depth observed in seismic tomography.

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シンクロトロン放射光分析による鉱物の高圧相転移とレオロジーに関する研究
Synchrotron radiation study on rheological properties of minerals during high-pressure transformations

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Phase transformations of minerals have an important role on the rheology of subducting slabs. Flow properties and the dominant mechanism of deformation are possibly affected through changes of the crystal structure, grain size and polycrystalline texture during the transformation. In the peridotite layer of subducting slabs, the olivine-spinel and the post-spinel transformations are major reactions, which are thought to be origin of the 410 and 660 km seismic discontinuity in the mantle, respectively. In this study, to investigate effects of these transformations on rheological behavior of the subducting slabs, simultaneous deformation and transformation experiments were conducted using analogue reaction systems. Flow stress and transformed fraction were quantitatively obtained by in-situ X-ray observations during the constant strain rate deformation using deformation-DIA (D-DIA) apparatus.

High-pressure transformations of fayalite (Fe_2SiO_4) and albite ($NaAlSi_3O_8$) were used for the analogue of the olivine-spinel and the post-spinel transformation in $(Mg,Fe)_2SiO_4$, respectively. High-pressure deformation experiments were conducted using D-DIA apparatuses at the NE-7 of PF-AR and BL04B1 of SPring-8. The plastic deformation and high-pressure transformation processes were simultaneously observed by time-resolved two-dimensional X-ray diffraction (2DXRD) measurements using monochromatic X-ray (energy 50 keV). 2DXRD patterns were used to obtain the transformed fraction and the differential stress of the sample that was estimated from the distortion of the Debye ring. Plastic strain of the sample was measured from the X-ray radiography images. The microstructure and crystallography of recovered samples were observed using a FE-SEM with an EBSD system.

The olivine-spinel transformation experiments in polycrystalline fayalite were conducted at 973 and 1173 K under quasi-hydrostatic and non-hydrostatic (the samples deformed with the strain rate of $5*10^{-5}$ s^{-1}) conditions. Overpressure needed for the transformation under non-hydrostatic condition at 973 and 1173 K (2.9 and 0.6 GPa) was smaller than under quasi-hydrostatic condition (3.8 and 1.5 GPa). In deformed sample, creep curves indicated that the sample became harder with increase of the spinel fraction. This observation suggests that the olivine-spinel transformation under relatively small overpressure and high-temperature condition would not cause the slab weakening.

Both the post-spinel transformation and the albite decomposition are eutectoid reactions with having an alternating fine lamellar structure. To investigate the creep behavior during eutectoid transformation, two kinds of polycrystalline starting materials, parental albite and decomposed jadeite + quartz aggregate, were prepared. High-pressure deformation experiments were conducted at 2-4 GPa, 873-1073 K and the strain rate of 10^{-6}-10^{-5} s^{-1}. The microstructures of recovered samples as well as the flow and kinetic data suggest sequential variation of the creep mechanism from dislocation creep of the transformed eutectoid colony followed by the grain-size sensitive creep in the degenerated eutectoid structure. This study demonstrated that the creep behavior during the eutectoid transformation involves various processes than previously thought. The slabs may not be weaken promptly after entering into the lower mantle when the size of eutectoid colony is enough large, and keep their strength (or harden) over a period of time depending on the degeneration kinetics of the colony.

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オリビン－メルト系の拡散クリープ下での微細構造形成
Microstructural development under diffusion creep of olivine-melt system

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天然の岩石中に見出される結晶格子選択配向（LPO）は、岩石が変形を受ける過程において生じると考えられている。例えば、アセノスフェアにおける地震波異方性の成因は、マントル流動下での剪断変形に伴う LPO 形成にあると考えられる。こうした場所にはメルトの存在が指摘されており、部分溶融下でのマントル岩石のレオロジー及び変形による微細構造形成は、アセノスフェアの実態を知る上で重要である。これまで、オリビン－メルト系の変形実験は数多くなされ（例えば、Zimmerman et al. 1999; Holtzman et al. 2003）、変形によって生じたオリビン LPO のパターンには、いくつかの種類があることが明らかにされている。しかしながら、その LPO パターンの多様性の成因は、未だ明らかになっていない。

