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Grain boundary sliding as the major deformation mechanism of olivine in Earth's upper mantle

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Anisotropic propagation of seismic waves have been observed in the Earth's upper mantle, which is attributed to the crystallographic preferred orientation of olivine associated with mantle dynamics. The most likely deformation mechanism of olivine that explains the observed seismic anisotropy has been considered to be dislocation creep (e.g., Karato et al, 1986). Diffusion creep may also partly contribute to the deformation of olivine in the upper mantle, while another possible mechanism, grain boundary sliding, has been thought to play only minor roles in some limited circumstances such as in melt-bearing rocks or fine-grained rocks (Hirth and Kohlstedt, 1995; Hiraga et al., 2010). Hansen et al. (2011) proposed that the dislocation-accommodated grain boundary sliding (DisGBS) may dominate the upper mantle flow, based on deformation experiments for olivine at a pressure of 0.3 GPa and temperatures to 1523 K. Development of crystallographic preferred orientation (CPO) of olivine through DisGBS-controlled creep is so significant (Hansen et al., 2012) that this would be a potentially important deformation mechanism controlling the upper mantle flow. Nevertheless, most of experimental investigations on the deformation mechanism of olivine have been limited to the pressures below 0.5 GPa, which are lower than those in the actual upper mantle.

We conducted uniaxial deformation experiments on olivine aggregates with a composition of $Mg_{1.8}Fe_{0.2}SiO_4$ at pressures 1.5-6.7 GPa and at temperatures 1273-1473 K with strain rates of $0.3\text{-}7.2*10^{-5}$ s^{-1} using a deformation-DIA apparatus. The averaged values of stress exponent, activation energy, and activation volume were obtained to be 3.0, 423 kJ/mol, and 17.7 cm^3/mol, respectively. The obtained parameters supports the deformation of water-poor olivine controlled by DisGBS. A significant water-fugacity dependency of creep strength of olivine on water fugacity was observed, and the water fugacity exponent was obtained to be 1.25. The dependency of creep strength of olivine controlled by DisGBS on pressure is weak due to competing the pressure-hardening effect of activation volume and the pressure-softening effect of water fugacity. Because creep strength of olivine controlled by the grain boundary sliding is insensitive to pressure, the estimated viscosity of water-poor olivine is independent of depth and is in a range of 10^{20}-$10^{21.5}$ Pa s throughout the upper mantle, which is consistent with geophysically observed viscosity profiles. Viscosity of the deep upper mantle would be overestimated by ~10-10^4 times if we assume the conventional dislocation creep mechanism for water-poor olivine.

Keywords: grain boundary sliding, olivine, upper mantle, pressure, water, viscosity