Intragranular plasticity vs. grain boundary sliding (GBS) in forsterite: Microstructural evidence at high pressures (3.5–5.0 GPa)

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ABSTRACT

The plasticity of the mantle is still not well constrained, and satisfactory mineral-physics-based rheological laws are still missing. Despite olivine being the major component of the upper mantle, it is still debated which deformation mechanism (dislocation creep, diffusion creep, grain boundary sliding) dominates deformation. High-pressure research developments (state-of-the-art presses, synchrotron experiments, and so on) as well as competitive analysis utilities (software analysis, microscopy, and so on) allow considering intragranular and intergranular mechanisms (grain boundary sliding accommodated by diffusion/dislocation creep) simultaneously. To study the contribution of individual deformation mechanisms to the overall deformation in the upper mantle, we deformed polycrystalline forsterite at 3.5–5.0 GPa, 1000–1200 °C, 2 × 10^{-5}s^{-1} at different strains in a 6-axis Mavo press. Split-cylinder experiments allowed to characterize an “internal” surface of the sample before and after the deformation experiments. Intra- and intergranular deformation was tracked using a focus ion beam milled reference grid on this surface. Grain internal misorientation where obtained from electron backscatter diffraction (EBSD) data. Both techniques suggest the dominance of intragranular deformation, in agreement with the fact that the samples have been deformed in the dislocation creep regime, as usually defined. Moreover, strain markers and out-of-plane displacements of grains provide the first microstructural evidence for a contribution of grain boundary sliding to plastic deformation at upper mantle pressure. Whether these displacements are grain boundary sliding or involve grain boundary migration cannot be clarified, given the resolution of the strain markers. Our EBSD data suggest that grain boundary processes become increasingly relevant at temperatures above 1100 °C and ensure homogenous plastic strain distribution in the aggregate.

Keywords: Forsterite, crystal slip plasticity, grain boundary sliding, EBSD, deformation; Understanding of Reaction and Deformation Microstructures

INTRODUCTION

Flow in the mantle is directly related to plate tectonics, orogenesis, subduction, and volcanic eruptions. Thus, understanding flow mantle is essential for characterizing the dynamics of the Earth. Olivine represents 60% of the upper mantle (e.g., Nicolas and Poirier 1976; Bai et al. 1991; Mackwell 1991) and exhibits a strong elastic and plastic anisotropy (e.g., Poirier 1985; Nicolas and Christensen 1987; Mainprice and Silver 1993; Ben Ismail and Mainprice 1998; Mainprice et al. 2000; Hansen et al. 2012a). Consequently, observations of seismic anisotropy can be used to interpret flow directions in the mantle (e.g., Nicolas et al. 1973; Vinnik et al. 1984; Nicolas and Christensen 1987; Silver and Chan 1988; Mainprice and Silver 1993; Russo and Silver 1994; Vauche and Barruol 1996; Karato 2008). Indeed, seismic anisotropy is strong in the upper mantle and decreases down to the transition zone (e.g., Christensen 1984; Nicolas and Christensen 1987; Montagner and Tamimoto 1991; Ben Ismail and Mainprice 1998; Debayle et al. 2005). From the shallow to the deeper parts of the upper mantle, pressure (P) and temperature (T) increase and the deformation controlling mechanism of olivine changes. This results in the formation of different crystal preferred orientations (CPO) or in the destruction of the CPO (Mainprice et al. 2005), which may affect seismic anisotropy. The deformation mechanisms that were studied most intensely are dislocation creep (e.g., Karato and Wu 1993; Couvy et al. 2004), disclination-accommodated dislocation creep [(Cordier et al. 2014; disclinations were identified in samples deformed experimentally by Demouchy et al. (2012, 2014)], grain boundary sliding (GBS; Goldsby and Kohlstedt 2001; Karato 2008), elastically accommodated grain-boundary sliding (Jackson et al. 2013), and grain boundary sliding accommodated by dislocation creep (DisGBS; Hirth and Kohlstedt 1995a, 1995b, 2003; Hansen et al. 2012b) as well as diffusion creep (e.g., Miyazaki et al. 2013).

The rheological laws consider the contribution of each independent mechanism. The total strain rate (\dot{\varepsilon}) can be calculated as (e.g., Warren and Hirth 2006):

\dot{\varepsilon} = \dot{\varepsilon}_{app} + \dot{\varepsilon}_{Diff} + \dot{\varepsilon}_{GBS} + \dot{\varepsilon}_{LTP}

(1)