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Creep strength of ringwoodite measured at pressure–temperature conditions of the lower part of the mantle transition zone using a deformation–DIA apparatus

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ABSTRACT

Creep strength of ringwoodite is important for understanding complicated patterns of the mantle convection in and around the mantle transition zone. To determine the creep strength of ringwoodite, we expanded pressure–temperature conditions of in situ stress–strain measurements in a deformation–DIA apparatus combined with synchrotron X-ray to those of the lower part of the mantle transition zone. The expansion of the pressure–temperature conditions was made by shrinking anvil truncation to 2.0 mm and the development of a cell assembly for in situ deformation experiments up to 1700 K. Utilizing the developed technique, creep–strength measurements on polycrystalline ringwoodite were performed at 16.9–18.0 GPa and 1300–1700 K during axial deformation with strain rates of 1.48–3.59×10^{-5} s^{-1} to strains of 13.2–24.9%. Based on mechanical and microstructural observations, we infer that ringwoodite deformed by exponential dislocation creep through the Peierls mechanism at 1300–1400 K and power-law dislocation creep at 1500–1700 K. The creep strength of ringwoodite is apparently lower than that of bridgmanite, wadsleyite and olivine. The present result implies the possibility that the lower mantle transition zone is a low-viscosity layer. Further creep–strength data of these minerals are necessary to be determined above 13.5 GPa and high temperatures to determine viscosity structure in and around the lower mantle transition zone at strain rates relevant to the mantle convection.

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1. Introduction

Viscosity of ringwoodite is important in understanding complicated patterns of mantle convection in and around the lower part (∼520–660 km depth) of the mantle transition zone (MTZ). This is because ringwoodite is volumetrically dominant at the lower MTZ (e.g. Irifune and Ringwood, 1987) and is believed to control viscosity of the region. Viscosity contrast between the lower MTZ and the lower mantle plays a key role in controlling stagnation process of subducting slabs according to simulation studies on the mantle convection (e.g. Torii and Yoshioka, 2007). Moreover, the phase transformation from metastable olivine to ringwoodite may

weaken the subducting slabs because of change in their viscosities (Karato et al., 2001). Furthermore, viscosity contrast between ringwoodite-rich peridotite and former oceanic crust may cause chemical heterogeneity by separation of the former oceanic crust at the 660-km boundary (Karato, 1997). Consequently, the viscosity of ringwoodite is critical for understanding the mantle dynamics in and around the MTZ.

The viscosity of the lower MTZ has been controversial among geophysical models. Some models suggested presence of a low-viscosity layer at the MTZ (e.g. Mitrovica and Forte, 2004; Soldati et al., 2009) while such low-viscosity layer was not reported in other models (e.g. Peltier, 1998). Another way to determine the viscosity of the lower MTZ is to derive flow laws of ringwoodite by measuring its creep strength, i.e. stress magnitude at steady-state deformation. The 520-km seismic discontinuity is attributed to the phase transformation from wadsleyite to ringwood-

ite. Pressure–temperature (P–T) conditions there were estimated to be ∼17.5 GPa (Dziewonski and Anderson, 1981) and ∼1760 K (Akaogi et al., 1989) in the normal mantle. Therefore, the creep strength of ringwoodite is necessary to be measured at such high P–T conditions to determine the viscosity of the lower MTZ.

The creep strength of ringwoodite was measured by in situ stress–strain measurements at 21–23 GPa and 1800 K by using a rotational Drickamer apparatus (RDA) with synchrotron X-ray (Hustoft et al., 2013; Miyagi et al., 2014). The creep strength of ringwoodite was 1.6–3.2 GPa at strain rates of 5.8–18×10^{-5} s^{-1}. However, uncertainty in temperature was reported as ±200 K in their studies. Such large uncertainty in temperature leads difficulty in deriving the flow laws of ringwoodite by considering temperature dependence of Si self-diffusion coefficients in ringwoodite (Shimojuku et al., 2009). Moreover, there were variations in stress and strain rate across the sample in the RDA experiment because the sample was deformed in the torsional geometry.

The creep strength of ringwoodite was also measured to 10 GPa at room temperature by the in situ stress–strain measurements using a deformation–DIA (D–DIA) apparatus with synchrotron X-ray (Nishiyama et al., 2005). However, P–T conditions of the study were far below those of the lower MTZ. The in situ stress–strain measurements in the D–DIA apparatus were succeeded at 17 GPa at 600 K (Nishiyama et al., 2007) although temperature condition was limited because of technical difficulty in heating. Ringwoodite was deformed at P–T conditions up to 20 GPa and 1700 K using the D–DIA apparatus (e.g. Kawazoe et al., 2010c) although stress magnitude was not measured because they used anvils with no X-ray transparency. Recently, we expanded the P–T conditions of the in situ stress–strain measurements in the D–DIA apparatus to 14.5 GPa and 1700 K by improving a multianvil 6–6 (MA6–6) assembly (Kawazoe et al., 2011). Nevertheless, the pressure condition of the study was below that of the lower MTZ. Therefore, the P–T conditions of the in situ stress–strain measurements in the D–DIA apparatus has been necessary to be expanded to ∼17.5 GPa and ∼1700 K to determine the creep strength of ringwoodite in the lower MTZ.

