Flow Laws Describing Deformation of the Lithospheres of Terrestrial Planets Based on Experiments on Single Crystals of Olivine at Low Temperature and High Pressure.

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Introduction: Analyses of structural, topographic, and gravity data obtained for the terrestrial planets in terms of geodynamic processes require constitutive equations that accurately describe the rheological behavior of crustal and mantle rocks. To date, essentially all such analyses have been based on flow laws determined under high-temperature, low-stress, steady-state creep conditions. However, as emphasized by Evans and Kohlstedt [1], Kohlstedt et al. [2], and Hirth [3], at lower temperatures and higher stresses, the actual rheological behavior of peridotite deviates significantly from that predicted by high-temperature, low-stress flow laws, a point first demonstrated by Evans and Goetze [4]. Flow laws describing deformation under lower temperature, higher stress conditions are currently based either on the micro-indentation experiments of Evans and Goetze [4] or the load-relaxation experiments of Raterron et al. [5]; the uncertainties in both are large.

Our research aims to bridge the higher resolution results obtained at high temperatures in compressive creep experiments to the lower resolution data determined from indentation and load relaxation experiments, thus producing a reliable flow law describing deformation under lithospheric conditions. To do so, deformation experiments on olivine single crystals in a high-resolution gas-medium apparatus are being performed at temperatures between 800° and 1200°C and a confining pressure of up to 500 MPa. By using single crystal samples, it is possible to reach differential stresses that far exceed the confining pressure without inducing fracture.

Experimental Design: The complication with carrying out experiments required to develop a constitutive equation describing flow at low temperatures and high stresses is largely related to the relatively high confining pressures generally needed to suppress fracturing. The rule-of-thumb often applied in this area is the Goetze criterion [1], which simply states that the differential stress should not exceed the confining pressure. This criterion is not rigid, however, as demonstrated by studies of the deformation behavior of single crystals [e.g., 6] and fine-grained aggregates [e.g., 7] of olivine at ambient pressure.

Therefore, we have carried out compressive deformation experiments on olivine single crystals in a high-resolution gas deformation apparatus [8] in order to extend the experiments on single crystals to lower temperatures and high stresses than previously used. Samples are enclosed in relatively thick Ni capsules. The flow strength of Ni in our experiments is less than 5% of that of olivine, and measured loads are routinely corrected to remove the effect of the Ni sleeve and thus obtain the load on and strength of the samples [9]. In this abstract, we report results from single crystals deformed in compression along the $[101]_c$ direction. Here the subscript indicates that the axes are referenced to those of a cubic crystal; that is, the load was applied at 45° to the [100] and [001] crystallographic directions of the olivine crystals.

Results: Results from triaxial compressive creep experiments on olivine single crystals deformed along the $[101]_c$ direction are presented in Figures 1 and 2. In the plot of differential stress as a function of strain in Figure 1, data collected at 1000°C from a crystal of olivine deformed at constant strain rate are compared to those from three crystals deformed at constant stress. The sample deformed at a strain rate of 10^{-5} s^{-1} to a strain of 16% initially work hardens rapidly, up to a strain of ~5%, at which point the hardening rate decreases. Data obtained from three crystals deformed at constant stress are in good agreement with those obtained at constant strain rate.

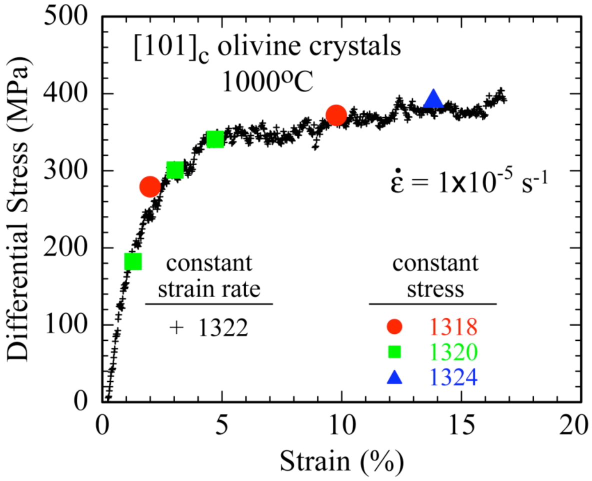

Figure 1: Differential stress versus strain for crystals deformed at 1000°C. Results for a crystal deformed at a constant strain rate of 10^{-5} s^{-1} (#1322) are compared to those for three crystals deformed at constant stress (#1318, #1320, #1324). All samples work hardened.

