WATER INCORPORATION MECHANISMS AND MECHANICAL PROPERTIES OF HYDROUS OLIVINE SINGLE CRYSTALS: INSIGHT INTO THE RHEOLOGICAL PROPERTIES OF MANTLE ROCKS OF TERRESTRIAL PLANETS. Jacob Tielke, Yang Li, Mark Zimmerman, and David Kohlstedt, University of Minnesota, Department of Geology and Geophysics, Pillsbury Hall, Minneapolis, MN 55455 (Jake Tielke, tielk003@umn.edu).

Introduction: Olivine is the most abundant and weakest mineral in the mantle of terrestrial planets and therefore largely controls the rheological properties of these important regions. Laboratory experiments have shown that trace amounts of hydrogen or "water" result in weakening of olivine single crystals [1]. However, consideration of laboratory data in the context of mantle conditions of terrestrial planets requires considerable extrapolation in strain rate and stress. Therefore, an understanding of the underlying physical processes of water incorporation and weakening in olivine is essential to confidently apply laboratory data to models of mantle processes on terrestrial planets.

In order investigate water incorporation and weakening mechanisms in olivine, an investigation is underway to characterize the water content and flow behavior of olivine single crystals under hydrous conditions. In this study, experiments were carried out under conditions of differing silica activity are used to examine water incorporation mechanism and evaluate the climb-controlled dislocation creep mechanism.

Experimental Methods: Single crystals of San Carlos olivine were oriented using Laue x-ray diffraction or electron backscatter diffraction and cut into rectangular prisms. The crystals were surrounded by mixtures of talc and brucite to supply water and buffer silica activity. Two types of experiments were carried out, (1) hydration anneals and (2) triaxial deformation of hydrated crystals. All experiments were carried out at a confining pressure of 300 MPa. Ni capsules were used to buffer oxygen fugacity near Ni/NiO. The Ni capsules were positioned between alumina and zirconia pistons and jacketed in an iron sleeve. The Paterson (1982) calibration was used to determine water concentration from Fourier transform infrared (FTIR) spectra gathered with an unpolarized beam parallel to [010].

For deformation experiments, the crystals were oriented with the compression axis at 45° to [100] and [001], to simultaneously activate the (100)[001] and (001)[100] dislocation slip systems.

Experimental Results: Water concentrations as determined by FTIR analyses revealed a dependence of hydrogen concentration on silica activity. Samples buffered under high silica activity conditions contained ~190 ppm H/Si, whereas samples buffered under low silica activity conditions contained ~90 ppm H/Si. The dominant peaks in FTIR spectra are at 3572 and 3529 cm^{-1} as presented in Figure 1. Additional peaks at 3353 and 3329 cm^{-1} are evident in samples buffered under high silica activity conditions.
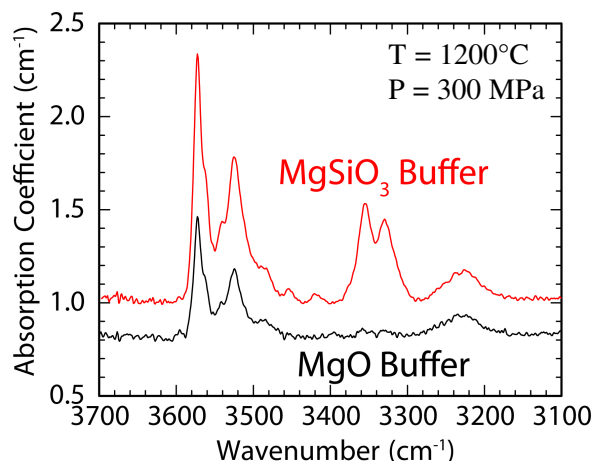

Figure 1: FTIR spectra from samples annealed at 1200°C for 5 hours.

Results from triaxial deformation experiments indicate a significant water-weakening effect and reveal a marked dependence of creep rate on silica activity. The results from creep experiments on four samples deformed under hydrous ("wet") conditions are presented in Fig. 2 along with those for one sample deformed under anhydrous ("dry") conditions from [2]. The experiments were carried out at differential stresses ranging from 22 to 272 MPa resulting in strain rates ranging from 1.7×10^{-6} to 2.2×10^{-3} s^{-1}. 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 stress of 100 MPa, talc-buffered (hydrous) samples deform a factor of ~3 faster than the orthopyroxene-buffered (anhydrous) sample. Under hydrous conditions, the brucite-buffered (low-silica activity) samples deformed a factor of ~3 faster than the talc-buffered (high-silica activity) samples.
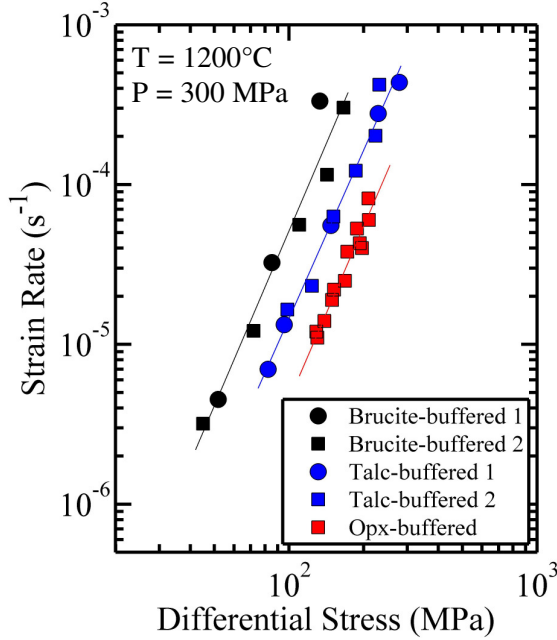
Figure 2: Mechanical data from hydrous deformation experiments buffered by talc or brucite and from an anhydrous deformation experiment buffered by orthopyroxene.

