Earth and Planetary Science Letters 335–336 (2012) 59–71

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

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

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ARTICLE INFO

Article history:
Received 15 June 2011
Received in revised form
1 April 2012
Accepted 23 April 2012
Editor: T. L. Stixrude
Available online 14 June 2012

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

ABSTRACT

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 in order to explore the effect of intergranular fluids on the plastic flow of olivine in Earth's upper mantle. 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. The dependence of creep rate on melt fraction is known to be expressed empirically as $\dot{\varepsilon}(\phi)=\dot{\varepsilon}(0)\ \exp(\alpha\phi)$, where α is a constant and ϕ is the melt fraction. The experimentally obtained value of α was in the range of 150–230, corresponding to 5–7 times the reported values for the olivine–basalt system at 0.3 GPa (i.e., creep strength of dunite was efficiently reduced by the hydrous melt). 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.

1. Introduction

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, 1995a). 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., 2010a, b; lower mantle: Karato et al., 1995). Although superplasticity is classically defined phenomenologically as the ability of a material to be deformed under tension to large strains ($\gg 100\%$), the term "superplasticity" has been used as the meaning of the mechanism of deformation which appears to be the same as dislocation- and diffusion-accommodated grain boundary sliding in the Earth science community (e.g., Goldsby and Kohlstedt, 2001). We use the term "superplasticity" as the meaning of the deformation mechanisms.

Plastic flow of minerals at high temperatures is usually described as shown below:

$$\dot{\varepsilon}=A\frac{\sigma^n}{G^p}f_{H_2O}^r\ \exp\left(-\frac{E^*+PV^*}{RT}\right) \quad (1)$$

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http://dx.doi.org/10.1016/j.epsl.2012.04.032

where $\dot{\varepsilon}$ is the strain rate; A a pre-exponential constant; f_{H_2O} the water fugacity; σ the differential stress ($=\sigma_1-\sigma_3$); n the stress exponent; G the grain size; p the grain size exponent; E^* the activation energy; V^* the activation volume; P the pressure; T the temperature; and R the gas constant (e.g., Mei and Kohlstedt, 2000a). Eq. (1) shows that activation volume (V^*) is an important parameter controlling the creep strength of minerals at high pressures. The effects of pressure on the plastic flow of minerals become significant when pressure exceeds a few percent of the bulk modulus of a given material (e.g., Karato and Jung, 2003). Recently, new types of deformation apparatuses such as the rotational Drickamer apparatus (RDA: Yamazaki and Karato, 2001) and deformation-DIA apparatus (D-DIA: Wang et al., 2003) have been developed, and many experimental studies on the V^* of "dry" olivine have been conducted (e.g., Li et al., 2006; Durham et al., 2009; Kawazoe et al., 2009).

It has been recognized that a significant amount of water is distributed in the asthenospheric upper mantle (e.g., 810 ± 490 ppm H/Si: Hirth and Kohlstedt, 1996), showing that the dynamics of the asthenospheric upper mantle needs to be discussed based on the rheology of hydrous olivine rather than on anhydrous olivine. Despite the importance of hydrous olivine in upper mantle rheology, the effects of pressure on the creep of hydrous olivine have not been fully investigated. The creep strength of olivine is drastically decreased by the effect of water (i.e., dissolved water in olivine) (e.g., Chopra and Paterson, 1984). Mei and Kohlstedt (2000a) conducted deformation experiments on olivine at 0.1–0.45 GPa and 1473–1573 K under water-saturated conditions and obtained values of V^* for the diffusion creep of hydrous olivine as 0 and 20 cm^3/mol in the case of $r=0.7$ and 1, respectively (because of narrow pressure ranges, they were unable to determine r and V^* uniquely). Similarly, Mei and Kohlstedt (2000b) obtained the values of V^* for the power-law dislocation creep of hydrous olivine as 4, 20, and 38 cm^3/mol in the case of $r=0.75$, 1, and 1.25, respectively. Karato and Jung (2003) determined the value of V^* for the power-law dislocation creep of hydrous olivine as 24 cm^3/mol from the experimental data obtained at 0.3–2 GPa.

