

DUNITE VISCOSITY DEPENDENCE ON OXYGEN FUGACITY. J. W. Keefner,¹ S. J. Mackwell,² and D. L. Kohlstedt³, ^{1&3}University of Minnesota (Dept. of Geology and Geophysics, 310 Pillsbury Dr. SE, Suite 108, Minneapolis, MN 55455, John@solarvision.org, dlkohl@umn.edu), ²Lunar and Planetary Institute (3600 Bay Area Boulevard, Houston, TX, 77058, mackwell@lpi.usra.edu).

Introduction: A detailed understanding of the behavior of dunite flow is crucial because small errors in a laboratory-derived constitutive equation become large errors when extrapolated to mantle conditions. The oxidation state of the upper mantle of the Earth, Mars, and Venus may play a role in the development of endogenic processes that lead to observable surface features. Oxygen fugacity is known to have an effect on the viscosity of olivine single crystals under constant stress [1, 2]. However, the behavior of polycrystalline olivine samples deformed under different oxidation states is less well understood. Deformation experiments were performed on Åheim dunite over ranges of temperature, stress, and solid state buffer to investigate the dependence of viscosity on oxygen fugacity. In many studies of kinetic properties on olivine single crystals and polycrystalline aggregates, oxygen fugacity was buffered at the iron-wüstite (IW) buffer by the sample jacket. In the present study, we explicitly compare the strength of samples deformed at the nickel-nickel oxide (NNO) and the iron-wüstite solid state buffers in order to quantify the dependence of creep rate on oxygen fugacity.

Sample: Åheim dunite, a coarse grained olivine aggregate from Norway, was chosen for this experiment because it has been extensively studied in previous dunite creep studies [3, 4] and the large grain size (900μm) minimizes the effect of grain growth. However, the large grain size is susceptible to dynamic recrystallization. The samples had a moderate foliation, apparently more distinct than those used in previous studies. The composition of olivine grains determined from electron microprobe analyses, was averaged from three sites on three grains with one standard deviation of 0.62% between sample measurements. The samples used in this study have a slightly higher magnesian number than Åheim dunite used in other studies [3, 4], attributable to local variations in chemistry. Other components identified by wavelength dispersive spectroscopy include pyroxenes, secondary alteration products, and spinels, consistent with previous studies [3].

Methods: The methods used in this study were similar to those used by Chopra & Paterson [3], except that our experiments were performed at constant load, whereas their experiments were at constant strain rate. In both studies, samples were deformed at strain rates from approximately 10^{-3} to 10^{-6} and temperatures from

1400-1550 K in a gas-medium deformation apparatus at 300 MPa confining pressure. Differences required to control oxygen fugacity are listed below:

- Samples were dehydrated in a 1-atm furnace at 1273 K for 12 hours at the NNO or IW buffer controlled by a mixture of CO/CO₂ gas or argon and excess iron.
- NiO powder was painted onto the dunite surface to insure the presence of oxide in NNO experiments.
- Dehydrated samples were stored in a vacuum oven at 413 K before deformation. Metal sleeves and thin foil caps sealed the sample surface during deformation – Ni was used for NNO experiments and Fe for IW.
- Samples were deformed at a confining pressure of 300 MPa, constant load, and constant temperature until steady state creep was reached at approximately 0.5% strain.
- After NNO experiments, the Ni sleeve was dissolved in an aqua regia acid bath, and the surface was examined for green NiO as an indicator of appropriate oxygen fugacity.