本研究では、オリビン-メルトの流動特性と微細構造の関係を明らかにする目的で、オリビン - メルト系での室内変形実験を行った。まず鉄を含まないオリビンにアノーサイト成分に富むメルト（10~20vol %）を加えたバルク体を合成した。圧縮試験は、管状炉が付設されたインストロン型の変形試験機を用い、大気圧下・温度 1260 度、歪速度 10e-5~10e-4/s の条件で行った。変形中の試料に加わる応力と変位速度を測定することで、応力-歪速度の関係を得た。

それによると、応力指数は概ね 1 であり、このことから本実験における変形のメカニズムは、拡散クリープであったと考えられる。試料回収後、バルク体中のオリビンの結晶方位を走査型電子顕微鏡下での電子後方散乱回折（EBSD）法を用いて測定した。その結果、オリビン結晶の b 軸が圧縮方向に配向することが見出された。また、メルトの分布にも特徴的な変化がみられた。変形後の試料中では、大きなメルトポケット（>100 μ m）は、圧縮方向に垂直なメルトバンドを作り、一方で粒間の小さなメルトポケットは、圧縮方向に平行な方向に並んでいる様子が観察できた。前者は、メルトがオリビン結晶より柔らかいため、選択的に大きく変形したものであり、後者は引張軸方向にオリビン粒子が分離し、その間をメルトが埋めたものであると考えている。オリビンの選択配向は、オリビン粒子平衡形の短軸が b 軸に一致していたことによるのかもしれない。

キーワード: 拡散クリープ, オリビン－メルト系, 格子選択配向
Keywords: diffusion creep, olivine-melt system, LPO

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オリビン拡散クリープ下での様々なLPOパターン発現
Development of olivine LPO under diffusion creep

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Lattice preferred orientation (LPO) of olivine is considered to be a main cause of anisotropic mantle especially of its elasticity, which can tell its dynamic state such as flow direction of the mantle. Olivine LPO is considered to be a consequence of dislocation creep process in the mantle so that intense investigations of the easy slip systems of the mineral under various geological conditions such as temperature, pressure and water fugacity have been conducted. Here we show that synthetic polycrystalline forsterite (+ Ca-bearing enstatite) aggregates demonstrate strong LPO after deformation under diffusion creep where large contribution of grain boundary sliding (GBS) to the sample strain. Combining the LPO patterns developed under tensile and compression tests, our observations correspond to A- and E-type fabrics, previously identified in experimental and natural samples, depending on temperature conditions without the effect of water and pressure on intragranular slip systems. Development of LPO under GBS creep strongly correlates the shape of grains which is crystallographically controlled. Such crystal shape provides grain boundary planes corresponding to crystallographic planes so that GBS and its consequence of grain rotation proceed at specific direction of the crystal resulting in an alignment of specific crystallographic axis to the flow direction forming LPO. Our finding adds new interpretations of the mechanism to form mantle anisotropy.

キーワード: オリビン, LPO, 拡散クリープ
Keywords: olivine, LPO, diffusion creep

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含水かんらん岩における転位すべりと粒界すべりの競合
Cooperation of dislocation gliding and grain boundary sliding in hydrous peridotite

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Deformational behavior of olivine in mantle wedge strongly affects subduction dynamics and geological processes at convergent margins (mantle flow, volcanism, earthquakes and orogeny). Many experimental works are addressed on the deformation under wet conditions. However, there are some difficulties in extrapolating the results to the conditions in subduction zones, especially for temperature conditions. A recent experimental study showed that a mechanism of grain boundary sliding (GBS) can be prevailing in polycrystalline olivine with interstitial hydrous melt, suggesting that a superplastical flow due to GBS of olivine possibly affects on a coupling between mantle wedge and subducting slab. Our EBSD analyses of natural hydrous peridotite revealed transitional structures due to cooperation of GBS and dislocation gliding. Here we present results of microstructural analyses that constrain a GBS flow law under wet conditions.

