Effect of Water on the Dislocation Creep of Enstatite Aggregates at 300 MPa

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Abstract To investigate the effect of water on the rheological properties of enstatite, we have conducted triaxial compressive creep experiments on enstatite aggregates using a gas medium apparatus at a confining pressure of 300 MPa and temperatures of 1373–1473 K under both water-saturated and anhydrous conditions. Samples were mainly deformed in the dislocation creep regime; analyses of mechanical data yield activation energies of 603 and 567 kJ/mol for hydrous and anhydrous conditions, respectively. Under similar differential stress and temperature, the creep rate of enstatite under water-saturated conditions is a factor of ~50 greater than that under anhydrous conditions. Based on a comparison of creep strength between olivine and enstatite in the dislocation creep regime, our results suggest that, at least under limited pressure and temperature conditions, enstatite is weaker than olivine. The results from this study provide a solid database for modeling geological processes occurring within Earth’s interior.

1. Introduction

Numerous geological and experimental studies have demonstrated that water (hydrogen) is incorporated abundantly in nominally anhydrous minerals within Earth’s upper mantle (Bell & Rossman, 1992; Hirschmann et al., 2005; Ingrin & Skogby, 2000; Kohlstedt et al., 1996; Skogby, 2006), and its presence can significantly influence minerals’ mechanical and physical properties such as rheological behavior (Chopra & Paterson, 1984; Karato et al., 1986; Mei & Kohlstedt, 2000a, 2000b; Hier-Majumder et al., 2005; Chen et al., 2006; Xu et al., 2013), seismic wave attenuation (Aizawa et al., 2008; Karato, 1995), and electrical conductivity (Wang et al., 2006; Yang et al., 2011). As the distribution of water in the upper mantle is inhomogeneous, varying laterally and vertically (Li et al., 2018; Liu et al., 2017; Ni et al., 2017; Peslier et al., 2017), the influence of water on minerals’ mechanical and physical properties may correlate closely with the heterogeneity of geodynamical processes in relevant tectonic settings. Particularly, water weakening of nominally anhydrous minerals of Earth’s upper mantle has been interpreted as a reasonable model for the presence of the asthenosphere for our planet (Bürgmann & Dresen, 2008; Green et al., 2010; Mierdel et al., 2007; Sakurai et al., 2014). Therefore, experimental investigation of the effect of water on the rheological properties of nominally anhydrous minerals is important for understanding and modeling the geodynamic behavior within Earth’s interior.

The flow behavior of Earth’s upper mantle is determined mainly by rheological properties of its constituent minerals such as olivine, orthopyroxene, and garnet. Orthopyroxene (opx) is an important mineral in mantle rocks such as peridotite, harzburgite, and lherzolite (Boyd, 1989; Moradpour et al., 2017). Its content in pyroxene-rich regions is likely associated with various geophysical processes, such as SiO2-melt metasomatism (Hong et al., 2017; Straub et al., 2008), lower crust delamination (Lustrino, 2005), and oceanic crust recycling (a large igneous province magma source) (Day et al., 2009; Ren et al., 2017).

Despite study of mineral strength over the past several decades with important implications for modeling plate tectonics, the rheological behavior of opx remains poorly constrained and the effect of water on the rheology of opx has barely been studied. Although some experimental studies have been conducted to understand the rheological properties of opx (Bystricky et al., 2016; Hitchings et al., 1989; Mackwell, 1991; Ohuchi et al., 2011; Raleigh et al., 1971; Raterron et al., 2016; Ross & Nielsen, 1978; Zhang et al., 2017), the published results are sparse and inconsistent. The error in the viscosity of enstatite is up to 3 orders of magnitude based on different experimental datasets.
on previous studies, making it impossible to evaluate rheology contrast among opx and other major constituent minerals of Earth’s upper mantle such as olivine and garnet. In addition to the uncertainty of measurements (e.g., some pioneering studies using solid-medium apparatuses were plagued by poor stress resolution), one cause for the discrepancy among those mentioned studies may result from the variation of water content among samples used (Bystricky et al., 2016; Raterron et al., 2016). If chemical environments for experiments are not well controlled and water contents in samples differ from one to the other, then, with a strong water-weakening effect, discrepant mechanical results are inevitable.