In the present study, we expanded the P–T conditions of the in situ stress–strain measurements in the D–DIA apparatus up to 18 GPa and 1700 K. First, pressure generation tests were performed to reach ∼18 GPa at a relatively small press load (0.50 MN) because breakage of the X-ray transparent anvils at higher press loads limited the accessible P–T conditions. Second, we developed a cell assembly suitable for both temperature generation to 1700 K at 17–18 GPa and the in situ stress–strain measurements with synchrotron X-rays. Third, the in situ stress–strain measurements on polycrystalline $(Mg_{0.9}, Fe_{0.1})_2SiO_4$ ringwoodite were demonstrated at 17–18 GPa and 1300–1700 K during axial deformation at a synchrotron facility. Moreover, we characterized deformation microstructure and water content of recovered samples. In this paper, we report the creep strength of ringwoodite under the P–T conditions of the lower MTZ and discuss deformation mechanisms of ringwoodite and change in the creep strength by the phase transformations relevant to ringwoodite.

2. Materials and methods

2.1. Pressure generation experiment

Pressure generation experiments were conducted to optimize dimensions of a truncated edge length (TEL) of second-stage anvils, a cubic pressure medium and preformed gaskets to reach ∼18 GPa at 0.50 MN. The pressure generation experiments were performed using a cubic anvil apparatus MADONNA-II, which is identical to the apparatus used for the in situ stress–strain measurements at the synchrotron facility. The multianvil 6–6 (MA6–6) assembly

(Kawazoe et al., 2010b; Nishiyama et al., 2008) was adopted with first-stage anvils made of tungsten carbide with a TEL of 27.0 mm. For this purpose, we used six second-stage anvils made of tungsten carbide with ultra-fine grains (Fujilloy TF05, Fuji Die Co. Ltd.) with a TEL of 2.0 mm.

The pressure mediums were made of semi-sintered (Mg, Co)O (Mino Ceramic Co. Ltd.). Edge lengths of the pressure mediums were 2.8–4.0 mm (Table S1). The gaskets were made of pyrophyllite and were fired at 973 K for 30 min for its plastic hardening. Thickness of the gaskets was chosen to fill initial gaps between the second-stage anvils (Table S1). Width of the gaskets was 0.5 mm. In the runs with no gaskets, Teflon spacers were used for initial positioning of the second-stage anvils and to prevent material of the pressure medium from falling during compression.

The sample pressure was evaluated at room temperature by measuring changes in electrical resistance in ZnTe (9.6 and 12.0 GPa; Kusaba et al., 1993) and GaAs (19.3 GPa; Yagi and Akimoto, 1976). A sample powder was packed into the central part of a hole in the pressure medium. The powder was sandwiched with a pair of copper wire electrodes, whose outer ends contacted with top faces of the top and bottom second-stage anvils.

2.2. Deformation experiment

The deformation experiments were conducted using the multianvil apparatus SPEED-Mk.II (Katsura et al., 2004) combined with a D–DIA guide block system (Wang et al., 2003) at the BL04B1 beamline of the synchrotron facility SPring-8, Japan. We adopted the MA6–6 assembly modified for the in situ stress–strain measurements (Kawazoe et al., 2011). Two second-stage anvils made of cubic BN (BNS800, Sumitomo Electric Inc.) were used on the downstream side because of their low X-ray absorption. The other second-stage anvils were made of tungsten carbide with ultra-fine grains (Fujilloy TF05). Diffracted monochromatic X-rays were detected at 2θ angle of up to ∼10° through a conical X-ray path on the first-stage anvils and sliding blocks on the downstream side. Deformation rate was controlled with feedback system controlling displacements of the top and bottom anvils.

Starting material for the deformation experiments was an olivine aggregate. The aggregate was sintered from a mixture of a San Carlos olivine $((Mg_{0.9}, Fe_{0.1})_2SiO_4)$ powder and 8 wt% pyroxene powder (Kilosa, Tanzania) in a Ni capsule at 4 GPa and 1373 K for 1.5 h using a Kawai-type multianvil apparatus. The pyroxene powder was added to control activities of oxide components in the samples. The olivine aggregate contained water (or hydrogen) of 440 wt ppm H_2O (7100 H/10^6 Si).

The cell assembly used for the deformation experiment was composed of the semi-sintered (Mg, Co)O pressure medium, dense Al_2O_3 pistons, an MgO electrical insulator, a LaCrO$_3$ furnace, Mo and Cu electrodes and crushable Al_2O_3 backup rods (Fig. S1). The pressure medium with an edge length of 3.2 mm was used with the fired pyrophyllite gaskets with a thickness of 0.85 mm. The starting olivine aggregate was packed in a Mo foil capsule whose wall thickness was 5–10 μm. The capsule prevented reaction between the sample and the surrounding materials and kept oxygen fugacity in the sample under the Mo–MoO$_2$ buffer. The capsule foils between the sample and the pistons were 10-μm thick and served as strain markers for the strain measurement. The sample temperature was measured with a $W_{97}Re_3$–$W_{75}Re_{25}$ thermocouple. Materials of the furnace and the gaskets along the X-ray path were replaced with graphite and boron-epoxy, respectively, for the in situ stress–strain measurements.

The samples were compressed to a press load of 0.50 MN for 150 min at room temperature. Temperature was then increased to 1500 K (runs M1267, M1299, M1303 and M1305) or 1700 K (run M1219) at 0.50 MN and kept for 26–42 min for synthesis of