We used three dunite samples with different proportions of olivine porphyroclasts (SGB) (about 20, 40 and 60%), representing the various degrees of recrystallization. They were exposed at the Gongen outcrop that belongs to the Higashi-akaishi ultramafic body in the Sanbagawa metamorphic belt. All the samples include mm-sized planar grains of amphibole that define the strain geometry of samples. Strain shadows of chlorite and phlogopite around amphibole porphyroclasts indicate water-rich conditions during deformation. Geothermometry for fine Opx and Cpx in the matrix suggests deformational temperature of 700-770 oC. Pressures are inferred to be in a range of 1-2 GPa.

Using well indexed EBSD maps for these samples, olivine grains are separated into two fractions with and without significant internal misorientation (MO): we call them as wSGB and w/oSGB grains respectively. Then, we analyzed grain size, axial ratio and crystallographic preferred orientation (CPO) for each fraction and internal MOs of representative porphyroclasts using MTEX and HKL software.

The olivine CPO of wSGB is stronger in a more recrystallized sample and shows a weak concentration of a-axis parallel to amphibole lineation. On the other hand, the CPO of w/oSGB is weak and independent of the extent of recrystallization. Grains with SGB are elongated (aspect ratio = 2.0) whereas those without SGB are close to equant. Frequency distributions of grain sizes for wSGB and w/oSGB can be approximated as distinctive log-normal distributions and the mean values are $10^{2.3}$ micron for wSGB and $10^{2.0}$ micron for w/oSGB.

These observations suggest that larger grains are dominated by intracrystalline deformation with a dislocation mechanism. Sub-grain structures in porphyroclasts are consistent with [100] slip in {0kl} planes. On the other hand, smaller grains have been deformed under a mechanism without CPO strengthening. Almost equant shapes of olivine grains and high frequency of quadruple junctions of grain boundaries are consistent with GBS mechanisms rather than diffusion creep. Recrystallizing porphyroclasts is associated with nucleation of neoblasts in support of grain boundary migration, implying that diffusional processes have accommodated displacements among grains.

We interpreted that the microstructures of the hydrous dunite record a mechanism transition from dislocation gliding to diffusion-accommodated GBS due to grain size reduction. The critical grain size for mechanism transition lies between representative grain sizes of wSGB (200 micron) and w/oSGB (120 micron). Differential stress is estimated as 30-130 MPa based on recrystallized grain size piezometers. These values are, however, inconsistent with an extrapolation of an experimentally determined GBS flow law. This indicates that some refinement of the flow law parameters are required in order to discuss deformational mechanisms in cold thermal conditions expected for subduciton zones.
Keywords: olivine, microstructure, rheology, grain boundary sliding, hydrous peridotite, subduction zone

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カンラン岩中の変形したオリビンの微細組織観察
Microstructural observation on naturally deformed olivine in peridotite

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上部マントルのダイナミクスを理解する上で，マントル起源の塑性変形したオリビンの微細組織観察は重要である。転位のすべり系，転位密度，再結晶粒径と言った微細組織は，鉱物が受けていた変形状態を反映するからである。そこで我々は，佐賀県高島，福岡県黒瀬，秋田県目潟，ハワイオアフ島ソルトレイクで採取された上部マントル起源のカンラン岩捕獲岩を対象に微細組織観察を行い，各カンラン岩が受けた塑性変形の履歴を推測した。

本研究では，オリビンのすべり系を 1）電子線後方散乱回折（EBSD）を用いた結晶方位定向配列（LPO）と 2）透過型電子顕微鏡（TEM）を用いた Weak-Beam Dark-Field（WBDF）法から決定した。転位密度の決定には TEM を用い，再結晶粒径は主に偏光顕微鏡観察を基に決定した。オリビンのすべり系は温度と差応力によって変化する事が知られている（Carter and Ave Lallemant, 1970）。また、Jung et al. (2006) は変形実験を基に，差応力と含水量によって変化する 5 つのすべり系を報告している。従って，これらの研究結果とマントル起源の変形したオリビンのすべり系を比較する事で，上部マントルに於いてオリビンが受けていた変形状態を推測できる。また，転位密度と再結晶粒径は地質差応力計として使用可能である。転位密度と再結晶粒径は差応力に対する応答速度（定常値に達する速度）が異なる為に，この 2 つの地質差応力計から求めた差応力値が異なる場合には，岩石の受けた差応力履歴を推定する事ができる（例えば，Matsumoto and Toriumi, 1989）。

