

THE INFLUENCE OF HYDROGEN CONTENT ON THE VISCOSITY OF OLIVINE SINGLE CRYSTALS UNDER LITHOSPHERIC CONDITIONS

Jacob A. Tielke, Mark E. Zimmerman, and David L. Kohlstedt, University of Minnesota, Department of Geology and Geophysics, Pillsbury Hall, Minneapolis, MN 55455 (Jake Tielke, tielk003@umn.edu).

Introduction: Modeling of geodynamic properties of terrestrial planets requires rigorous constitutive equations that describe the rheological properties of mantle rocks. Extensive results are available from high-temperature, high-pressure deformation experiments of olivine and mantle rocks [1-3]. However, extrapolation of these data to relatively low-temperature and high-stress lithospheric conditions results in significant overestimation of the strength of the lithospheric mantle [4]. Although work has been done on low-temperature deformation of olivine single crystals under anhydrous [5] and hydrous [6] conditions, a constitutive equation describing the rheology of olivine single crystals as a function of water concentration has yet to be established.

In order to more fully characterize the rheological properties of the lithospheric mantles of terrestrial planets, an investigation is underway to derive constitutive equations that describe the flow behavior of hydrous olivine single crystals under controlled chemical and physical environments. Olivine is generally considered to be the most abundant and weakest mineral in the lithospheric mantle of terrestrial planets and therefore should largely control the rheological behavior of these important regions. Constitutive equations derived from data obtained by carrying out deformation experiments of olivine single crystals in $[101]_c$, $[110]_c$, and $[011]_c$ orientations (see [3] for a notation explanation) allow the relative strengths of slip systems to be assessed. These experiments must be carried out at temperatures, confining pressures, differential stresses, and water concentrations that are consistent with lithospheric mantle conditions.

Experimental Methods: Single crystals of San Carlos olivine were oriented using electron backscatter diffraction and cut into rectangular prisms of dimensions 3.9 x 4.1 x 8.0 mm. Each crystal was placed in a cylindrical Ni capsule with a 7 mm outer diameter and a 5 mm inner diameter. Talc powder was inserted into the capsules to supply water and set the silica activity with an orthopyroxene buffer. The capsules were then sealed by laser welding a Ni cap onto each end. In some instances, a thin coating of alumina was applied to the outside of the Ni capsule to limit hydrogen loss during the experiment. The Ni capsules were positioned between alumina and zirconia pistons and jacketed in an iron sleeve. Each assembly was then inserted into a gas-medium deformation apparatus to ensure

precise measurement of temperature and stress. The samples were hydrostatically annealed at 1250°C and 300 MPa for 2 hours and subsequently deformed at 1200°C, 1100°C, or 1000°C in a series of constant stress steps. Water concentrations were calculated after each experiment from Fourier transform infrared (FTIR) spectra using the Paterson (1982) [7] calibration for determining hydrogen content in olivine.

FTIR Analyses: FTIR analyses reveal significant absorption at wavenumbers between 3100 and 3600 cm^{-1} for samples annealed and deformed under hydrous conditions, as shown in Figure 1. Absorption bands in this wavenumber range are indicative of O-H stretching bonds from hydrogen incorporated in the olivine structure.

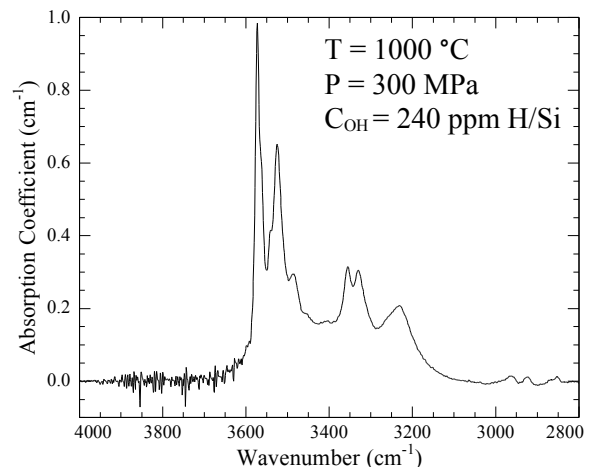


Figure 1: Unpolarized FTIR spectrum taken after a deformation experiment. The spectrum was taken with the IR beam coaxial with the $[010]$ axis of the olivine crystal.

