Silicon self-diffusion rates in wadsleyite: Implications for rheology of mantle transition zone and subducting slabs

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1. Introduction

Mantle convection is accomplished by the plastic deformation (diffusion creep or dislocation creep) of its constituent minerals. When understanding the rheological properties of Earth's mantle, it is very crucial to investigate the diffusion rate of the slowest diffusing species in silicate minerals. There are numerous studies on the diffusivity in olivine which has shown that Si is the slowest diffusing species. However diffusion studies in wadslyite, high-pressure polymorph of olivine and one of the major constituent minerals in the mantle transition zone, have been limited to Mg-Fe interdiffusion. In this study, we report experimental results on Si self-diffusion rates at 18.0 GPa and 1703-1903K. Based on these results, rheology of the mantle transition zone and subducting plates are discussed.

2. Experimental procedure

High-pressure experiments were performed using a Kawai-type multi-anvil apparatus installed at Tohoku University. The sample assembly is composed of sintered ZrO2 pressure medium and LaCrO3 heater. Temperature was monitored with W3%Re-W25%Re thermocouple. The starting material of wadsleyite polycrystals was synthesized at 18.0 GPa and 2003K from powdered forsterite. The water content of starting material was estimated using Fourier Transformed Infrared Spectroscopy (FTIR). The concentrations of hydroxyl groups were determined using the calibration by Paterson (1982). Surface of the polycrystalline wadslyite was polished with diamond paste (0.25 micron in diameter). Then the polished surface was coated with a 29Si enriched thin film. Diffusion annealing was conducted at 18.0 GPa and 1703-1903K in which Mg2SiO4 wadsleyite coexists SiO2 stishovite. The sample was enclosed by NaCl powder and the coated surface was contacted with Au foil to avoid reacting with NaCl. After the diffusion annealing, concentration profiles of 29Si were measured by the depth profiling method using secondary ion mass spectrometry (SIMS) at Tokyo Institute of Technology.

3. Results and discussion

The average grain size and the water content in the starting wadsleyite were estimated to be about 12 micron and 353-507 weight ppm H2O, respectively. The obtained diffusion profiles were composed of two regions. It could be interpreted that volume diffusion is the dominant mechanism in the region near the sample surface, whereas grain-boundary diffusion is dominant in the deeper region. The volume diffusion coefficients were calculated using the solution of thin film diffusion model. The grain-boundary diffusion was calculated by the model of LeClaire (1963). The volume diffusion coefficient (Dv) and grain boundary diffusion coefficient (dDgb) were determined to be Dv = 2.16*10^-11[m2/s] exp (-295 [kJ/mol] / RT) and dDgb = 7.59*10^-17[m3/s] exp (-281 [kJ/mol] / RT), respectively. Si self-diffusion rates are about 5 orders of magnitude slower than Mg-Fe interdiffusion rates in wadsleyite. Despite the slowest diffusion species is still unclear in wadslyite because oxygen diffusion rate has never been reported, Si is possibly the slowest diffusion species in wadslyite like olivine. Assuming that Si is the rate-controlling species and controls the plastic deformation in wadsleyite, we have calculated the viscosity deformed by the diffusion creep using obtained Si diffusion coefficients. The viscosity deformed by the dislocation creep has also been calculated by using creep law parameters of spinel in the work of Karato et al. (2001). Compared with the temperature and the viscosity of the mantle transition zone, both diffusion creep and dislocation creep mechanisms can be dominant in the mantle transition zone. In cold subducting slabs, diffusion creep is the dominant deformation mechanism. Therefore, the slab possibly weakens if the grain size is reduced after the olivine-spinel transformation.