以下に結果をまとめる。LPO から推測されるオリビンのすべり系は，黒瀬，目潟，ソルトレイクの試料では同一であり，(010)[100]-A-type，{0kl}[100]-D-type，(001)[100]-E-type のいずれかであると考えられる。高島の試料に関しては LPO の集中度が弱い為にすべり系を判断することが困難であるが，(010)[001]-B-type，もしくは (100)[001]-C-type の可能性が考えられる。

一方，WBDF 法より得られたすべり系は，高島とソルトレイクは (010)[100]-A-type，黒瀬と目潟は (001)[100]-E-type が卓越していた。黒瀬，目潟，ソルトレイクの結果は LPO から得られるすべり系を支持する結果となっている。Jung et al. (2006) によると，A-type と E-type はそれぞれ“ 低差応力・低含水条件 ”と“ 低差応力・高含水条件 ”で形成されるすべり系なので，高島とソルトレイク及び黒瀬と目潟の捕獲岩はそれぞれ“ 低差応力・低含水条件 ”と“ 低差応力・高含水条件 ”で塑性変形したと考えられる。高島に関しては，LPO から推測されるすべり系と WBDF 法より得られたすべり系が一致しない。これは高島の受けた差応力の履歴を反映していると考えられる。

転位密度と再結晶粒径は，高島で約 $2.8 \times 10^7 cm^{-2}$ と約 1.1mm，黒瀬で約 $3.5 \times 10^7 cm^{-2}$ と約 0.3mm，目潟で約 $1.8 \times 10^7 cm^{-2}$ と約 1.3mm，ソルトレイクで約 $3.7 \times 10^7 cm^{-2}$ と約 0.5mm であった。これらの値から，Kohlstedt and Goetze (1974) と Jung and Karato (2001) の転位密度-差応力と粒径-差応力の関係式を用いて差応力値を求めた。粒径-差応力に関してはドライな条件と含水条件の 2 種類の関係式が提示されており，各々を高島とソルトレイク及び黒瀬と目潟の捕獲岩に適用した。その結果，目潟，高島，ソルトレイクに関しては転位密度から得られた差応力が再結晶粒径から得られた差応力よりも大きな値を示した。転位密度は再結晶粒径に比べ，新しい応力へ早く応答する為に，これらの試料は定常クリープ後に付加的な応力を受けたことが示唆される。一方，黒瀬の試料は，転位密度と再結晶粒径から得られた差応力はほぼ一致していた。従って，この試料は定常クリープ状態を保持していたと考えられる。

現在は Alpine type のペリドタイト試料に関して、同様の観察と分析を進めている。

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Keywords: Olivine, Peridotite, Slip system, Dislocation, Weak-Beam Dark-Field method

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石英岩の格子定向配列に及ぼす動的再結晶の役割
Role of dynamic recrystallization in lattice preferred orientation of quartz rocks