Not only dissolved water but also 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, 1995a). 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 have developed experimental techniques for deformation experiments under wet conditions using a D-DIA apparatus (Ohuchi et al., 2010a). In this study, we used palladium–silver capsules for deformation experiments and succeeded in conducting measurements of in-situ strain and stress values of olivine in hydrous melt-bearing dunite at high pressures (1.3–5.7 GPa) and high temperatures ($T=1270$–1490 K). Here we show that superplasticity is an important creep mechanism for the deformation of fluid-bearing peridotites in the upper mantle. The superplasticity of olivine, which is caused by the addition of fluids to peridotite shear zones, promotes shear localization in the upper mantle resulting in the initiation of subduction.

2. Experimental procedure

2.1. Starting materials

The starting material for dunite was prepared from a mixture of powdered San Carlos olivine (Fo_{90})+8 wt% pyroxenes (clinopyroxene: 4 vol%; orthopyroxene: 4 vol%: Bancroft, Canada). Pyroxenes were added to generate partial melt and to inhibit the grain growth of olivine. The fine-grained mixed powder was placed into a nickel capsule and was sintered at 4.0 GPa and 1373 K for 1.5 h using a Kawai-type multi-anvil high-pressure apparatus (Orange 3000) at Ehime University. The entire cell assembly for the synthesis of dunite was not dried before the sintering experiment in order to provide moisture to the powders. The synthesized dunite (OT-821) consists of 92 vol% of olivine and 8 vol% of pyroxenes (clinopyroxene: 4 vol%; orthopyroxene: 4 vol%). In order to remove water dissolved in the OT-821 sample, a part of the OT-821 sample (OT-821 F) was fired at 0.1 MPa and 1170 K under reducing conditions ($\log_{10} f_{O_2}\sim-16$ bar) for 6 h. The OT-821F sample was used for the deformation of melt-free dunite (TO-13). The dunite sample was core-drilled with a diameter of 1.2 mm and a length of 1.5 mm.

2.2. Deformation experiments

We conducted deformation experiments on dunite at pressures of 1.3–5.7 GPa, temperatures of 1270–1490 K, and strain rates of 0.7–8.2×10^{-5} s^{-1} using a deformation-DIA apparatus (D-CAP) at the AR-NE7A beam line of the Photon Factory (High Energy Accelerator Research Organization, Tsukuba, Japan). Details of the deformation-DIA apparatus and the beam line are described in Shiraishi et al. (2011). Two of the four sliding blocks on the down-stream side have a conical X-ray path (maximum 2θ angle $\sim10^\circ$). The MA-6-6 system, which consists of six second-stage anvils with truncated edge lengths (TEL) of 5 mm, an anvil guide, and cell assembly, was adopted for the experiments (e.g., Ohuchi et al., 2010a). Two X-ray transparent anvils, which were made from cubic boron nitride (cBN), were used for the second-stage anvils on the lower-stream side. The anvil guide was made of engineering plastic (columns along X-ray path) and stainless steel (other parts) (Kawazoe et al., 2011).

A sketch of the cell assembly used for the deformation experiments is shown in Fig. S1. The design of the cell assembly was based on Ohuchi et al. (2010a). A semi-sintered cobalt-doped magnesia ((Mg, Co)O) cube with an edge length of 7 mm was used as the pressure medium. A graphite heater was located at the inner bore of a tubular $LaCrO_3$ thermal insulator. Copper and molybdenum electrodes, hard alumina pistons, and machinable alumina rods were placed along the direction of the axial differential stress ($\sigma_1-\sigma_3$). Two X-ray transparent rods, which were made from a mixture of amorphous boron and epoxy, were placed along the X-ray path in the pressure medium. A cored sample of dunite (OT-821F for the TO-13 run; OT-821 for other runs) was placed into a palladium–silver (Pd75%–Ag25%) capsule and then sandwiched between two tungsten or single crystal diamond pistons (Table 1). Alumina pistons were used for the TO-13 run. Two platinum strain-markers, with a thickness of 20 μm, were placed between the sample and the pistons. About 15 wt% of distilled water was added to the palladium–silver capsule using a microsyringe (distilled water was not added to the TO-13 sample), and then the capsule was sealed with a