Superplasticity in Hydrous Melt-Bearing Dunite and its Implications for Shear Localization in the Earth's Upper Mantle

In order to explore the effect of intergranular fluids on the plastic flow of olivine in the Earth's upper mantle, deformation experiments on hydrous melt-bearing dunite were conducted under the conditions of the upper mantle (pressure: 1.3-5.7 GPa; temperature: 1270-1490 K). Superplasticity dominated the deformation of olivine, and 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 at low temperatures. Therefore, geological fluids are likely to play an important role in the shear localization and thus the initiation of subduction in the upper mantle.

Olivine is the major constituent mineral in the Earth's upper mantle and controls its dynamics. Many experimental studies have been performed on the plastic flow behavior of olivine at high temperature (i.e., the temperatures in the upper mantle). Previous studies showed that the plastic flow of olivine at high temperature is controlled by two creep mechanisms: power-law dislocation creep and diffusion creep [1]. 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. Both of these mechanisms are often called "superplasticity" [2].

It has been recognized that the dynamics of the asthenospheric upper mantle need to be discussed based on the rheology of hydrous olivine rather than on anhydrous olivine. Not only dissolved water but also intergranular melt/fluid phases decrease the creep strength of olivine. In the olivine-basalt and olivine-aqueous fluid systems, power-law dislocation creep and diffusion creep are enhanced by the presence of a melt/fluid phase [3, 4]. However, the effects of intergranular fluids on the creep strength of olivine aggregates have not been evaluated at the pressures found in the Earth's upper mantle (pressure range in previous studies: 0.3-0.6 GPa).

Based on deformation experiments on hydrous melt-bearing dunite (92 vol.% of olivine and 8 vol.% of pyroxenes with less than 2.5 vol.% of the melt phase) under the conditions of the Earth's upper mantle, we showed that superplasticity is an important creep mechanism for the deformation of fluid-bearing peridotites in the upper mantle [5]. We conducted deformation experiments on hydrous melt-bearing dunite at pressures of 1.3-5.7 GPa, temperatures of 1270-1490 K, and a constant strain rate (in the range of $0.7\text{-}8.2\times10^{-5}$ s^{-1}) using a deformation-DIA apparatus (D-CAP) installed in MAX-III at the AR-NE7A beamline. Strain of the samples was measured by the distance between two platinum strain-markers which were monitored by using *in-situ* monochromatic X-ray radiography (Fig. 1). Axial differential stress and generated pressure were measured by using the radial diffraction of monochromatic X-rays (energy 50 keV, wavelength 0.245 Å). See [5] for the details of the experiments.

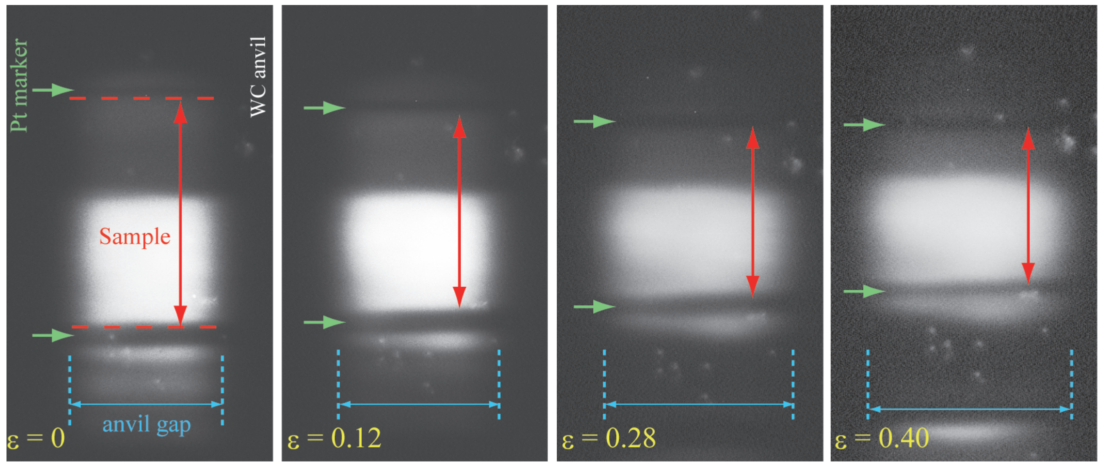

Figure 1: X-ray radiographs acquired before (ε = 0) and during the deformation (ε = up to 0.40) at 1.7 GPa and 1370 K. Positions of platinum strain markers (black lines) are shown by green arrows. Blue and red double arrows represent the anvil gap and the range of sample, respectively. ε represents the sample strain.