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From the microstructural analysis of plastically deformed rocks, the c-axis lattice preferred orientation (LPO) of quartz has been utilized to infer deformation conditions: sense of shear, deformation temperature, and/or water content. The c-axis LPO patterns change from type I crossed-girdle at lower temperature to point maxima at Y axis of strain ellipsoid (Y max LPO) at intermediate temperature, to point maximum at X axis (X max LPO) at higher temperature. The change in LPO patterns is known to reflect the change in the dominant slip systems of quartz from basal <a> and rhomb <a> slip, to mainly prism <a> slip, to prism [c] slip with deformation temperature (Stipp et al., 2002). Most naturally deformed rocks with a strong LPO are dynamically recrystallized. It is not clear whether the LPO patterns are controlled only by the dominant slip systems or by dynamic recrystallization processes such as grain boundary migration and subgrain rotation. Recent experiments have clarified the formation of Y max LPO patterns with increasing strains and degree of dynamic recrystallization where grain boundary migration is the dominant mechanisms of dynamic recrystallization (Heilbronner and Tullis, 2006; Muto et al., 2011). However, the effect of other mechanisms occurring under lower temperature conditions has been not clear yet. In order to clarify how dynamic recrystallization affects the LPO development under lower temperature than previous experiments, we conducted general shear experiments in a Griggs apparatus using single crystals of synthetic quartz. We utilized three different initial orientations to activate three dominant slip systems of quartz: basal <a>, prism <a> and prism [c] slip. The c-axes of samples with initial orientations for basal <a> slip system and prism [c] slip system progressively rotated with the sense of shear with strains. The amount of the rotation at a given strain is larger in the samples with prism [c] initial orientation than those of basal <a> initial orientation, implying the rapid consumption of the harder slip system. The c-axis of samples in the basal <a> initial orientation rotated 90 degrees to prism [c] orientation at gamma of 2 and further to the orientation suitable for basal <a> slip. The samples of the prism [c] initial orientation rotated 90 degrees to orientation suitable for basal a slip and completely recrystallized at gamma ˜ 6. Recrystallized grains show symmetric broad single maximum at the Z axis of the strain ellipsoid, consistent with the c-axis LPO of recrystallized grains (Heilbronner and Tullis, 2002) where bulging is the dominant recrystallization mechanism. On the other hand, the samples with prism <a> initial orientations did not show any recrystallization up to strains as high as gamma of 7 and kept its c-axis orientation located at the Y axis of the strain ellipsoid. This indicates that grains in basal <a> and prism [c] initial orientations were recrystallized to activate easy basal <a> slip with progressive deformation. On the other hand, the grains with prism <a> initial orientation do not change their c-axis orientations with progressive shear. Therefore, the activation of easy basal <a> slip and additional prism <a> and/or rhomb <a> slip to satisfy von Mises criterion results in the development of type-I crossed or inclined single girdle depending on the deformation geometry. With increasing deformation temperature to higher greenschist to amphibole facies conditions where rapid grain boundary migration can occur, grains oriented for weak prism <a> slip can grow at the expense of grains in other orientations, results in development of Y max LPO with dynamic recrystallization (Heilbronner and Tullis, 2006; Muto et al., 2011). Therefore, the LPO transition observed in natural deformed rocks from type I crossed or single girdle to Y max LPO may basically reflect the change in dominant mechanisms of dynamic recrystallization with temperature.

キーワード: 格子定向配列, 石英, 動的再結晶, 地殻のレオロジー
Keywords: Lattice preferred orientation, Quartz, Dynamic recrystallization, Rheology of crust

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メジャーライトガーネット中のアルミニウム、シリコン相互拡散と転位微細構造
Al, Si interdiffusion in majoritic garnet and the dislocation microstructures.

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Plastic deformation by dislocations and atomic diffusion by vacancies of minerals at high pressures are important for the rheology of the Earth's mantle. Because those processes are controlled by moving of two agents (line and point defects) in deformations at high temperature, the post-mortem examination by analytical transmission electron microscope is indispensable for evaluating those agents (carriers). Majoritic garnet (MajGt) and magnesium silicate perovskite (MgPv) are major constituents in the mantle transition zone and the lower mantle, respectively. Diffusivity differences of the slowest species between these mantle minerals are very important to understand the changes of the nature of chemical heterogeneity, viscosity through those creep raw, and other various transport properties across the upper and lower mantle boundary.

Here I report an Al + Al = Si + Mg interdiffusion between MajGt and pyrope garnet. The diffusion couples using a multi-anvil press are pre-synthetic $Mg_3Al_2Si_3O_{12}$ pyrope and majoritic garnet. The annealing condition is at 18.5 GPa and 1750-1950 degree Celsius for 120-300 minutes, corresponding to a MajGt-single phase region in the binary system $MgSiO_3$-$Al_2O_3$3. Diffusion profiles of the recovered sample were examined with electron probe microanalyser (EPMA), scanning electron microscopes (SEM) and scanning transmission electron microscopes (STEM) equipped with an energy dispersive X-ray spectrometer (EDXS). Dislocation microstructures were also examined in weak-beam dark-field images using the thickness-contour fringe method (Ishida et al., 1980; Miyajima and Walte, 2009).

