Grain growth kinetics in pyrolite composition: Implications for grain-size evolution of lower-mantle slab

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Viscosity of lower-mantle slab largely depends on grain size in constituent minerals. It consists of bridgmanite (Brg), ferro-periclase (Fp), Ca-perovskite (Capv), and majoritic garnet (Mjgt) in the case of pyrolite composition. The grain-size evolution of lower-mantle slab is mainly controlled by grain growth process after the significant grain-size reduction due to the post-spinel transformation. Grain growth kinetics can be described by $d^n-d_0^n=kt$ (d: grain size, d_0: initial grain size,n: grain growth exponent, k: Arrhenius-type rate constant, t: time). In the multiphase system, Zener pinning is an important process and grain growth of the primary phase is controlled by Ostwald ripening of the secondary phase, which can be 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 the present study, we conducted grain growth experiments in pyrolite composition under lower mantle conditions, and discuss the grain-size evolution of lower-mantle slab.
Annealing experiments in pyrolitic material were conducted at 25-27 GPa and 1600-1950°C for 30-3000 min using a Kawai-type apparatus at Kyushu University. FE-SEM was used for microstructural observations and chemical analysis. Four phases of Brg (~70 vol%), Fp (~15 vol%), Mjgt (~13 vol%), and Capv (~2 vol%) were observed in recovered samples annealed at 25 GPa. To avoid the effects of the eutectoid texture on the kinetics, we took the grain growth data only from the sample exhibiting relatively homogeneous polygonal texture. Both secondary phases of Fp and Mjgt are homogeneously distributed in the Brg-dominant sample after the polygonal texture was achieved. The grain size ratio of d_{Brg}/d_{Fp} and d_{Brg}/d_{Mjgt} are almost constant during the grain growth and estimated to be ~1.7 and ~1.2, respectively. These microstructural observations imply that the Brg grain growth is pinned by the secondary phases, and the rate is controlled by Ostwald ripening kinetics. We obtained n values of 6.2, 3.3, and 3.1 for Brg, Fp, and Mjgt, respectively. The averaged n value of ~4.2 is consistent with the multiphase grain growth model when the secondary phase grows by Ostwald ripening process (n=4, grain-boundary diffusion controlled). When assuming the n-value of 4, the activation enthalpies for Brg, Fp, and Mjgt are estimated to be ~410, ~240, and ~500 kJ/mol, respectively, implying that the rate-controlling species are different between Ostwald ripening processes of Fp and Mjgt, and the Brg grain growth is controlled by both processes. If we treat Fp and Mjgt as a secondary phase ($d_{II=Fp+Mjgt}$) ignoring Capv, the activation enthalpies are almost the same between the primary and secondary phases. The grain size ratio of $d_{I=Brg}/d_{II=Fp+Mjgt}$ is ~1.5 with the $f_{II=Fp+Mjgt}$ of 0.3, which is almost consistent with the previous systematic study in the olivine-enstatite system (Tasaka and Hiraga, 2013). On the other hand, three phases without Mjgt were present at higher pressure of 27 GPa, in which the grain size was slightly larger probably due to the smaller proportion of the secondary phases (~77 vol% of Brg).
On the basis of the results obtained above, we estimated grain-size evolution of lower-mantle slab assuming that Zener parameters are the same as the previous study (Tasaka and Hiraga, 2013). The grain size of Brg in a pyrolitic composition with ($f_{II=Fp+Mjgt}$=0.3) and without ($f_{II=Fp}$=0.2) bearing Mjgt is estimated to be ~5-650 μm and ~50-900 μm, respectively, at 800-1600°C in 10^8 years. When considering an olivine-like ($f_{II=Fp}$=0.3) and a perovskitic ($f_{II=Fp}$=0.1) compositions, the Brg grain size decreases to ~40-720 μm and increases to ~80-1270 μm, respectively. Thus, the grain size in lower-mantle slab is likely kept smaller than 1 mm, suggesting that grain-size sensitive creep is dominant. Viscosity variations in lower-mantle slab will be discussed considering a dynamic grain-growth effect.