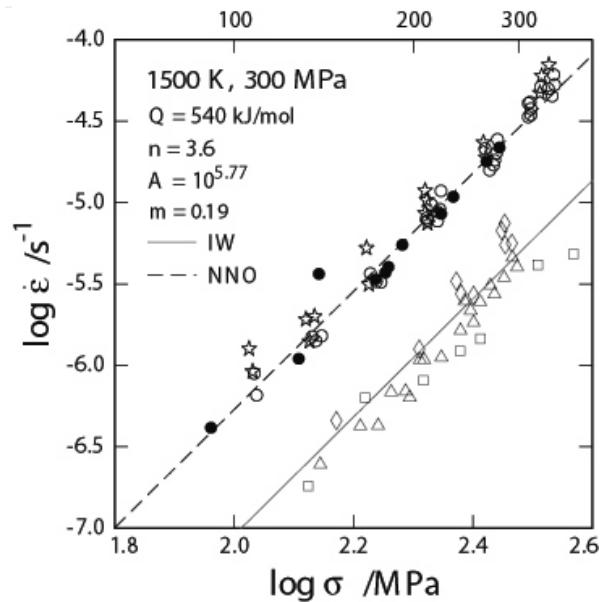


Figure 1: Log strain rate versus log stress data from several experiments normalized to a common temperature. Stars, filled circles, and empty circles are from samples buffered by iron wüstite. Diamonds, triangles, and squares are from samples buffered by nickel/nickel oxide.

Results: Analysis of the stress, strain, and temperature data yielded strain rate vs stress and Arrhenius plots. The data were then fit to the following

$$\text{power law relationship: } \dot{\varepsilon} = A\sigma^n fO_2^m \exp\left(\frac{-Q}{RT}\right),$$

where $\dot{\varepsilon}$ is strain rate, A is a material-dependent parameter, σ is differential stress, fO_2 is oxygen fugacity, Q is activation energy, n and m are power law exponents. R and T have the usual meaning. The results were normalized to 1500 K using the average activation energy derived from NNO and IW experiments performed at multiple temperatures. A fit of the normalized data was performed to determine the average value of n . Flow parameters were then obtained from a non-linear global fit to the data for each buffer. These values were used to solve for m . Using constant values for n and m , a final global fit was used to find values of A and Q that encompass the results for both IW and NNO. The normalized data plus the fit for both buffers are presented in Figure 1.

Implications: Geobarometry measurements on xenoliths from the Kaapvaal Craton in Africa [5] yield oxygen fugacity increasing five orders of magnitude with increasing depth. Based on our results, such an increase would decrease viscosity by a factor of approximately nine. If the oxidation state of the mantle changed from near IW to NNO since differentiation, the mantle would have weakened. An upper estimate of the weakening effect over the full IW/NNO range of ~4 orders of magnitude would produce a viscosity 6 times lower assuming constant stress. Heterogeneity in the mantle oxidation state would also effect viscosity

Conclusions: Samples buffered at NNO have a higher oxygen fugacity and thus flow faster than IW buffered samples. The strength difference between experiments at different solid state buffers demonstrates a power law exponent of 0.19. The results come from overlapping experiments performed on two different deformation rigs that illustrate the robustness of this conclusion.

The results compare favorably with previous experiments performed in the dislocation creep regime [3, 6, 7]. Chopra & Paterson used Fe and Ni sleeves, however, the sample was probably buffered at or near IW by the presence of an outer iron jacket that was used to confine the sample at pressure. Our creep results for IW buffered samples are comparable to the flow law from Chopra & Paterson. In addition, our NNO buffered sample flowed around a factor of six faster than the IW sample consistent with single crystal studies that report a power dependence close to ours along the strongest axis [1].

Higher viscosities under more reducing conditions probably reflect micromechanical processes at the scale of the dislocations [1, 2]. Lower diffusivities for silicon and/or oxygen defects at more reducing conditions may lower the rate of dislocation climb and, hence, increase aggregate strength.

The effect of a power law dependence of viscosity on oxygen fugacity could influence the viscosity as a function of depth. Geobarometry studies of xenoliths [5] report systematic variations in oxygen fugacity with depth that would introduce variations in mantle viscosity. Mantle-wide changes in oxidation state from near the IW buffer to the NNO buffer could produce significant mantle weakening.

References:

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