



Effect of water on rheological properties of garnet at high temperatures and pressures



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ABSTRACT

The effect of water on the rheological properties of garnet was investigated with triaxial compressive creep experiments at high temperatures ($1223 \leq T \leq 1423$ K) and high pressures ($1.6 \leq P \leq 5.6$ GPa) using a deformation-DIA (D-DIA) apparatus. Samples fabricated from a natural polycrystalline garnet ($\text{Py}_{723}\text{Alm}_{20}\text{Gro}_{57}$) together with samples prepared from San Carlos olivine were deformed under water-saturated conditions with water supplied by the dehydration of talc during the experiments. Experiments were carried out on a synchrotron X-ray beamline. In each experiment, differential stress and sample displacement were determined using synchrotron X-ray diffraction and time-resolved radiography techniques, respectively. Water fugacity was calculated based on equation of state for water at experimental P - T conditions. A fit of our experimental results on the creep of garnet samples to a power law demonstrates strong dependencies of strain rate on water fugacity with a water fugacity exponent of $r = 1$ and on pressure with an activation volume of $V^* = 28 \times 10^{-6}$ m³/mol. Importantly, under water-saturated conditions, the water content of deformed garnet samples measured by infrared spectroscopy increases with increasing pressure (i.e., increasing water fugacity) up to an average value of $\sim 21\,000$ H/10⁶Si at ~ 3.0 GPa and then decreases with increasing pressure down to ~ 3000 H/10⁶Si at 5.6 GPa. The flow law for garnet quantified in this study provides an important constraint on the strength of the subducted oceanic crust. For a water-enriched environment, the viscosity of a garnet-rich layer will be low above the shallow upper mantle because the water content in garnet increases with increasing pressure at relatively low pressures. However, at greater depth, the viscosity will be high because the *direct* effect of pressure on the creep through thermally activated processes outweighs the *indirect* effect on the creep through water solubility.

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1. Introduction

Garnet is an important constituent mineral in subducted slabs and in the transition zone. As subducting oceanic crust plunges into the mantle, the mid-ocean ridge basalt (MORB) transforms to eclogite with >40 vol% garnet in the lowermost part of thickened crust or mantle at a depth of about 100 km. It further transforms into a garnetite layer (>90 vol% garnet) with majorite \pm stishovite in the transition zone at depths ranging from 410 to 660 km (Irifune and Ringwood, 1987; Irifune et al., 1986; Ringwood, 1991). Hence, knowledge of rheological properties of garnet is essential to understanding the geodynamic response of a subducted slab and of the transition zone. However, relatively little is currently

known about the creep strength of garnet at high pressure. Although several studies have been made to constrain the rheological properties of garnet or garnet analogs (Cordier et al., 1996; Karato et al., 1995; Voegelé et al., 1998; Wang and Ji, 1999, 2000), experimental results mainly focused on deformation microstructures or mechanical data at lower pressures. Quantitative experimental investigations of the creep strength of garnet at mantle conditions have been hindered due to technical limitations. With the development of the high-pressure D-DIA apparatus, recent studies on the rheology of garnet at high pressures (e.g., Li et al., 2006; Mei et al., 2010) directly provided constrains on the rheological properties of subducted oceanic crust under anhydrous conditions.

Extensive infrared (IR) spectroscopic analyses on 'nominally anhydrous minerals' (NAMs), such as olivine, pyroxene and garnet, have revealed that they have a considerable ability to dissolve water and, hence, the upper mantle and the transition zone can be large reservoirs for water in Earth's interior (Bell and Rossman, 1992a; Hirschmann et al., 2005). (In this study, 'water' refers to any

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water-related species such as hydrogen, hydroxyl and/or molecular water detected as O–H stretching with infrared spectroscopy.) Garnets from ultrahigh-pressure metamorphic rocks have water contents up to ~ 1000 wt. ppm H_2O (Bell and Rossman, 1992a, 1992b; Langer et al., 1993), while garnets from kimberlite xenoliths contain as much as 400 wt. ppm H_2O (Bell and Rossman, 1992a, 1992b). Experiments on water solubility in garnets indicate that pyrope and pyrope-rich garnets can dissolve substantial amounts of H, ranging from a few hundred to up to ~ 1000 wt. ppm H_2O (Lu and Keppeler, 1997; Mookherjee and Karato, 2010; Withers et al., 1998).

It has been demonstrated that the rheological properties of minerals can be significantly influenced with the presence of water (e.g., Mackwell et al., 1985). A recent experimental study on the rheological behavior of eclogite observed that garnet grains deformed under wet conditions are strongly flattened by comparison with grains deformed under dry conditions, indicating a strong influence of water on the mechanical strength of garnet (Zhang and Green, 2007). Furthermore, some researchers have suggested that elongated grains of naturally deformed garnet result mainly from water weakening (e.g., Smit et al., 2011; Su et al., 2002). However, to date, very few studies have been carried out on quantifying the effect of water on the creep behavior of garnet. In their investigation of the creep behavior of pyrope-rich garnet under hydrous conditions at 2 GPa, Katayama and Karato (2008) reported results from only two experiments. Therefore, to provide a better constraint on the rheological properties of subducted oceanic crust, especially for those regions where water is present, it remains important to explore experimentally the influence of water on the deformation of garnet at high temperatures and pressures.