Compared with olivine, the rheological properties of opx have received little attention. This may be due to the assumption that olivine, despite its high abundance, is the least viscous phase among the main components in the upper mantle. However, such an early made assumption is problematic because any conclusion would be unreasonable if the rheological properties of one mineral are not well constrained. For example, as mentioned above, the uncertainty in viscosity of enstatite from reported studies varies by 3 orders of magnitude, and different conclusions can be drawn by comparing with its lower and upper bounds. Several recent experimental studies have shown that opx may be weaker than olivine, at least in the shallow lithosphere (Raterron et al., 2016; Zhang et al., 2017). If the rheological strength of opx is lower than that of olivine, the role played by opx in geodynamic processes should not be overlooked because of its abundance.

It has been well documented that the rheological properties of mantle rocks can be strongly affected with the presence of even a trace amount of water (e.g., Chopra & Paterson, 1984). For opx, the effect of water on its diffusion creep was investigated by Zhang et al. (2017). The water effect on its dislocation creep, however, has not been reported. To make up for this gap, in this study, we conducted compressive creep experiments on polycrystalline samples of enstatite (commonly used to represent opx) using a gas medium apparatus under both water-saturated and anhydrous conditions. At these pressure and temperature conditions, all experiments were performed in the phase stability field of orthoenstatite. Based on our experimental results, the effect of water on the rheological properties of opx and the strength contrast between olivine and opx were analyzed.

2. Experimental Details

2.1. Sample Preparation and Assembly

Samples were prepared from powdered natural enstatite from Bamble, Norway. Based on electron microprobe analyses, the chemical composition of the enstatite is approximately (Mg$_{0.85}$Fe$_{0.14}$Al$_{0.005}$Ca$_{0.005}$)SiO$_3$ (Zhang et al., 2017). To prepare samples for deformation experiments, enstatite powders with particle sizes ranging from 15 to 25 μm were first cold-pressed hydraulically at ~125 MPa into nickel capsules and then hot-pressed using a gas medium apparatus at 300 MPa and 1473 K for 3 hr.

Two kinds of samples, dry and wet, were prepared for anhydrous and hydrous experiments, respectively. For preparing dry samples, enstatite powders were cooked in a 1-atm furnace at 1173 K for 4 hr with oxygen fugacity controlled near the Ni/NiO phase boundary. While preparing wet samples, we added ~75 mg of deionized water to the enstatite powders (~2.7 g) during the process of cold pressing. Because the dependence of water solubility on pressure for olivine has been well established, oriented olivine single crystals were embedded into the samples (except for PI-1891, PI-1896, and PI-1922) to help evaluate the water saturation level of experiments, especially for those conducted under hydrous conditions.

The sample assembly was specially designed for hydrous experiments to ensure a water-saturated condition. A hot-pressed sample of cylindrical shape, wrapped with 25-μm-thick nickel foil for buffering the oxygen fugacity, was inserted into a sleeve composed of two talc rings separated by a nickel ring; each ring was approximately one third the length of the sample. There, talc, which dehydrates at a temperature of ~1075 K for a confining pressure of 300 MPa, serves for supplying water for the sample during deformation. After dehydration, talc transfers into enstatite and quartz. Because of dehydrated talc’s strength, the load applied to the sample could be unexpectedly shared by the dehydrated talc sleeve, which will complicate the stress distribution within the sample. To avoid this, a nickel ring was placed between those two talc rings. This ensures that (1) any load supported by the sleeve would lead the deformation of the nickel part because the strength of nickel would be much weaker than that of dehydrated talc at high temperatures and (2) the
load, if any, supported by the nickel ring could be estimated for necessary correction because the flow behavior of nickel has been well quantified (Frost & Ashby, 1982).

