Physics of the Earth and Planetary Interiors 259 (2016) 34–44

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

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

Effect of pressure on the strength of olivine at room temperature

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ARTICLE INFO

Article history:
Received 24 November 2015
Received in revised form 11 July 2016
Accepted 22 August 2016
Available online 23 August 2016

Keywords:
Olivine
Rheology
Low-temperature plasticity
X-ray diffraction
High-pressure
Peierls stress
Yield strength

ABSTRACT

A fine grained fully-dense olivine aggregate was deformed in a D-DIA press at room temperature and pressures ranging from 3.5 to 6.8 GPa, at constant strain rates between 6×10^{-6} and 2.2×10^{-5} s^{-1}. A weighted non-linear least square fit of a dataset including our results and data from other high-pressure studies to a low-temperature plasticity flow law yields a Peierls stress $\sigma_P^0 = 7.4$ (0.5) GPa and an activation energy $E^* = 232$ (60) kJ.mol^{-1}. The dependence of the Peierls stress to pressure, $\sigma_P = \sigma_P^0 (1 + 0.09P)$, appears to be larger than the value predicted by the formulation proposed by Frost and Ashby (1982). With such a dependence, the activation volume is very small ($V^* = 1.6$ (1.7) cm^3.mol^{-1}). Extrapolation to natural conditions yields a viscosity of $\sim 10^{23} - 10^{24}$ Pa.s for a cold subducting slab at depths of 50–100 km.

1. Introduction

As the most abundant and possibly the weakest phase of the upper mantle, olivine has been the subject of a large number of experimental deformation studies performed either in the dislocation creep (*e.g.*, Carter and Avé Lallemant (1970), Chopra and Paterson (1984), Karato et al. (1986), Li et al. (2006), Keefner et al. (2011)), the diffusion creep (*e.g.*, Hirth and Kohlstedt (1995), Mei and Kohlstedt (2000), Nishihara et al. (2014)) or the dislocation-accommodated grain boundary sliding regime (Hansen et al., 2011; Ohuchi et al., 2015). However, while high-temperature creep mechanisms are typically considered the main deformation mechanisms in the bulk mantle, low-temperature plasticity may play an important role in the shallow upper mantle and may also control the rheology of subducting slabs (Karato et al., 2001). In particular the strength of olivine is a key parameter to determine the stress storage capacity of subducting rocks that may be released in deep earthquakes.

Because of the technical difficulties encountered when performing high stress deformation experiments, the low-temperature strength of olivine has rarely been studied. Evans and Goetze (1979) determined a low-pressure and low-temperature ($\leqslant 800$ °C) flow law for olivine from indentation experiments on single crystals. Recent innovating studies allowed the determination of a Peierls stress by room-temperature nanoindentation experiments (Kranjc et al., 2016) or by TEM nanomechanical testing (Idrissi et al., 2016). Katayama and Karato (2008) performed shear deformation experiments under wet conditions between 1000 and 1100 °C and at 2 GPa using a Griggs-type apparatus. In the same apparatus, Druiventak et al. (2011) focused on the evolution of the microstructure of a natural peridotite deformed in uniaxial compression as a function of temperature (between 25 and 600 °C) and pressure (between 1 and 3 GPa). Demouchy et al. (2013) deformed dry single crystals of San Carlos olivine in a gas-medium apparatus at a pressure of 300 MPa between 800 and 1090 °C. These latter authors predict a low strength for olivine at low temperature based on their own experimental results and on selected data from previous deformation studies performed on olivine single crystals (Phakey et al., 1972; Demouchy et al., 2009) and aggregates (Durham and Goetze, 1977; Evans and Goetze, 1979; Long et al., 2011).

Experiments at higher pressures were conducted by Meade and Jeanloz (1990) and Chai et al. (1998). In both studies, the shear strength of olivine was estimated by ruby spectroscopy in a Diamond Anvil Cell (DAC) at pressures up to 30 GPa and at room temperature. They observed an increase in strength from ~2–3 GPa at room pressure to ~7–9 GPa at a mean pressure of 30 GPa.

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http://dx.doi.org/10.1016/j.pepi.2016.08.004
0031-9201/

Thanks to the development of synchrotron high-pressure beamlines, X-ray diffraction can now be used to determine pressure and differential stress *in situ* (Uchida et al., 1996; Weidner et al., 1998; Singh et al., 1998). Consequently, high-pressure low-temperature rheology of olivine has been studied using the relaxation technique (DIA- and Kawai-type presses; Chen et al. (1998), Raterron et al. (2004), Yamamoto et al. (2008), Nishihara et al. (2010)) and by performing deformation experiments under compression (Deformation-DIA or D-DIA) or torsion (Kawazoe et al., 2009; Mei et al., 2010; Long et al., 2011). In addition, Hunt et al. (2009) used neutron diffraction to estimate the evolution of strength with temperature at a pressure of 5 GPa during relaxation experiments in a Paris-Edinburgh press.

In all of these studies, the effect of pressure remains poorly constrained. For instance, Kawazoe et al. (2009) deformed a polycrystalline olivine aggregate in a RDA press at pressures ranging from 5 to 10 GPa. Comparison with other flow laws leads to an estimation of an activation volume around 30 $cm^3.mol^{-1}$. On the other hand, Mei et al. (2010) observed a behavior apparently mostly insensitive to pressure between 5 and 9 GPa.