In the present study, we report results from high-temperature, high-pressure deformation experiments on garnet aggregates carried out under water-saturated conditions. Our results quantify the relationship between the creep strength of garnet and water fugacity, and thus provide a constraint on the rheological properties of garnet within Earth's interior.

2. Sample preparation and experimental procedure

2.1. Sample preparation

Samples were prepared from powdered natural garnet that was hand-picked from crushed eclogite rocks collected from Sulu 'ultrahigh-pressure' (UHP) metamorphic belt, part of the Dabie–Sulu orogenic belt of China. The garnet, with a composition of $\text{Py}_{23}\text{Alm}_{20}\text{Gro}_{57}$, contains up to 300 wt. ppm H_2O (Zhang et al., 2004). To prepare samples for experiments, garnet powders with particle size of $< 25 \mu\text{m}$ were cold-pressed into small cylinders ~ 1.0 mm in length and 1.1 mm in diameter.

In each experiment, a fine-grained polycrystalline sample of olivine was stacked with a garnet sample for investigating the strength contrast between garnet and olivine, a separate study. Furthermore, the olivine samples served as a measure of the degree of water saturation since water solubility for olivine as a function of temperature, pressure and water fugacity has previously been experimentally determined, while little is known about water solubility in garnets of our composition. The olivine samples were cored from a hot-pressed rod prepared from powdered San Carlos olivine + 5% by mass enstatite + 3 drops (~ 0.06 mL) of distilled water. The average grain size of olivine samples was $\sim 15 \mu\text{m}$.

As shown in Fig. 1, the sample assembly consisted of a garnet and an olivine sample wrapped cylindrically in Ni foil with thickness of $25 \mu\text{m}$. Both hard alumina pistons and machinable alumina plugs were stacked above and below the pair of samples. This deformation column was assembled with a talc sleeve and graphite resistance heater into a 6.2-mm edge length cubic

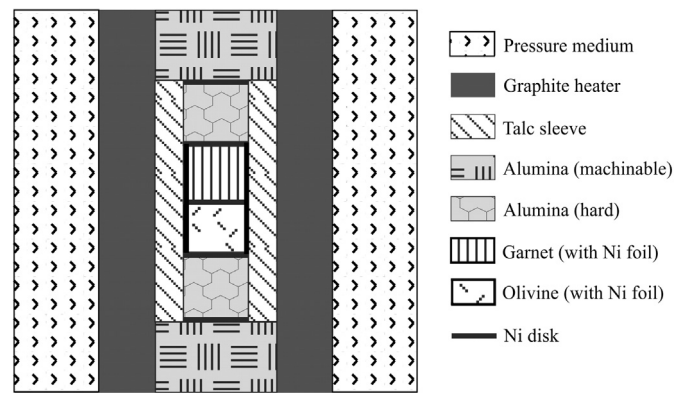


Fig. 1. Sketch of sample assembly. Samples (garnet and olivine) wrapped in Ni foil were assembled with hard alumina pistons, machinable alumina plugs, a talc sleeve, and a graphite resistance heater into a 6.2-mm edge length cubic pressure medium. Nickel disks placed between samples and hard alumina pistons serve as strain markers, while those between hard alumina piston and machinable alumina serve as monitoring the position of pistons.

pressure medium, composed of a mixture of amorphous boron and epoxy. Dehydration of the talc sleeve worked as a water source for establishing a hydrous environment during an experiment. A nickel disk was placed at each end of the samples to act as a strain marker.

2.2. Deformation experiments

Creep experiments were carried out in a D-DIA apparatus (Durham et al., 2002; Wang et al., 2003) installed at beam line X17B2 of the National Synchrotron Light Source (NSLS), Brookhaven National Laboratory. In each experiment, the garnet plus olivine pair was first compressed at room temperature to a target pressure and then heated to a target temperature. To densify the cold-pressed garnet sample, the sample column was annealed at the target temperature and pressure for ~ 1 h before deformation. The temperature during the experiments was determined based on calibrations of furnace power versus temperature for identical assemblies prepared with a thermocouple (e.g., Durham et al., 2009). Careful calibrations were conducted offline for different pressures and different deformation rates. Temperature variations from several calibrations were less than 30 K at a given power. We take this variation as temperature uncertainty for our experiments. The paired samples were then deformed at a constant deformation rate at constant temperature and pressure.

Synchrotron X-rays provided the means of *in situ* determining the strain rate, stress and pressure of the sample. During deformation, a white beam of X-rays passed through the deforming sample column, from which time-resolved X-ray radiographs of the samples were collected every ~ 12 min during the deformation experiments. Two radiographs of a deforming sample column collected ~ 26 min apart are shown in Fig. A.1. Such images make it possible to measure the length change of the sample, outlined with X-ray opaque nickel strain markers, with a resolution of few microns, from which the strain was calculated. Steady-state strain rate was then computed from the slope of the strain versus time curve. Pressure and differential stress were determined based on the elastic lattice strain within the crystalline sample from analyses of X-ray diffraction data combined with published equations of state (Murnaghan, 1937) as described by Singh (1993), Singh et al. (1998) and Weidner et al. (2010). The application of this method to data analyses for D-DIA experiments is detailed elsewhere (Li et al., 2004; Mei et al., 2008). With recent upgrades of the X-ray energy dispersive detector system, the resolution in the pressure and differential stress is ~ 20 MPa (Mei et al., 2010; Weidner et al., 2010).

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