2.2. Deformation Experiments
Compressive creep experiments were conducted in a stepwise fashion using a servo-controlled, internally heated gas medium apparatus (Paterson, 1990). Specifically, multistep creep experiments were conducted in one run, by varying load and/or temperature, and each step was conducted under different designated thermodynamic conditions. Typically, in each step, the creep rate reaches a constant when the deformation strain of the sample reaches ~1%. Experimental procedures of such step-loading experiments conducted in gas medium apparatuses are detailed in literature (Hirth & Kohlstedt, 1995; Mei & Kohlstedt, 2000a, 2000b).

2.3. Analysis Techniques
2.3.1. Analyses of Microstructure
The microstructure of both hot-pressed and deformed samples was analyzed by an electron probe microanalyzer (EPMA) integrated with back-scattered electron (BSE) detectors and by scanning electron microscopy (SEM) using orientation contrast and electron backscatter diffraction (EBSD) techniques. For these analyses, thin pieces of samples were first cut from a sample column along the cylindrical axis then polished with diamond lapping films of grit size down to ~0.5 μm and further with SYTON fluid (0.05-μm colloidal silica) for ~3 hr. EPMA and BSE analyses were used to determine mineralogical components of the samples and the chemical composition of each mineral. SEM analyses provide information on the grain size distribution and microstructural evolution during deformation.

2.3.2. Analyses of Phase
Enstatite has three polymorphs at low pressure (<1 GPa): low-temperature clinoenstatite, orthoenstatite, and protoenstatite. At ambient pressure, Mg-enstatite transforms from low-temperature clinoenstatite into orthoenstatite at a temperature above ~550 °C (Anastasiou & Seifert, 1972) and then further into protoenstatite at a temperature above ~985 °C (Atlas, 1952). The temperature of transformation from orthoenstatite to protoenstatite increases with increasing pressure, and the phase boundary moves to higher temperature with the incorporation of Fe in enstatite (Bystricky et al., 2016). To examine whether there is any phase modification during our experiments, X-ray diffraction (XRD) analyses were performed on the starting enstatite powder and on the sample before and after deformation using a Rigaku–MiniFlex diffractometer with a cobalt target. The XRD data were collected over a 2θ range of 40–160° with a step size of 0.02° at a scanning speed of 0.5°/s. In addition, EBSD analyses performed on both hot-pressed and deformed samples provide supporting information for phase identification.

2.3.3. Analyses of Water Contents
Infrared absorption spectra were collected with a Bruker Tensor 37 Fourier transform infrared (FTIR) spectrometer. Thin sections of enstatite aggregates and embedded olivine single crystals from each experiment were double-polished to a thickness of 200–300 μm with diamond lapping film down to a 1-μm finish for FTIR absorption measurements. During the FTIR measurements, to avoid the influence of moisture from the air, a continuous stream of dried air was used to purge the sample chamber of the microscope. All the infrared spectra were obtained in a wavenumber range of 2,400–4,000 cm⁻¹ using 256 scans with a resolution of 2 cm⁻¹. With an aperture of 60 × 60 μm², FTIR spectra were collected from five spots from the center to the edge of each sample. Water contents in the experimental samples were computed by integrating infrared absorption intensities ranging from 3,000 to 3,750 cm⁻¹ using the Paterson (1982) calibration in the following form:

\[
C_{OH} = \frac{\Omega}{150\xi} \int \frac{H(\nu)}{(3,780-\nu)} d\nu,
\]

where \(C_{OH}\) is the hydroxyl content in H/10⁶ Si; \(\Omega\) is the molar volume (4.4 × 10⁴ mm³/mol for olivine and 6.3 × 10⁴ mm³/mol for enstatite); the orientation factor \(\xi\) is 1/2 and 1/3 for unpolarized spectra from single crystals and polycrystalline samples, respectively; and \(H(\nu)\) is the absorption coefficient at wavenumber \(\nu\).