Discussion: The results give some insight into water incorporation mechanisms in olivine. A comparison of the FTIR spectra in Figure 1 indicate that water concentration (C_{OH}) increases with increasing silica activity (a_{SiO_2}). This observation can be expressed as

$$C_{OH} \propto a_{SiO_2}^p .$$ (1)

The presence of orthopyroxene (high silica activity) acts to enhance the formation of water-derived point defects, which form in association with metal vacancies. That is, this observation is consistent with incorporation of water into the olivine lattice primarily in association with metal vacancies.

The results presented above are roughly consistent with the climb controlled dislocation creep model [3], which predicts strain rate ($\dot{\varepsilon}$) as a function of stress (σ) and diffusion (D) of the slowest diffusing ionic species

$$\dot{\varepsilon} \propto \sigma^3 D .$$ (2)

The experimentally determined relationship between strain rate, stress, water fugacity (f_{H_2O}), and silica activity is

$$\dot{\varepsilon} \propto \sigma^{3.5-3.7} \left(\frac{f_{H_2O}^r}{a_{SiO_2}^q} \right) .$$ (3)

For the case of olivine, silicon is the slowest diffusing species under both anhydrous [4] and hydrous conditions [5]. Under hydrous conditions, silicon dif-

fusivity increases with increasing f_{H_2O} [4] and is predicted to decrease with increasing a_{SiO_2}, thus following a relation of the form

$$D_{Si} \propto \left(\frac{f_{H_2O}^r}{a_{SiO_2}^q} \right) .$$ (4)

The discrepancy between the dependence of strain rate on stress predicted by climb-controlled dislocation creep models, $n = 3$ in Eq. (1), and that observed experimentally, $n = 3.5$-3.7 in Eq. (2), has recently been addressed [6]. The value of $n = 3$ obtained in climb-controlled models arises from the Orowan equation by making the usual assumption that the dislocation density is proportional to the square of the stress, that is, $\rho \, \alpha \, \sigma^2$ with the dislocation velocity $v \, \alpha \, \sigma$. Empirically, however, $\rho \, \alpha \, \sigma^{1.37}$. With $v \, \alpha \, \sigma$, a value of $n \approx 2.4$ is predicted. However, if Si diffuses along dislocation lines, then $\dot{\varepsilon} \propto \rho^2 v \propto \sigma^{2.74}\sigma \approx \sigma^{3.7}$.

Therefore, the experimentally derived flow law presented in Eq. (3) is in good agreement with climb-controlled dislocation creep provided that short-circuit diffusion along dislocations dominates mass transport of silicon. In this case, the measured dependences of strain rate on stress, water fugacity, and silica activity are all consistent with values predicted by theory.

Conclusions: (1) Our hydrogen solubility data demonstrate that *hydrogen concentration increases with increasing silica activity*, consistent with incorporation of hydrogen in olivine primarily by the formation of defect associates with metal vacancies. As minority point defects, the Si vacancies also interact with hydrogen ions to form defect associates.

(2) Our creep data demonstrate that under hydrous conditions at a fixed water fugacity, *strain rate decreases with increasing silica activity*, consistent with a climb-controlled creep process rate limited by Si diffusion via a vacancy mechanism.

References: [1] Mackwell, S.J. *et al.* (1985) *J. Geophys. Res.* 90, 11319-11333. [2] Schneider, S.E. (2008) *M.S. Thesis, U. of Mn.* 87 pp. [3] Dohmen, R. *et al.* (2002) *Geophys. Res. Lett.* 29, 26-1. [4] Costa, F., and Chakraborty S. (2008) *Phys. Earth. Plan. Int.* 166, p. 11-29. [5] Poirier, J.P. (1985) *Camb. Univ. Pres.*, 260 pp. [6] Hirth, G., and Kohlstedt, D.L. (2013) *Tectonophys.* in review.