In the present study, a synthetic fine-grained aggregate of olivine was deformed in a D-DIA press at room temperature and at pressures between 3.5 and 6.8 GPa. The experiment consisted of four different shortening-lengthening cycles at different pressures and at constant displacement rates. Our results and existing experimental data from previous studies were used to determine a flow law taking pressure dependence into account. The evolution of the Peierls stress (σ_P) with pressure is discussed below and we conclude with some remarks on the rheology of subducting slabs.

2. Experimental procedure

2.1. Starting material

The starting material was prepared by mixing nano-size powders of MgO, SiO_2 and Fe_2O_3 in stœchiometric proportions to obtain $Mg_{1.8}Fe_{0.2}SiO_4$. The resulting mixtures were dried and reacted at high temperature (1000–1100 °C) for 2 h in a one-atmosphere furnace under a controlled oxygen fugacity close to the iron-wüstite (IW) oxygen buffer. We verified that the final powder was pure olivine by X-ray diffraction. Imaging using a field emission gun scanning electron microscope (FEG-SEM JEOL 6700F) shows a highly-dispersed powder with a grain size between 100 and 200 nm (Fig. 1a).

Dense aggregates were obtained by spark plasma sintering (SPS) at a pressure of 100 MPa and a temperature of 1000 °C. Details of the experimental setup can be found in Béjina and Bystricky (2009) and Guignard et al. (2011). Analysis of the sintered olivine ceramic (grain size, grain size distribution and porosity) was performed on SEM images (same microscope as above). The microstructure appears well equilibrated and composed of grains with a low aspect ratio and a homogeneous grain size around 200 nm (Fig. 1b). The porosity estimated by image analysis is consistent with that measured by the Archimedes method (less than 1%). The grain sizes in the microstructure and in the powder are similar, indicating that grain growth was limited during sintering.

A cylinder of 1.2 mm in diameter and 1.2 mm in length was cored in the olivine ceramic for the deformation experiment.

2.2. Deformation experiment

A deformation experiment was performed at the European Synchrotron Light Source (ESRF, Grenoble, France) using the 2000-ton uniaxial D-DIA press installed at the ID06 beamline (setup described in Guignard and Crichton, 2015). The cell-assembly was a 10-mm edge boron epoxy (BE) cube drilled at the center of a face and pressure was generated by 6-mm truncation WC anvils. In the assembly (Fig. 2), the sample was surrounded by dense and crushable alumina pistons. Sample and pistons were placed in an hexagonal boron nitride (hBN) jacket which was used as a pressure medium and as a pressure marker. The column was placed in a graphite heater which was not used during the experiment. In this study, a second sample, orthoenstatite, was also loaded in the cell assembly with our olivine specimen. We will only focus here on olivine rheology. Iron foils were placed at both ends of the samples in order to monitor changes in their length by X-ray radiographies during the experiment.

The experiment consisted of four deformation cycles (named steps 1 to 4) at different pressures and room temperature. Before the beginning of each cycle (except for steps 1 and 2) the vertical differential rams were retracted in order to place the sample in extension. A uniaxial compression was then applied on the sample by approaching the vertical differential rams at a constant speed of 200 μm per hour. After a finite strain of about 10%, the differential rams were retracted at the same speed until a new extension configuration was reached. At the end of the cycle, pressure was increased and another deformation cycle was performed. Unfortunately, the deformed sample could not be recovered because of a blowout at the end of the experiment.

2.2.1. Angular-dispersive diffraction

A collimated monochromatic beam ($\lambda = 0.22542$ Å) was used to obtain angular-dispersive diffraction patterns collected on a linear detector. Rotation of the detector around the beam axis allowed diffraction data to be recorded as a function of the azimuth ψ, defined as the angle between the diffraction vector and the

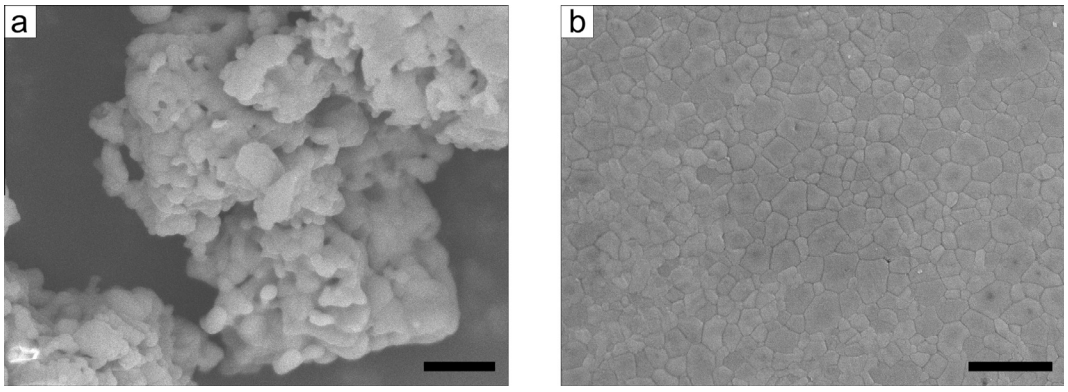

Fig. 1. SEM images of the starting material: a. Highly dispersed olivine powder, before sintering. The scale bar represents 500 nm. b. Fully-dense aggregate sintered by SPS. The scale bar represents 1 μm.