2.3.4. Analyses of Mechanical Data
Values of load, displacement, temperature, and pressure versus time data were collected every second during each deformation experiment. Differential stress was determined from the applied load and corrected for the
load supported by the iron jacket, nickel capsule, and nickel ring based on the published flow laws of iron and nickel (Frost & Ashby, 1982). The strain rate was determined from displacement versus time data. Previous theoretical treatments and experimental observations demonstrate that dislocation creep of rocks under hydrous conditions can be well described by a flow law in which the strain rate ($\dot{\varepsilon}$) is a function of differential stress ($\sigma$), water fugacity ($f_{H_2O}$), confining pressure ($P$), and temperature ($T$):

$$\dot{\varepsilon} = A\sigma^n f_{H_2O}^r \exp\left(-\frac{E+PV}{RT}\right),$$  \hspace{1cm} (2)

where $A$ is a material-dependent parameter, $n$ is the stress exponent, $r$ is the water fugacity exponent, $E$ is the activation energy, $V$ is the activation volume, and $R$ is the gas constant. The values of $n$ reflect indicatively the rate-controlling processes of deformation; $n \approx 3$ is commonly applied for climb-controlled dislocation creep (Weertman & Weertman, 1975).

Because all of our experiments were conducted at a confining pressure of 300 MPa, the value of the $PV$ term in equation (2) is constant and relatively small. (Based on Raterron et al. (2016), the value of the $PV$ term is less than 2% of the value of $E$ at a pressure of 300 MPa.). Consequently, the $PV$ term can be incorporated into the activation energy as an apparent activation energy $Q$. Moreover, at a constant confining pressure and over a narrow change of temperatures, the variation of water fugacity, which is a function of temperature and pressure, is limited: from 313 to 325 MPa as temperature increases from 1373 to 1473 K at a pressure of 300 MPa (Pitzer & Sterner, 1994). As the variation in the value of water fugacity in our experiments is too narrow to quantify the water fugacity exponent ($r$), the $f_{H_2O}$ term that remains approximately a constant is incorporated into $A$. Equation (2) can then be simplified as follows:

$$\dot{\varepsilon} = A\sigma^n \exp\left(-\frac{Q}{RT}\right).$$  \hspace{1cm} (3)

3. Experimental Results

3.1. Microstructural Characterization

Based on EPMA and BSE analyses, the starting material consists of almost pure enstatite with less than 1% olivine by volume (supporting information Figure S1). There were no noticeable amounts of any other mineral phases or melt observed in our hot-pressed samples. Orientation contrast SEM images reveal that the grain size of dry samples (Figures S2b and S2d) is finer than that of wet samples (Figures S2a and S2b), and there were no significant changes in grain sizes during deformation under both hydrous and anhydrous conditions.

3.2. Phase Stability

XRD spectra obtained from enstatite samples before and after the experiments were highly similar and nearly identical to the standard XRD pattern of orthoenstatite (Figure S3), implying that our experiments were conducted in the orthoenstatite stability field and that no phase transition occurred before and after deformation. Moreover, in the EBSD analyses, all Kikuchi patterns acquired from scanning hot-pressed and deformed samples match the standard Kikuchi pattern of orthoenstatite rather than protoenstatite or clinoenstatite, further demonstrating that no phase transition occurred during the experiments. Based on the phase diagram from Gasparik (2014, Figure 2.1), under a pressure of 300 MPa, pure Mg-enstatite can be transformed into protoenstatite when $T \geq 1423$ K. However, with the incorporation of iron into enstatite, the stability regime of orthoenstatite shifts toward higher temperature. For example, the phase transition temperature of enstatite with a composition of (En91Fs9) is ~1523 K at 300 MPa (Bystricky et al., 2016, Figure 1). As the enstatite used in this study (En85Fs14) has a higher iron content, it is reasonable that, at experimental conditions of $T \leq 1473$ K and $P = 300$ MPa, our enstatite samples were deformed in the orthoenstatite stability field.

3.3. Water Content

FTIR spectra obtained from deformed enstatite aggregates and olivine single crystals embedded in deformed samples are shown in Figure S4. The calculated water contents of enstatite aggregates from deformation...
experiments performed under hydrous conditions are in the range of 2,760–5,120 H/10^6 Si (Table 1). For deformation experiments performed under anhydrous conditions, the water contents of enstatite aggregates are only ~100 H/10^6 Si.

