Grain boundary sliding as the major flow mechanism of Earth's upper mantle

Earth's surface plates (thickness, ~60 km), on which we live, move and are subducted along with the flow of the upper mantle (depths 60–410 km), which is composed mainly of olivine. Natural phenomena, such as earthquakes and volcanic eruptions, occur as a result of the subduction of plates. For over 45 years since 1970, the generally accepted theoretical model has explained that the flow of the upper mantle is controlled by the motion of dislocations in olivine (i.e., dislocation creep: [1]). However, the dislocation creep model cannot explain the geophysical viscosity profiles because a strong depth dependence of mantle viscosity is expected in the case of the dislocation creep of olivine. Here, we report that dislocation-accommodated grain boundary sliding (DisGBS), rather than dislocation creep, dominates the deformation of olivine under middle and deep upper mantle conditions [2]. The estimated viscosity of olivine controlled by DisGBS is independent of depth and ranges from $10^{19.6}$–$10^{20.7}$ Pa·s throughout the asthenospheric upper mantle with a representative water content (50–1000 ppm H/Si), which is consistent with geophysical viscosity profiles.

We have conducted uniaxial deformation experiments on olivine aggregates combined with synchrotron *in situ* X-ray observations at pressures of 1.5–6.7 GPa, temperatures of 1273–1473 K, and strain rates of 0.3–7.2 × 10^{-5} s^{-1} using a deformation-DIA apparatus at beamline **BL04B1**. The temperature and pressure ranges are equivalent to the conditions in the shallow to middle region of the upper mantle. Plastic flow of minerals at high temperatures is commonly described by the power-law equation. Using the steady-state creep strength of olivine obtained under experimental conditions, we determined the flow-law parameters for olivine aggregates as follows:

$$\dot{\varepsilon} = 10^{-4.89\pm0.24}\frac{\sigma^{3.0\pm0.3}}{G} f_{\mathrm{H2O}}^{1.25} \exp\left(-\frac{423\pm56\,\mathrm{kJ/mol} + P\times 17.6\pm0.8\times10^{-6}\,\mathrm{m^3/mol}}{RT}\right) \quad (1)$$

where $\dot{\varepsilon}$ is the strain rate (in s^{-1}), G is the grain size (in m), σ, f_{H2O} and P are the differential stress, water fugacity and pressure, respectively (in MPa), R is the gas constant, and T is the temperature. The obtained values of the stress exponent and the grain-size exponent in Eq. (1) show that the deformation of olivine is controlled by DisGBS. The obtained value of the activation energy is close to that for DisGBS of dry olivine (445 ± 20 kJ/mol) [3] and is between the activation energies for dislocation creep (530 ± 4 kJ/mol) and diffusion creep (375 ± 50 kJ/mol) of dry olivine [4].

Steady-state creep strength, which is normalized at a fixed temperature and strain rate, is plotted against pressure in Fig. 1. The pressure dependence of the creep strength of olivine aggregates controlled by DisGBS is apparently weak owing to a combination of a relatively small activation volume and a strong water-weakening effect. In contrast, the pressure dependence of the creep strength of olivine controlled by dislocation creep is much

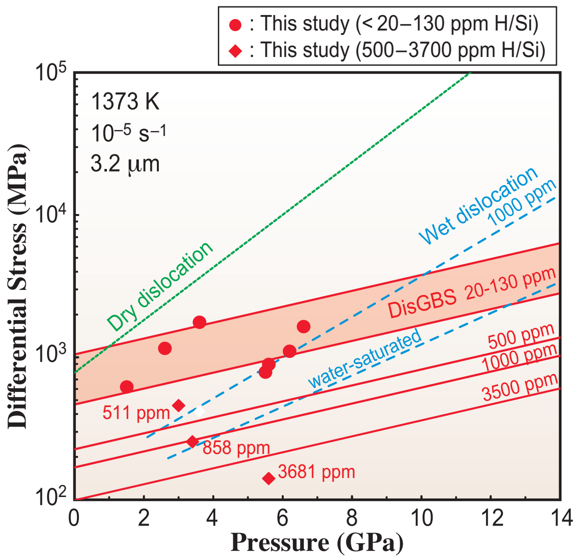

Fig. 1. Pressure dependence of creep strength of olivine aggregates. All data are normalized to an axial strain rate of 10^{-5} s^{-1}, a temperature of 1373 K, and a grain size of 3.2 µm (i.e., a typical experimental condition). Solid circles and diamonds represent the strength of dry olivine aggregates (< 20–130 ppm H/Si) and wet olivine aggregates (500–3700 ppm H/Si; water content is shown near the symbols), respectively. Red lines represent the strength of olivine aggregate controlled by DisGBS obtained using Eq. (1) (thick lines with hatched area: < 20–130 ppm H/Si; thin lines: 500–3500 ppm H/Si of water in olivine). The green dotted line represents the strength of dry olivine aggregates controlled by dislocation creep. Blue dashed lines represent the strength of wet olivine aggregates controlled by wet dislocation creep (1000 ppm H/Si and water-saturated cases are considered). See Ohuchi *et al*. [2] for the references.

stronger than that in the case of DisGBS. In order to determine which creep mechanism controls the upper mantle flow, we calculated deformation mechanism maps as a function of stress and grain size under representative upper mantle conditions (Fig. 2). Figure 2 shows that the viscosity of the dry upper mantle is controlled by DisGBS of olivine at high pressures (≥ 7 GPa), while the contributions of dislocation and diffusion creep to mantle flow are limited to only the shallow upper mantle [2].

