Plastic flow of pyrope at mantle pressure and temperature

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ABSTRACT

Despite the abundance of garnet in deforming regions of the Earth, such as subduction zones, its rheological properties are not well defined by laboratory measurements. Here we report measurements of steady-state plastic properties of pyrope in its stability field (temperature up to 1573 K, pressure up to 6.8 GPa, strain rate ~10^-5 s^-1) using a Deformation-DIA apparatus (D-DIA) coupled with synchrotron radiation. Synthetic pyrope (Py100) and natural pyrope (Py70Alm16Gr14) are both studied in a dry environment. Transmission electron microscopy (TEM) investigation of the run products indicates that dislocation glide, assisted by climb within grains and dynamic recrystallization for grain-boundary strain accommodation, is the dominant deformation process in pyrope. Both synthetic-and natural-pyrope's stress and strain-rate data, as measured in situ by X-ray diffraction and imaging, are best fitted with the single flow law:

\[ \dot{\varepsilon}(s^{-1}) = 3.5 \times 10^8 \text{exp} \left[ \frac{(270 \pm 40) \times 10^3}{R(T/\text{K})} \right] \text{exp} \left[ \frac{16.3}{T/\text{K}} \right] \]

where \( \dot{\varepsilon} \) is the strain rate, \( \sigma = |\sigma_1 - \sigma_3| \) is the differential stress, \( R \) is the gas constant and \( T \) the absolute temperature. Synthetic forsterite and synthetic pyrope were stacked along the uniaxial compression direction in the same cell assembly during deformation to compare their strength at mantle condition. Forsterite is observed to be stronger than pyrope, deforming at a rate about 10% slower than the pyrope at 5.2 GPa and 1573 K. San Carlos olivine and natural pyrope were compared in a similar fashion at 6.8 GPa and 1473 K. In this case, San Carlos olivine deformed 2~3 times faster than natural pyrope. The experimental data suggest that pyrope is stronger (by more than a factor of 4) than the dominant mineral (olivine) in the upper mantle when temperatures exceed 1273 K.

Keywords: Garnet, high pressure, high temperature, synchrotron X-ray imaging, stress, strain

INTRODUCTION

Garnet is an important mineral in the mantle. It is the primary carrier of trivalent cations (e.g., Al) above 700 km; it is the third most abundant phase in the upper mantle and is second only to ringwoodite in the transition zone (Ringwood 1991). Its presence significantly affects the structure of major mantle discontinuities (Weidner et al. 2000). Subduction zones, where oceanic basalts are converted to eclogite with pressure, are even richer in garnet (Irifune and Ringwood 1987). A large strength contrast between garnet and olivine/wadsleyite has been implicated as an agent for delamination of the subducting slab (Ji and Zhao 1994; Karato 1994, 1997; Karato et al. 1993, 1995). It is, thus, critical to investigate the rheological properties of garnet, and to compare its strength with that of olivine, the most abundant mineral in the upper mantle.

Based on the examination of natural rocks, garnet has been considered as a strong mineral when compared with its associated minerals (Boullier and Nicolas 1975). Its creep strength is also reported as considerably high (Karato et al. 1993). Garnet high Peierls’ stress (minimum shear stress promoting glide of dislocations in their planes) is related to its microstructure, e.g., to its large cell parameters implying large dislocation Burgers vectors (Karato et al. 1995; Rabier et al. 1981). In naturally deformed garnet, the brittle/ductile transition is observed to occur around 873 K, a temperature below which deformation is characterized by a high Peierls’ friction, and above which diffusion assisted dislocation glide is responsible for deformation (Voegele et al. 1998b). These flow mechanisms are also observed in experimentally deformed garnets recovered from high-pressure experiments (Voegele et al. 1998b).

Quantitative characterizations of pyrope flow laws (Cordier et al. 1996; Karato et al. 1993; Smith 1982; Voegele et al. 1998a, 1998b; Wang and Ji 2000; Wang et al. 1999b) have been limited by its stability field. At low pressure and high temperature (e.g., 1.6 GPa and 1073 K), pyrope goes through a phase transformation to pyroxenes and some aluminum-bearing phases (Gasparik 2003). At 1673 K, pyrope is stable only above 2 GPa. Our present

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