To evaluate the water saturation level in the experiments, water contents of embedded olivine single crystals from hydrous experiments were carefully examined. The water contents of embedded olivine single crystals from the hydrous experiments (PI-1922, PI-1912, PI-1991, PI-1904, PI-1940, and PI-1946) are approximately 320, 310, and 340 H/10^6 Si at temperatures of 1373, 1423, and 1473 K, respectively, while the water contents of embedded olivine single crystal from anhydrous experiments are below the detection limits of the FTIR spectrometer. Comparing water contents in our deformed samples with the published results of water solubility in olivine as a function of water fugacity, temperature, pressure, and iron content (Zhao et al., 2004) shows that our hydrous experiments were performed under water-saturated conditions.

3.4. Mechanical Results

Two groups of experiments, one under hydrous conditions and the other under anhydrous conditions, were conducted on enstatite aggregates. The results from 50 creep tests conducted on eight samples are summarized in Table 1.

Creep data, plotted as stress versus strain rate on log-log axes in Figures 1a and 1b, exhibit an approximately linear relationship for each temperature under both hydrous and anhydrous conditions. Linear least squares fits to those data obtained from three different temperatures yield a stress exponent of $n = 3.0 \pm 0.4$, indicating that samples were deformed in the dislocation creep regime.
Because the experiments were conducted at different temperatures under both hydrous and anhydrous conditions, activation energies for creep at each case were determined to evaluate the effect of temperature on the strain rate. In the Arrhenius plot of log strain rate versus inverse temperature for the creep of enstatite

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<th>P (MPa)</th>
<th>Stress (MPa)</th>
<th>Strain (%)</th>
<th>Strain rate (s(^{-1}))</th>
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<th>(C_{\text{H}_2\text{O}}^{\text{enstatite}}) (H/10(^6) Si)</th>
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(see Figures 1c and 1d), data obtained at different stresses were normalized to 200 MPa using $n = 3$. Linear least squares fits to the data yield activation energies of 603 ± 54 and 567 ± 39 kJ/mol for hydrous and anhydrous conditions, respectively.

With a known stress exponent ($n = 3$) and activation energies for both hydrous and anhydrous conditions, nonlinear least squares fits to data with equation (3) yield $A_{\text{wet}} = 1.1 \times 10^{11} \text{s}^{-1} \text{MPa}^{-3}$ and $A_{\text{dry}} = 9.2 \times 10^7 \text{s}^{-1} \text{MPa}^{-3}$ for hydrous and anhydrous conditions, respectively. Therefore, the flow laws for enstatite obtained from this study are as follows:

\begin{align*}
\text{hydrous conditions: } \dot{\varepsilon} &= 1.1 \times 10^{11} \times \sigma^3 \exp \left( \frac{-603}{RT} \right), \quad (4) \\
\text{anhydrous conditions: } \dot{\varepsilon} &= 9.2 \times 10^7 \times \sigma^3 \exp \left( \frac{-567}{RT} \right). \quad (5)
\end{align*}

4. Discussion

4.1. Effect of Water on the Creep of Enstatite

To evaluate the effect of water on the creep behavior of enstatite, creep results of enstatite determined under hydrous conditions were compared to those obtained under anhydrous on a log-log plot of stress versus strain rate in Figure 2a. Data obtained at different temperatures for each case are normalized to 1373 K using equations (4) and (5), respectively. As illustrated in Figure 2a, at a given stress, under hydrous conditions, the sample crept at a rate that was a factor of ~50 greater than that under anhydrous conditions, indicating that water has a strong water-weakening effect on the creep of enstatite aggregates.

An explanation for the physical processes responsible for the water-weakening effect can be proposed based on point defect chemistry. In theory, at high temperatures ($T \geq 0.75T_m$), dislocation creep of a solid (such as a mineral) proceeds in a mode of climb-controlled dislocation movement. Hence, strain results from dislocation slip while the strain rate is controlled by dislocation climb, which, in turn, is controlled by the diffusivity of the slowest species in the solid. In addition, the formations of kinks and jogs on dislocation lines will promote the slip of dislocations, and the increase of the concentration of the rate-limiting species in the solid will enhance the diffusivity of the species and thus the climb of dislocations.