MajGt displays <100> and 1/2 <111> free dislocations and subgrain textures consisting of a dislocation array, suggesting that climb of dislocations was occurred during diffusion annealing. The obtained Al + Al = Mg + Si interdiffusion coefficient (D_{Al}) of MajGt at 18.5 GPa and 1750 degree Celsius is 6.2(4) x 10^{-19} (m^2/s), which is comparable with those of Mg and Si self-diffusion coefficients in MgPv under lower mantle conditions (Xu et al., 2011). However, the DAl is significantly higher than those of in previous studies in majoritic garnets at temperatures less than 1750 degree Celsius (e.g., Nishi et al. 2013). The preliminary obtained activation energy in this study is much higher in the temperature from 1750 to 1950 degree Celsius, where is likely to be the intrinsic regime in the interdiffusion. Comparisons with Al, Si interdiffusion in Fe-bearing majoritic garnets are given to highlight the effect of impurities and temperature on those diffusion rates. Considerations for further diffusion experiments in MajGt and aluminous MgPv are discussed toward the rheology from the transition zone from the lower mantle. I thank the generous support from BGI colleagues for commissioning of this study.

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Keywords: majoritic garnet, Al, Si interdiffusion, analytical transmission electron microscope, weak-beam dark-field image, dislocation microstructures

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SIT38-16 会場:304 時間:5 月 23 日 16:30-16:45

二次元単色 X 線回折を用いたカンラン石の粒成長実験
Grain-growth experiments of olivine using 2D monochromatic X-ray diffraction pattern.

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Rheology is one of the most important mineral properties which plays a major role in controlling dynamic processes in the Earth's mantle. Olivine is the most abundant mineral in the upper mantle (60vol% in pyrolite mantle). Rheology in the upper mantle is dominated by this mineral. If diffusion creep is the most dominant deformation mechanism, the rheology of an aggregate is a function of the grain size of the constituent minerals. Thus, knowledge of grain size of olivine is important for understanding the rheology of the upper mantle.

The grain size of rock is controlled by several mechanisms (e.g. grain-growth, dynamic recrystallization and recrystallization by phase transformation). Grain-growth is one of the most important processes in controlling the grain size of the rock by which grain size is enlarged. Grain-growth experiments of olivine were conducted by some workers (e.g.Karato 1989, Ohuchi and Nakamura 2006). However grain-growth exponent, which is a parameter of time dependence, is controversial between previous studies.

Thus, in this study, we have investigated grain-growth kinetics in the olivine single phase system at high pressure and temperature (1373 - 1573 K, 2.3 - 10.5 GPa) using a in situ monochromatic X-ray diffraction and Kawai-type multi-anvil apparatus (SPEED-1500) installed at the synchrotron beam line, BL04B1, in the SPring-8 at the Japan Synchrotron Radiation Research Institute. The San Carlos olivine powder was used as starting material. The grain size was estimated by the relationship between the number of diffraction spot and the number of grains per radiated volume reported by Hirsch (1955).

The grain-growth kinetics of olivine is described by $G^n - G_0^n = k_0 \exp(-(E+PV)/RT)t$ where G is the average grain size at annealing time t; G_0, the initial average grain size; k_0 is the pre-exponential constant, E is activation energy, P is pressure, V is activation volume, R is the gas constant and T is absolute temperature, with n = 2.5 +- 0.2, $\log_{10} k_0$ = -9.2 +- 2.6 $m^{2.5}/s$, E = 184 +- 10 kJ/mol, V = 0.4 +- 0.2 cm^3/mol. The activation energy of grain-growth is similar to that of grain boundary migration (Toriumi, 1982). Thus, in terms activation energy and grain-growth exponent, in this study, grain-growth could be caused by grain boundary migration in the single phase system.