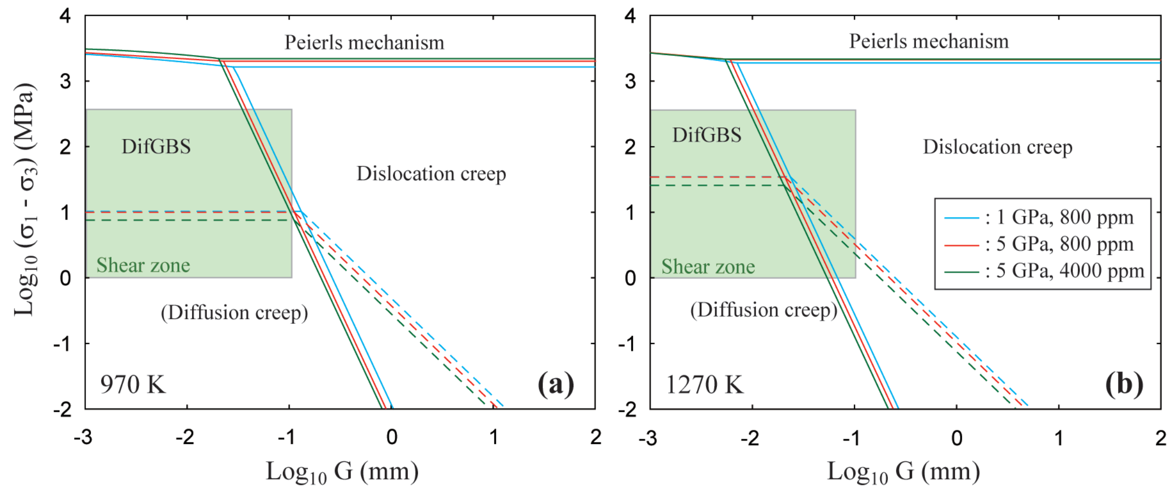

Figure 2: Deformation mechanism maps for olivine in the hydrous melt-bearing dunite at pressures of 1 and 5 GPa and temperatures of (a) 970 K and (b) 1270 K. Water content in olivine was fixed at 800 or 4000 ppm H/Si for calculating the maps. The solid lines represent the boundaries between deformation fields (DifGBS: diffusion-accommodated GBS). Because diffusion creep of olivine has not been reported in fluid-bearing dunite, the diffusion creep dominant region is hypothetically shown by dashed lines. The green-shaded area in (a) and (b) represents the conditions observed in natural peridotite shear zones [7]. $\sigma_1 - \sigma_3$: differential stress; *G*: grain size.

The strain rate was proportional to steady-state creep strength to the 2.1 power, and the steady-state creep strength was proportional to grain size to the ~3 power. The activation energy of the deformation was found to be 329 kJ/mol. This value is close to the activation energy for diffusion creep of "wet" olivine (295 kJ/mol: [6]), suggesting that the creep mechanism is mainly controlled by the diffusion process. These results show that the dominant deformation mechanism of olivine is diffusion-accommodated grain boundary sliding (i.e., superplasticity). The creep strength of the melt-bearing samples was factors of 2-4 lower than that of olivine controlled by the power-law dislocation creep of hydrous olivine in the case of the same water content. Deformation mechanism maps of hydrous-melt bearing dunite as a function of stress and grain size under mantle wedge conditions are shown in Fig. 2. The region of diffusion-accommodated grain boundary sliding (GBS) is distributed in the area of fine-grain (< 0.1 mm) and high-stress (> 10 MPa) conditions. The diffusion-accommodated GBS field expands with decrease in temperature. Therefore, diffusion-accommodated GBS would be the dominant creep mechanism of olivine in fluid-bearing fine-grained peridotites under the conditions of low temperature and high stress (i.e., mylonites in shear zones). In fact, many petrological observations have shown that grain-size-sensitive creep processes promote strain localization in fine-grained mylonites in shear zones [7]. Shear localization caused by the diffusion-accommodated GBS is expected to play an important role in the initiation of subduction of the oceanic lithosphere.

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