In previous studies, Mei and Kohlstedt (2000b) worked out, based on point defect chemistry, a framework for explaining how water enhances the creep of olivine under hydrous conditions. In their analyses, under hydrous conditions, water-derived point defects enter into olivine and, once they become major defects, modify the concentrations of intrinsic point defects including that of kinks and/or jogs. In this way, the dependence of the creep rate of olivine on water fugacity revealed from experiments can be successfully explained because the concentration of intrinsic point defects including kinks and jogs, essential elements contributing to deformation, is water fugacity dependent under hydrous conditions.

Because olivine and enstatite both belong to an orthorhombic-dipyramidal crystal system and consist of the same elements, they have similar point defect chemistry (Zhang et al., 2017). Hence, it is reasonable to speculate that the effect of water on the creep of enstatite results possibly from (1) increasing the diffusivity of its rate-limiting species by increasing its concentration and/or (2) promoting the formation of kinks and jogs along dislocation lines for enhancing dislocation slip.

4.2. Comparison to Other Studies

Previous studies on the creep of enstatite have been plagued by either the rather low working pressures of 1 atm and gas medium deformation rigs or by the limited resolution of stress and strain in solid-medium deformation rigs. In the former, enstatite could be transformed from orthoenstatite to protoenstatite at $T \geq 1273$ K when $P = 0.1$ MPa (Ji et al., 2001; Mackwell, 1991) or at $T > 1473$ K when $P = 300$ MPa (Bystricky et al., 2016). For iron-bearing enstatite, the transition temperature can increase with increasing iron content (Bystricky et al., 2016). Hence, the temperature in this study was limited to below 1473 K, and the phase of the sample was carefully analyzed before and after deformation. In the latter, though the solid-medium...
Figure 2. Comparisons of results. (a) Dislocation creep results for enstatite under hydrous (blue) and anhydrous conditions (pink) from this study. Data obtained at different temperatures were normalized to 1373 K. The solid lines show the flow laws of enstatite obtained under hydrous conditions (equation (4)) and anhydrous conditions (equation (5)). (b) Dislocation creep results for enstatite under anhydrous conditions for this study and previous studies. The results obtained from different studies were normalized to $T = 1373$ K and $P = 300$ MPa. Results for polycrystalline enstatite are denoted by solid lines, and those for single crystalline enstatite by dash lines. (c) Dislocation creep results for enstatite from this study (solid lines) along with those for olivine (dashed lines) from Hirth and Kohlstedt (2003) (H&K) under hydrous and anhydrous conditions. Results of all studies were normalized to $T = 1373$ K and $P = 300$ MPa. As illustrated, under both anhydrous and hydrous conditions, the creep strength of enstatite is weaker than that of olivine.
deformation rig provides sufficiently high pressure to ensure the stability field of enstatite in a wide range of temperature, the poor resolution of stress and strain results in large systematic error in the results. In addition to the issues of phase stability and measurement resolution mentioned above, owing to a strong water effect, any presence of water in samples under anhydrous conditions from previous studies would add another layer of complication in interpreting the discrepancy among results from different studies.