キーワード: カンラン石, 粒成長, その場観察実験, 上部マントル
Keywords: olivine, grain-growth, in-situ experiments, upper mantle

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DAC 実験における選択配向性および格子ひずみの解析手法の開発
Texture and strain analyses using 2-dimensional X-ray diffraction patterns under DAC experiments

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Angle dispersive X-ray diffraction experiments using area detectors (CCD and CMOS cameras and image-plate recorders) provide wide opportunity for the determination of lattice preferred crystallite orientation (LPO) and lattice strain under stress condition in polycrystalline materials. LPO is reflected in circumferential oscillations along Debye rings, while the effect of lattice strain appears in elliptic distortions of the each ring and a deviation of the original crystallographic geometry among rings. These are substantial factors of bulk physical properties in polycrystalline materials, including seismic velocity, thermal/electric conductivity and so on. Diamond anvil cell (DAC) is the only technique that can create at extreme pressures corresponding to the Earth's core, and it simultaneously involves non-hydrostatic, uniaxial stress in the sample. Although such non-hydrostatic effects under DAC experiments has been reported many previous studies, in many cases the quantitative treatments have not yet been developed into a standard technique.

In order to examine quantitative stress conditions under DAC experiments, high pressure experiments were carried out in a symmetrical DAC in the present study. Two stating materials, Al2O3 (˜1um in diameter) and MgO (<0.1 um), were used as stating materials, and no pressure media were loaded. Each runs were performed at the pressures from 0 GPa to 70 GPa by 10 GPa step under room temperatures, and synchrotron X-ray diffraction patterns were collected using a flat imag-plate at BL10XU at SPring-8. A software code was also developed by the author, which simulates a two-dimensional diffraction pattern based on given experimental parameters and (poly)crystalline properties. A fitting procedure was also incorporated into the code, where the orientation distribution and stress condition were iteratively modified according to a residual value of the simulated/observed patterns.

In runs of Al2O3 experiments, the diffraction peaks became distinctly broad and asymmetric shapes with increasing pressures, whereas the scattering angles (2theta) were apparently almost constant. This means that lattice compression involved by pressures was cancelled out by deviatoric stress. Nonetheless, the stress conditions could be derived mainly from the shapes of the peaks using the fitting procedure; e.g. at the highest pressure condition in the present study, maximum and minimum principal stresses could be estimated as 73GPa (parallel to compression axis) and 25 GPa, respectively, corresponding to the deviatoric stress of 50 GPa. The maximum principal stress was consistent with the estimated pressure by the diamond Raman pressure scale. On the other hand, MgO experiments maintained pseudo-hydrostatic conditions with small deviatoric stress only up to ˜1GPa under all performed pressures. A whole pattern fitting method such as the code developed in the present study may help us understand the stress conditions under DAC experiments

キーワード: 粉末 X 線回折, ダイヤモンドアンビルセル, 二次元検出器, 多結晶体, 選択配向, 格子ひずみ
Keywords: powder X-ray diffraction, diamond anvil cell, area detector, polycrystalline material, lattice preferred orientation, lattice strain

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部分溶融系の体積粘性率の測定
Experimental study of bulk viscosity of partially molten rock analogue

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Viscosities of partially molten rock change significantly due to melt fraction. However its quantitative effects have not been well constrained theoretically nor experimentally. Deformation of partially molten rock is controllled by two independent viscosities: shear viscosity for shear deformation and bulk viscosity for compaction/decompaction. Bulk viscosity and its ratio to shear viscosity, h_b/h_s , play an important role in melt segregation dynamics (Katz, 2008). Most numerical studies have used the theoretically predicted value of h_b/h_s = ~f^{-1}, where f is the melt fraction. However, Takei and Holtzman (2009a) theoretically obtained a constant value of h_b/h_s by taking into account a diffusion creep mechanism. The discrepancy between two models is significant at small melt fractions. There has not been experimentally determined value of h_b/h_s because very few experimental studies have been done about bulk viscosity although shear viscosity has been measured extensively. Therefore, the purpose of this study is to measure a pair of the bulk and shear viscosities for the same sample. As the first step of the experimental examination, we measured bulk viscosity experimentally as a function of melt fraction using a partially molten rock analogue.

Samples were polycrystalline aggregates of borneol-diphenylamine binary with eutectic temperature of 316K, which has a quite similar equilibrium microstructure to olivine + basalt system (Takei, 2000). Initial melt fraction can be controlled precisely by the concentration of diphenylamine because of its simple eutectic reaction. Before deformation experiments, samples were annealed at 320K for ~100 hours in a sealed capsule to make those grain size large enough (~0.030 mm), resulted in negligible grain growth during the successive deformation tests at the same temperature.