Figure 3 shows the viscosity-depth profiles in the upper mantle based on the present results. Figure 3 shows a strong depth dependence of viscosity controlled by dislocation creep. In contrast, the upper mantle is estimated to have relatively constant viscosities in a limited range of $10^{20.1}$–$10^{20.7}$ Pa·s (in the case of 50 ppm H/Si of water) or $10^{19.6}$–$10^{20.1}$ Pa·s (in the case of 1000 ppm H/Si of water) at depths greater than ~100 km when the constant-stress flow is controlled by DisGBS (Fig. 3). The viscosity-depth profiles derived from geophysical observations of post-glacial rebound (e.g., [5]) are well explained by DisGBS with 50 ppm H/Si of water (the 1000 ppm H/Si case is marginally consistent with the observations). Therefore, we conclude that water content in the upper mantle is between 50–1000 ppm H/Si. Assuming dislocation creep of dry olivine significantly overestimates the deep upper mantle viscosity by ~10–10^2 times. Such an estimate of upper mantle viscosity leads to the highly unlikely conclusion that the deep upper mantle may have a viscosity of ~10^{23} Pa·s, which corresponds to the upper bound of the lower mantle viscosity (10^{21}–10^{23} Pa·s). The dynamics of the upper mantle should be re-evaluated using our new flow law for DisGBS of olivine (Eq. 1).

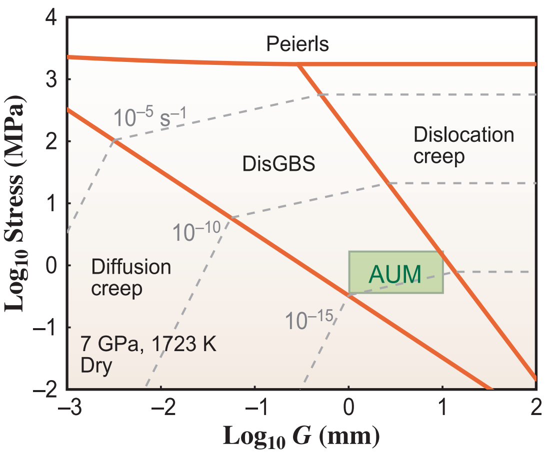

Fig. 2. Example of deformation mechanism maps for dry olivine on the axes of differential stress *versus* grain size (G) at a pressure of 7 GPa and temperature of 1723 K. The thick orange lines represent the boundaries between two deformation mechanisms (i.e., dislocation creep, diffusion creep, the Peierls mechanism, and DisGBS). See Ohuchi *et al*. [2] for the references). The green-hatched area represents typical conditions of the asthenospheric upper mantle (AUM). The gray dashed lines represents the contours of strain rates.

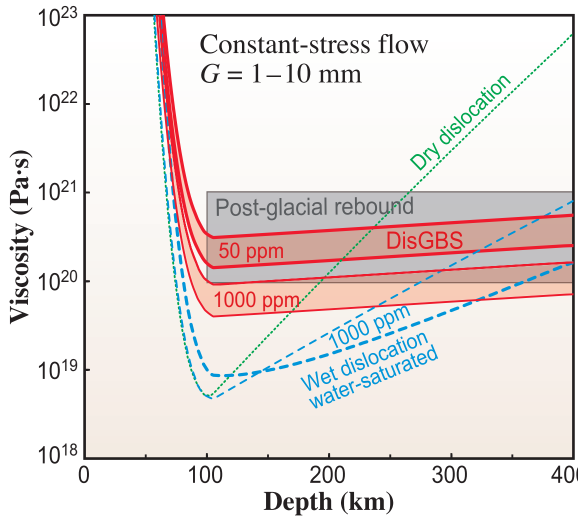

Fig. 3. Depth dependence of the viscosity of olivine. The dominant deformation mechanism is assumed to be DisGBS (red solid curves with red-hatched areas, thick: 50 ppm H/Si of water; thin: 1000 ppm H/Si) or dislocation creep (green dotted curve: dry; blue dashed curves, thin: 1000 ppm H/Si; thick: water-saturated). The constant stress and geotherms below the oceans of 50 m.y. old and mantle adiabat are used for the calculation. The gray-hatched area represents the range of upper mantle viscosity estimated from geophysical observations of post-glacial rebound (e.g., [5]).

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