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Superplasticity in hydrous melt-bearing dunite: Implications for shear localization in Earth's upper mantle

OHUCHI, Tomohiro[1*], NISHIHARA, Yu[2], KAWAZOE, Takaaki[1], SPENGLER, Dirk[3], SHIRAISHI, Rei[4], SUZUKI, Akio[4], KIKEGAWA, Takumi[5], OHTANI Eiji[4]

[1]Geodynamics Research Center, Ehime University, [2]Senior Research Center, Ehime University, [3]Institute of Earth and Environmental Sciences, Potsdam University, [4]Department of Earth and Planetary Materials Science, Graduate School of Science, Tohoku University, [5]Photon Factory, High Energy Accelerator Research Organization

The rheological properties of olivine, the major constituent mineral in Earth's upper mantle, control the dynamics of the upper mantle. Many experimental studies have been performed on the plastic flow behaviors of olivine at high temperatures (i.e., temperatures at the upper mantle) and low pressures ($<$ 0.5 GPa) (e.g., Durham and Goetze, 1977). Previous studies showed that the plastic flow of olivine at high temperatures (T $>$ 1500 K) is controlled by two creep mechanisms, power-law dislocation creep and diffusion creep (e.g., Karato et al., 1986). Some authors argued that other creep mechanisms such as dislocation-accommodated grain boundary sliding and diffusion-accommodated grain boundary sliding also play an important role in the upper mantle (e.g., Hirth and Kohlstedt, 1995). Both of them (dislocation- and diffusion-accommodated grain boundary sliding) are often termed as superplasticity. It has been reported that superplasticity may dominate the plastic flow of minerals in some parts of the Earth (glaciers: Goldsby and Kohlstedt, 2001; shear zones in the lower crust: e.g., Behrmann and Mainprice, 1987; shear zones in the upper mantle: Hiraga et al., 2010; lower mantle: Karato et al., 1995).

It has been reported that intergranular melt/fluid phases decrease the creep strength of olivine. In the olivine-basalt system, power-law dislocation creep and diffusion creep are enhanced by the presence of a melt phase (Mei et al., 2002). Moreover, it has been reported that grain boundary sliding (GBS) dominates the deformation of olivine in the olivine-basalt system with a high volume fraction of melt ($>$ 4 vol.%) (Hirth and Kohlstedt, 1995). Similar observations have been reported in aqueous fluid-bearing peridotites (McDonnell et al., 2000). It is known that the dihedral angle between olivine and fluid decreases with pressure (Mibe et al., 1999; Yoshino et al., 2007), which shows a reduction in the solid-solid grain boundary area with increase in pressure. Thus, a significant weakening of olivine aggregates by addition of fluids is expected at high pressures. However, the effects of intergranular fluids on the creep strength of olivine aggregates have not been evaluated at high pressures (pressure range in previous studies: 0.3-0.6 GPa).

In order to explore the rheological properties of fluid-bearing dunite (i.e., olivine aggregate) under the conditions of Earth's upper mantle, we conducted deformation experiments on hydrous melt-bearing dunite (olivine + 4 vol.% orthopyroxene + 4 vol.% clinopyroxene with less than 2.5 vol.% of the melt phase) were conducted at pressures of 1.3-5.7 GPa and temperatures of 1270?1490 K. The strain rate was proportional to steady-state creep strength to the 2.1 power, and the creep strength markedly increased with increase in grain size. Developments of the crystallographic preferred orientation of olivine and flattening of olivine grains were hardly observed even after 33?55 % shortening of the samples. These observations show that grain boundary sliding (GBS) dominated the deformation of olivine (i.e., superplasticity). The creep strength of hydrous melt-bearing dunite was 2?5 times lower than that of melt-free dunite. Superplasticity is the dominant creep mechanism of olivine in fluid-bearing fine-grained peridotites under low-temperature and high-stress conditions (i.e., peridotite shear zones in the upper mantle). Superplasticity induced by geological fluids would play an important role in the shear localization (and thus initiation of subduction) in the upper mantle.

Keywords: olivine, hydrous melt, grain boundary sliding, superplasticity, shear localization, subduction