To measure the bulk viscosity, we carried out compaction experiments in which melt was squeezed from the partially molten sample under the diffusion creep regime. A cylindrical sample contacted with a porous metal at the top end was compacted uniaxially in a rigid sleeve (horizontal strain = 0, vertical strain < 0). Melt can flow out into the porous metal until its fraction becomes nearly zero. Evolution of melt fraction in the sample was calculated from the sample length measured with digital gauge. Apparent viscosity is calculated as a function of melt fraction from an instantaneous strain rate and a constant stress. Precise measurements of melt fractions at very small amounts of melt ($f < 1$ %) is crucial to test the predictions of models. Data obtained so far show the viscosity is proportional to exp(-af) with a = ~30 at $f > 3$ %, which is quite consistent with the olivine + melt systems (Renner et al., 2003). At $f < 3$ %, deviation of the viscosity from the exponential curve occurs, suggesting the possible effects of permeability and change of rate limiting process of the volumetric creep (Takei & Holtzman, 2009b).

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キーワード: 粘性, 体積粘性率, 部分溶融
Keywords: viscosity, bulk viscosity, partial melt, compaction

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オリビン多結晶体クリープおよび電気伝導度同時測定実験－律速機構の解明に向けて
Simultaneous measurements of creep strength and electron conductivity of polycrystalline olivine

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高温・高歪速度 (高応力) 条件下で実験的に得られる鉱物の流動則を地球内部流動に適用するにあたっては、高精度の流動則、特に、高精度の活性化エネルギーを求める必要がある。本研究では、岩石流動の変形機構の詳細および温度に伴う流動応力変化を調べるために高温下・大気圧下でのフォルステライト多結晶体の一軸圧縮クリープ試験を行った。また、インピーダンス法により、クリープ試験中に電気伝導度測定を行った。一般に、クリープは最も遅いイオン種の拡散過程により律速され、逆に電気伝導度は最も速いイオン種の拡散過程に律速されていると考えられている。温度によるクリープ速度と電気伝導度の変化 (活性化エネルギー) を高精度で求めることにより、拡散メカニズムの詳細が理解できると期待される。これより、地球内部流動における律速過程を推定し、実験室下で得られる流動則を活性化エネルギー値をもって地球内部に適用することができる。

試料は、体積比 90%のフォルステライト (Mg2SiO4) と 10%のエンスタタイト (MgSiO3) から成る多結晶焼結体である。圧縮クリープ試験は、管状炉が付設されたインストロン型の変形試験機を用いた。実験中の粒径変化を抑えるために、荷重を試料に負荷する前に、実験条件である最高温度で粒径を 24 時間かけて飽和させた。試験中の応力は 10-20MPa の一定値温度は 1360 ℃から 1200 ℃までゆっくり変化させた。降温速度は高温領域で 0.11 ℃/min、中温度領域で 0.03 ℃/min 低温領域で 0.02 ℃/min にした。これにより、各 1 ℃ごとに歪速度を得るに十分な試料歪を得ることができ、より精度の高い応力－歪速度値が得られた。この実験中、同時に、試料のインピーダンスを計測した。ピストンと試料の接触部である上部および下部の SiC をそれぞれ電極として、2V の交流電圧をかけることで応答電流を得ることができ、その電圧と電流の関係からインピーダンスは求められた。1360 ℃から 1200 ℃まで 10 ℃毎に計測を行った。実験後と実験前の試料を走査型電子顕微鏡法により観察し、粒径の計測を行った。全温度領域の粘性率・温度のアレニウスプロットにおいて、両者の関係は一直線で近似されることが分かった。706 ± 1kJ/mol の活性化エネルギーが求められた。この結果は、実験の温度領域で律速する拡散機構が変わらなかったこと、また、本実験手法によって、地球内部の低温領域に十分に適用できる流動側を得られることを示している。インピーダンス測定の結果は、電気伝導度が系統的に高温から低温にかけて小さくなることが示された。

キーワード: オリビン, クリープ, 多結晶, 活性化エネルギー, 電気伝導度, インピーダンス
Keywords: olivine, creep, polycrystal, activation energy, electrical conductivity, impedance