Grain-size evolution and rheology of the lower mantle

*Masahiro Imamura[1], Tomoaki Kubo[1]

1. Kyushu University

The rheology of the lower mantle depends on the grain size in the constituent minerals. Bridgmanite (Brg) is present as major phase in the lower mantle, and ferropericlase (Fp), Ca-perovskite (Capv) and majoritic garnet (Mjgt) are secondary phases (e.g., Irifune, 1994; Nishiyama and Yagi, 2003). Grain-size evolution in the lower mantle is affected by grain growth process after the grain-size reduction due to the post-spinel transformation. Grain growth kinetics generally described by d^n-d_0^n=kt (d: grain size, d_0: initial grain size, n: grain growth exponent, k: Arrhenius-type temperature-dependent rate constant, t: time). In the multi-phase system, Zener pining and Ostwald ripening by secondary phases controls the grain growth of major phase. Grain size ratio between primary and secondary phase is described by $d_I/d_{II}=\beta/f_{II}^z$ (d_I: grain size of primary phase, d_{II}: grain size of secondary phase, f_{II}: volume fraction of secondary phase, β and z: Zener parameters). In this study, annealing experiments in the multi-phase system of pyrolitic material were conducted under lower mantle condition. We analyzed the grain growth data based on the Zener relationship, and discussed grain-size evolution and rheology of the lower mantle.
Grain growth experiments in pyrolitic material were conducted at 25-27 GPa and 1600-1950°C for 30-3000 min using a Kawai-type high-pressure apparatus at Kyushu University and GRC. Grain growth microstructure and chemical compositions of existing phases were examined using FE-SEM with EDS. The grain growth data was taken from the sample showing equigranular microstructure, which was achieved after annealing for 600 minutes at 1700°C and for 30 minutes at 1800-1950°C (use these grain sizes as d_0), and not achieved even after annealing for 3000 minutes at 1600°C. The secondary phases are homogeneously distributed at grain boundaries of the major phase of Brg. The grain size ratio between major and secondary phases was roughly constant and estimated to be ˜1.4 and ˜1.8 at 25 GPa (four phases of Brg, Fp, Capv, and Mjgt) and 27 GPa (three phases of Brg, Fp, and Capv), respectively. These results suggest that the Zener pinning and Ostwald ripening of secondary phases by grain boundary diffusion control the grain growth of Brg. Although the n-value were not well constrained from present data, when assuming the n-value of 4 considering the Ostwald ripening by grain boundary diffusion, the activation enthalpies for the grain growth in Brg, Fp, and Mjgt are estimated to be ˜400, ˜320, ˜530 kJ/mol, respectively. The relationship between the grain size ratio (d_I/d_{II}) and the volume fraction of secondary phases (f_{II}) are almost consistent with the previous systematic study in the olivine-enstatite system (Tasaka and Hiraga, 2013), in which the Zener parameters of β and z were estimated to be 0.7 and 0.5, respectively.
On the basis of the results obtained above, we estimated grain-size evolution in the lower mantle. The grain sizes of Fp and Brg in a pyrolitic composition (f_{II}=0.2) were estimated to be ˜3-100 μm and ˜10-200 μm, respectively at 800-1400°C, and ˜400-2500 μm and ˜500-3000 μm, respectively at 1600-2400°C in 10^8 years. These grain sizes of Brg do not change significantly in different chemical compositions of an olivine-like (f_{II}=0.3) and a perovskitic (f_{II}=0.1) lower mantle. These results suggest that Brg deforms by diffusion creep however the deformation mechanism possibly changes into dislocation creep in high stress conditions around the subducting slabs and D” layer. Effects of the weaker phase of Fp with having smaller grain size on the lower-mantle deformation will be discussed.

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