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The influence of hydrogen on the transition from power-law creep to low-temperature plasticity of olivine at lithospheric temperatures

Jacob Tielke, Mark Zimmerman, and David Kohlstedt
University of Minnesota, United States (tielk003@umn.edu)

At high-temperature (asthenospheric) conditions, strain rate of olivine-rich mantle rocks follows a power-law dependence on stress. At lower-temperature (lithospheric) conditions, strain rate exhibits an exponential dependence on stress. However, the influence of water (hydrogen) on the transition from high-temperature to low-temperature behavior is poorly constrained. To investigate the influence of water on the transition in flow regimes at lithospheric conditions, deformation experiments on single crystals of San Carlos olivine under both wet (hydrogen-rich) and dry (hydrogen-poor) conditions were carried out. Crystals were oriented relative to the applied load to exert the maximum shear stress on the (100)[001] and (001)[100] dislocation slip systems, which are the dominate (weakest) slip systems at both low temperatures and under wet conditions. Experiments were carried out using a gas-medium apparatus with high resolution in stress ($\pm$2 MPa) and temperature ($\pm$2°C). For the wet experiments, hydrogen was supplied to the crystals using talc sealed in nickel jackets. Deformation experiments were carried out in either triaxial compression or direct shear geometries at 1000-1300°C, differential stresses of 120 to 670 MPa, and resultant strain rates of 6 x 10^{-6} to 4 x 10^{-4} s^{-1}. At high-temperature, under dry conditions, strain rate is a power-law function of stress with a stress exponent of 3.5 and an Arrhenius function of temperature with an activation energy of 520 kJ/mol. At low-temperature and high-stress conditions, under dry conditions, strain rate increases exponentially with increasing stress with an activation energy of 360 kJ/mol. These observations are consistent with a transition from a climb-controlled dislocation mechanism at higher temperatures to a glide-controlled dislocation mechanism at lower temperatures for hydrogen-poor olivine crystals. Under wet conditions, the strain rate dependence on stress follows a power-law relationship with a stress exponent of 3.5 and an activation energy of 330 kJ/mol and does not transition to an exponential dependence on stress. Post-deformation electron-backscatter diffraction analyses indicate development of low-angle boundaries with rotation about the [010] axis, consistent with deformation resulting from glide of dislocations on the (100)[001] and (001)[100] slip systems. Water concentrations in crystals from wet experiments determined using Fourier transform infrared spectroscopy were 157 to 190 ppm H/Si, similar to values obtained from xenoliths derived from the lithospheric mantle. These analyses indicate that the presence of water in the lithospheric mantle results in considerable weakening and that power-law flow behavior of mantle rocks may operate at shallower depths than previously thought.