

DEFORMATION OF OLIVINE SINGLE CRYSTALS IN A HYDROUS ENVIRONMENT: INSIGHT INTO THE RHEOLOGICAL BEHAVIOR OF THE LITHOSPHERIC MANTLE OF TERRESTRIAL PLANETS.

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 processes of terrestrial planets requires rigorous constitutive equations that describe the rheological properties of mantle rocks. Extensive literature is available on data obtained from high-temperature, high-pressure deformation 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 low-temperature deformation of olivine single crystals has been investigated under anhydrous [5] and hydrous [6] conditions, a constitutive equation describing the rheological behavior of olivine 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 olivine single crystals in a hydrous environment. Olivine is the most abundant and weakest mineral in the lithospheric mantle of terrestrial planets and, therefore, largely controls the rheological response 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. Our experiments described here were carried out on $[101]_c$ single crystals at temperatures, confining pressures, differential stresses, and water concentrations appropriate for lithospheric mantle conditions.

Experimental Methods: Single crystals of San Carlos olivine were oriented using electron backscattered diffraction and cut into rectangular prisms of dimensions $3.9 \times 4.1 \times 8.0$ mm. Each crystal was placed in a cylindrical Ni capsule with a 7 mm outer diameter and a 5 mm inner diameter. The Ni capsules were constructed from two, telescoping, single-ended Ni cans to provide a water-tight assembly. Shims of talc or compressed brucite powder were inserted to fill the Ni capsule and supply water. The Ni capsules were positioned between alumina and zirconia pistons and jacketed in an iron sleeve. Each assembly was then inserted into a high-resolution gas-medium deformation apparatus, annealed at a temperature of 1250°C and confining pressure of 300 MPa for 1.25 h. Sam-

ples were subsequently deformed at 1200°C in a series of constant stress steps.

Dislocation microstructures of deformed samples were observed using optical and scanning electron microscopy employing the oxidation/decoration technique [7,8]. Water concentrations were determined using Fourier transform infrared spectroscopy.

Experimental Results: Results from triaxial deformation experiments on $[101]_c$ olivine crystals not only indicate a significant water-weakening effect but also reveal a marked dependence of creep rate on silica activity. Strain rate as a function of differential stress data from creep experiments on four samples deformed under hydrous (wet) conditions are presented in Fig. 1 along with those for one sample deformed under anhydrous (dry) conditions [9]. The experiments were carried out at differential stresses ranging from 20 to 270 MPa and strain rates of 1.7×10^{-6} to $2.2 \times 10^{-3} \text{ s}^{-1}$. Brucite-buffered and talc-buffered samples contained similar OH concentrations. The stress exponent is similar for all three types of samples, ranging from 3.5 for talc-buffered to 3.6 for brucite-buffered to 3.7 for dry samples. At a differential stress of 100 MPa, talc-buffered samples deform a factor of ~ 3 faster than the dry sample, and the brucite-buffered samples deform a factor of ~ 3 faster than the talc-buffered samples, as illustrated in Fig. 1.

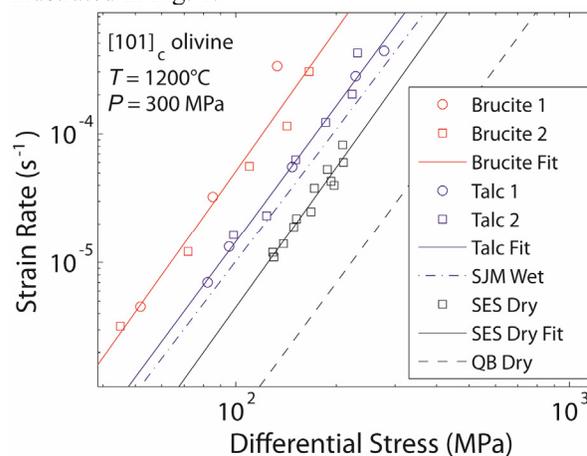


Figure 1: Stress versus strain rate plot from triaxial compressive creep experiments on brucite-buffered, talc-buffered, and dry $[101]_c$ olivine crystals. Red = brucite buffered, blue = talc buffered, and black = dry. SES = [9], SJM = [3], and QB = [1].

Discussion: Consistent with previous studies, samples of olivine deformed under hydrous conditions are weaker than those deformed under anhydrous conditions (e.g., [3,10-12]). This water-weakening phenomenon has largely been discussed in terms creep rate controlled by dislocation climb and thus by diffusion of the slowest ionic species. In olivine, the slowest diffusing species is Si, under hydrous as well as anhydrous conditions [13,14]. We continue this approach in our analysis.

