Viscosity-depth profiles of the oceanic upper mantle deforming by grain-boundary diffusion creep

*Kosuke Yabe[1], Takehiko Hiraga[1]

1. School of Science, The University of Tokyo

The mantle is known to have anisotropic elasticity, which is primarily explained by crystallographic preferred orientation (CPO) of olivine that forms during mantle flow. Because the CPO has long been considered to result uniquely from dislocation processes, diffusion creep has received less attention than dislocation processes. Recently, olivine CPO has been found to develop during diffusion creep under a condition that seems to correspond to the depth of seismically anisotropic mantle (Miyazaki et al., 2013). This motivated us to examine mantle viscosity in terms of olivine diffusion creep.
Diffusion creep of olivine is controversial. Differences of up to two orders of magnitude in viscosity at the same grain sizes and temperatures have been reported from experimental diffusion creep studies (Hirth & Kohlstedt, 1995; Faul & Jackson, 2007). Therefore, it remains difficult to determine the importance of diffusion creep as a mantle deformation mechanism from a mechanical perspective.
We synthesized fine-grained Fe-bearing olivine ($Mg_{1.8}Fe_{0.2}SiO_4$; so-called Fo_{90} olivine) aggregates that were variably doped with CaO and Al_2O_3 and conducted uniaxial deformation experiments at 1 atm. By comparing creep properties of undoped and doped olivine aggregates, we identified the roles of Ca and Al in enhancing grain-boundary diffusion creep at $>0.92T_s$ (in K), an effect became significant with increasing temperature. We considered the enhancement to result from grain-boundary disordering promoted by grain-boundary segregation. Based on the Arrhenius-like behavior of the disordering effect, we established an olivine diffusion creep law that suitably describes the creep rates in both temperature ranges of $<0.92T_s$ and $>0.92T_s$ using values of T_s and ΔQ. The latter term is an additional activation energy on top of that for the normal state of olivine diffusion creep.
We estimated solidus temperatures of the samples used in the previous diffusion creep experiments. These temperatures were used to compare previously reported diffusion creep rates for olivine with our established diffusion creep law. We found that the law explains a difference of up to two orders of magnitude in olivine creep rates at the same temperatures, stresses, grain sizes, and water contents in the previous studies. The geotherm normalized by the mantle solidus was calculated for the upper mantle with water contents up to 300 ppm wt., which predicts depths where weak (low-viscosity) mantle is expected to occur due to enhanced grain-boundary diffusion creep. Constructed viscosity-depth profiles reveal a mantle lithosphere with essentially zero thickness beneath mid-ocean ridges, with development of the lithosphere away from the ridge, leaving a low-viscosity region below. Given a grain size of 1 mm and depending on the water content, a viscosity of $1\text{-}5\times10^{19}$ Pas is predicted for the low-viscosity mantle beneath 50-million-year-old seafloor.

Keywords: olivine aggregate, grain-boundary diffusion creep, viscosity of the oceanic mantle