Because most of the previous studies on the creep of enstatite have been performed under anhydrous conditions, we can only compare our results obtained under anhydrous conditions with those previously reported, as shown in Figure 2b. Data from Raleigh et al. (1971), Ross and Nielsen (1978), Raterron et al. (2016), and Bystricky et al. (2016) were normalized to $P = 300$ MPa and $T = 1373$ K based on their published flow laws. Because there is no available activation volume for dislocation creep of polycrystalline enstatite, an activation volume of $V = 13.6$ cm$^3$/mol, which was quantified by Raterron et al. (2016) for dislocation creep of single-crystal enstatite via the $(100)[001]$ slip system, was chosen to normalize the data for creep of polycrystalline enstatite from different studies. This choice is reasonable because the creep of polycrystalline enstatite tends to the $(100)[001]$ slip system (Bystricky et al., 2016; Ross & Nielsen, 1978). As shown in Figure 2b, the line representing the flow law of polycrystalline enstatite lies reasonably in between those two dashed lines denoting flow laws of single crystalline enstatite, one with the operation of the easiest slip system $(100)[001]$ and the other with that of the hard slip system $(010)[001]$. Among polycrystalline enstatite samples, the creep strength of our sample is weaker than that from Bystricky et al. (2016) but stronger than that from those two pioneering studies (Raleigh et al., 1971; Ross & Nielsen, 1978). In the former, the discrepancy between our results and Bystricky et al.’s may be related to the different iron content in the samples. The iron content of our samples $(En_{85}Fs_{14})$ is higher than that of their samples $(En_{91}Fs_{9})$, and the higher the iron content, the weaker the creep strength. This conclusion is consistent with the observation that the creep strength of olivine decreases with increasing iron content (Tasaka et al., 2015; Zhao et al., 2009). In the latter, there may be several reasons responsible for the discrepancy among our results and the two pioneering studies. First, both pioneering studies were undertaken using a Griggs solid-medium apparatus, which has a poor measurement resolution, especially in the early stage. Second, both used natural enstatite rocks as samples without predrying. In that case, even if the experiments were conducted under “anhydrous” conditions, the results might be influenced by the presence of even a trace amount of water in their natural samples. As shown in Figure 2b, the creep strength of their polycrystalline enstatite is even weaker than that of single crystal enstatite operating with the easiest slip system. It is difficult to explain this result without considering the weakening effect of water.

To estimate the rheology contrast between olivine and enstatite, we compared our results on enstatite aggregates in the dislocation creep regime with the flow laws of olivine aggregates from Hirth and Kohlstedt (2003) at a confining pressure of 300 MPa and a temperature of 1373 K. As illustrated in Figure 2c, under both anhydrous and hydrous conditions, the creep strength of enstatite is weaker than that of olivine. For example, at a stress of 150 MPa, creep rates of enstatite are a factor of ~4 greater than that of olivine under both hydrous and anhydrous conditions. This result is consistent, to some extent, with that of Raterron et al. (2016), who suggested that the enstatite easy slip system $(100)[001]$ is weaker than the olivine easy slip system $(010)[001]$ in the shallow lithosphere (at a depth less than 60 km, with pressure lower than 2 GPa). Though deformation of polycrystalline material may involve more than one slip system including both easy and hard slip systems, several studies (Bystricky et al., 2016; Ross & Nielsen, 1978) indicated that the deformation of polycrystalline enstatite favors mainly its easy slip system $(100)[001]$. Thus, it is not impossible that polycrystalline enstatite can be weaker than polycrystalline olivine in a certain range of pressure (for instance, $P < 2$ GPa) if both enstatite and olivine favor their easy slip system during dislocation creep.

The rheological properties of solids depend on numerous thermodynamic parameters (e.g., temperature and pressure), mechanical conditions (e.g., stress), and the chemical environment (e.g., water fugacity and oxygen fugacity). At present, several important parameters including activation volume and the water fugacity index of enstatite have not been well constrained. Under this circumstance, it is still too early to infer which (olivine or enstatite) is weaker under a wide range of upper mantle pressure and temperature conditions. Moreover, the dependence of the water solubility of enstatite on pressure and/or temperature (Mierdel et al., 2007; Mierdel & Keppler, 2004) being remarkably different from that of olivine (Kohlstedt et al., 1996; Zhao et al., 2004) adds another layer of complexity on such comparisons.
5. Conclusions

Creep experiments were conducted under both hydrous and anhydrous conditions to reveal the effect of water on the rheological properties of enstatite. Through analyses, experiments were conducted in the orthoenstatite stability field. Under our experimental conditions, samples of enstatite aggregates under water-saturated conditions creep at a rate that was a factor of ~50 greater than that under anhydrous conditions, indicating a strong water-weakening effect. This result, which is the first determination of the water effect on the dislocation creep of enstatite, provides more robust constraints on the flow behavior of the upper mantle, especially in the hydrous and opx-rich pyroxenite regions within Earth’s interior.

Acknowledgments

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References