The dislocation climb velocity, v_c , is directly proportional to the self-diffusion coefficient for Si, D_{Si} . In turn, the Si self-diffusivity is proportional to the rate of diffusion of Si vacancies, $D_{V_{Si}}$, times the total concentration of Si vacancies, $[V_{Si}^{tot}]$:

$$v_c \propto D_{Si} \propto D_{V_{Si}} [V_{Si}^{tot}]. \quad (1)$$

The primary influence of water on silicon diffusion is through its effect on the concentration of Si vacancies. Because water enters the olivine lattice as hydrogen ions, that is, charged point defects, its presence will result in an increase in the concentration of V_{Si} . If, for example, the addition of hydrogen ions to olivine produces defect associates that involve four hydrogen ions and a silicon vacancy, $\{4H_i^+ - V_{Si}^{////}\}$, then the concentration of silicon vacancies will increase as the hydrogen concentration increases. Here, the Kröger-Vink notation has been used to specify species, site, and charge. In the case that the concentration of these defect associates significantly exceeds the concentration of other silicon vacancies, the total concentration of silicon vacancies can be approximated by

$$[V_{Si}^{tot}] \approx [\{4H_i^+ - V_{Si}^{////}\}]. \quad (2)$$

In turn, the concentration of defect associates is a function of water fugacity, f_{H_2O} , oxygen fugacity, f_{O_2} , and the activity of the silica buffer, expressed here as the activity of orthopyroxene, a_{opx} :

$$[\{4H_i^+ - V_{Si}^{////}\}] \propto f_{O_2}^0 f_{H_2O}^2 a_{opx}^{-2}. \quad (3)$$

Thus, by combining Eqs. (1) to (3), we conclude that strain rate, $\dot{\epsilon}$, increases with increasing water fugacity and decreasing opx activity:

$$\dot{\epsilon} \propto f_{H_2O}^2 a_{opx}^{-2}. \quad (4)$$

The experimental results presented in Fig. 1 are consistent with the behavior predicted by Eq. (4). First, strain rate increases with increasing water fugacity. This point is evident from the fact that olivine crystals buffered by either brucite or talc are significantly weaker than olivine deformed under dry conditions. Second, strain rate increases with decreasing silica activity. This result is clear from a comparison of the results in Fig. 1 for samples buffered by brucite

with those buffered by talc. At lower silica activity (brucite buffer), olivine crystals deform a factor of three faster than at high silica activity (talc buffer). Note also in Fig. 1 that our results are in good agreement with those of [3] for talc-buffered olivine crystals and that the high-temperature flow law of [1] over predicts the strength of olivine at lower temperatures.

As a final point, it should be emphasized that the above argument does not indicate that silicon vacancies are the primary sites for incorporation of hydrogen ions in olivine. The main defect associates involved in the uptake of hydrogen ions in olivine are metal cation (magnesium/iron vacancies) [15,16]. This conclusion is supported by the measured dependence of hydrogen concentration on water fugacity and is consistent with the observation that metal cation diffusion is orders of magnitude faster than silicon diffusion not only under anhydrous but also under hydrous conditions [14,17].

In summary, the viscosity of olivine crystals depends not only on water fugacity but also on silica activity. This result is consistent with point defect models for the incorporation of some fraction of the hydrogen in olivine as hydrogen ions associated with silicon vacancies thus increasing the concentration of silicon vacancies and consequently the diffusivity of silicon and the rate of dislocation climb.

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] Kohlstedt, D.L. *et al.* (1976) *Science* 191, 1045-1046. [8] Karato, S. (1987) *Phys. Chem. Mineral* 14, 245-248. [9] Schneider, S.E. (2008) *M.S. Thesis, U. of MN.* Pp. 87 [10] Chopra, P.N. and Paterson, M.S. (1984) *J. Geophys. Res.* 89, 7861-7876. [11] Karato, S. *et al.* (1986) *J. Geophys. Res.* 91, 8151-8176. [12] Mei, S. and Kohlstedt, D.L. (2000) *J. Geophys. Res.* 105, 21471-21481. [13] Kohlstedt, D.L. (2006) *Rev. Mineral. Geochem.*, 62, 377-396. [14] Costa, F. and Chakraborty, S. (2008) *Phys. Earth Planet. Inter.* 166, 11-29. [15] Kohlstedt *et al.* (1996) *Contrib. Mineral. Petrol.* 123, 345-357. [16] Kohlstedt, D.L. and Mackwell, S.J. (1998) *Zeitschrift für Physikalische Chemie* 207, 147-162. [17] Hier-Majumder, S. *et al.* (2005) *J. Geophys. Res.*, 110, doi:10.1029/2004JB003292.