Mechanical Results: Results from triaxial deformation experiments on $[101]_c$ crystals of olivine indicate a significant water-weakening effect and reveal a marked dependence of creep rate on temperature, as shown in Figure 2. The experiments were carried out at differential stresses ranging from 22 to 570 MPa and strain rates ranging from 1.7×10^{-7} to $4.0 \times 10^{-4} \text{ s}^{-1}$. The stress exponent for all experiments was 3.5 ± 0.1 . This power-law relationship between stress and strain rate remained constant throughout the experiments, which suggests variation in hydrogen content remained

minimal throughout the deformation portion of the experiments.

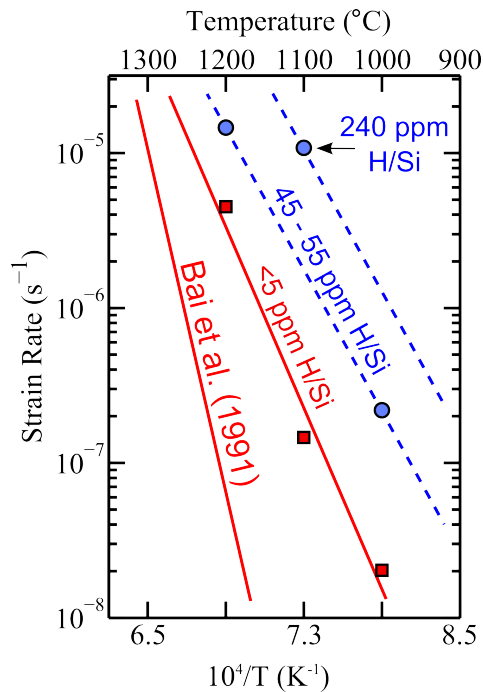


Figure 2: Semi-log plot of strain rate versus inverse temperature for [101]_c San Carlos olivine at a differential stress of 100 MPa. The red squares at 1200°C and 1000°C are data from [8].

Discussion: In all of the experiments, samples with structurally incorporated hydrogen are weaker than “dry” samples. At the same temperature and stress, samples containing 45-55 ppm H/Si deformed 3 times faster than dry samples. These results are in agreement with previous studies of hydrous olivine crystals [3].

These data show that strain rate is influenced by the amount of hydrogen present. The sample containing 240 ppm H/Si deformed two orders of magnitude faster than the dry sample at the same temperature and stress. These results, when considered with mechanical data from experiments with lower hydrogen concentration, suggest a gradual decrease in viscosity with increasing hydrogen concentration.

The results indicate a dependency of activation energy on hydrogen content for olivine under lithospheric conditions. Mechanical data from experiments with < 5 ppm H/Si yield an activation energy of ~420 kJ/mol. In contrast, data from experiments containing 45-55 ppm H/Si produce an activation energy of ~330 kJ/mol. These data suggest a relative decrease in dependence of viscosity on temperature for hydrous olivine crystals under lithospheric conditions.

The results of these experiments have important consequences for understanding the strength of the lithosphere of terrestrial planets. The highly variable nature of hydrogen content of Earth’s lithospheric mantle is evidenced by studies of mantle xenoliths [9]. This implies that a range of hydrogen content is likely to be present in the lithospheric mantle of terrestrial planets and that flow laws derived from experiments carried out over the range of lithospheric conditions are needed when modeling geodynamic processes on terrestrial planets.

Acknowledgments: We are grateful to NASA for providing support for this project through grant NNX10AM95G.

References: [1] Bai, Q. *et al.* (1991) *J. Geophys. Res.* 96, 2441-2463. [2] Raterron, P. *et al.* (2009) *Phys. Earth Planet Inter.* 172, 74-83. [3] Mackwell, S.J. *et al.* (1985) *J. Geophys. Res.* 90, 11319-11333. [4] Demouchy, S. *et al.* (2009) *Geophys. Res. Lett.* 46, L04304. [5] Mei S. *et al.* (2010) *J. Geophys. Res.* 115, B08204. [6] Katayama, I. and Karato, S. (2008) *Phys. Earth Planet. Inter.* 168, 125-133. [7] Paterson, M.S. (1982) *Bull. Mineral.* 105, 20-29. [8] Schneider, S.E. (2008) *M.S. Thesis, U. of Mn.* 87 pp. [9] Wang, Q. (2010) *Lithos* 120, 30-41.