In the plot of differential stress as a function of temperature in Figure 2, results from two triaxial compressive creep experiments on olivine single crystals compressed along the $[101]_c$ direction at temperatures of 800° and 1000°C and a strain rate of 10^{-5} s^{-1} are compared to published high-temperature and low-temperature flow laws. The high-temperature flow law was determined from triaxial compressive creep experiments on coarse-grained dunite [10], while the low-temperature flow laws were obtained from indentation [4] and load relaxation [5] experiments. In this figure, the high-temperature flow law markedly overestimates the strength of our olivine crystals. Our results fall between the low-temperature flow laws of Evans and Goetze [4] and Raterron et al. [5].

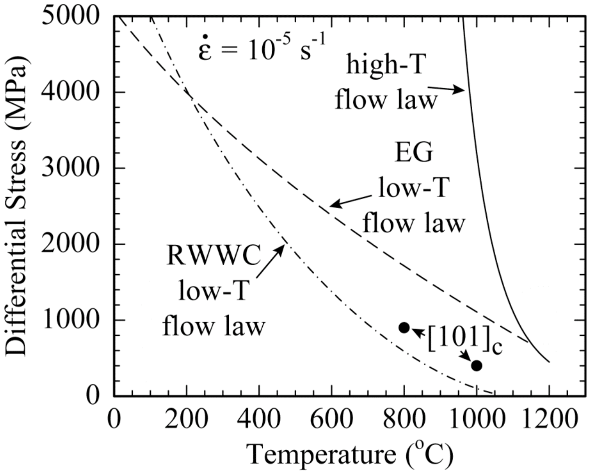

Figure 2: Differential stress versus temperature comparing the high- and low-temperature flow laws with results from two triaxial deformation experiments on single crystals of olivine compressed along $[101]_c$ at 10^{-5} s^{-1}, T = 800° and 1000°C, and P = 300 MPa. The high-temperature flow law [10] significantly over estimates the low-temperature flow stress. Our deformation results obtained on single crystal samples in our gas-medium apparatus fall between the values predicted by the two low-temperature flow laws [4,5].

Discussion: Previously reported flow laws for low-temperature deformation of olivine differ markedly from one another. The flow law obtained from load-relaxation experiments predicts a much weaker lithosphere than does the flow law determined from micro-indentation tests.

Under high-temperature conditions, single crystals oriented for deformation along $[101]_c$ are a factor of ~2 weaker than coarse-grained samples [11]. If this difference in strength extends to lower temperatures, then the results obtained in this study on single crystals would be in reasonably good agreement with those reported from micro-indentation tests, based on data presented in Figure 2. Further experiments are in progress to quantify the flow behavior of single crystals compressed along the $[110]_c$ and $[011]_c$ directions, which are weaker and stronger, respectively, than crystals deformed along the $[101]_c$ direction, at least at high temperatures [e.g., 12]. The results of these experiments will further constrain flow laws appropriate for describing deformation under lithospheric conditions.

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References: [1] Evans B. and Kohlstedt D.L. (1995) in *Rock Physics and Phase Relations: A Handbook of Physical Constants*, ed. Ahrens T.J., AGU Monogr., 148-165. [2] Kohlstedt D.L. et al. (1995) *JGR*, *100*,17587-17602. [3] Hirth G. (2002) in *Plastic Deformation in Minerals and Rocks*, eds. Karato S.I. and Wenk H.R. Reviews in Mineralogy and Geochemistry, Mineral. Soc. Amer., *51*, 97-120. [4] Evans B. and Goetze C. (1979) *JGR, 84,* 55058-5524. [5] Raterron, P. et al. (2002) *PEPI, 145,* 149-159. [6] Kohlstedt D.L. and Goetze C. (1974) *JGR, 79,* 2045-2051. [7] Cooper R.F. (1990) *JGR, 95,* 6979-6992. [8] Paterson M.S. (1990) in *The Brittle-Ductile Transition in Rocks*, AGU Geophys. Monogr. Ser., *56*, 187-1994. [9] Zimmerman M.E. and Kohlstedt D.L. (2004) *J. Petrol, 45*, 275-298. [10] Chopra P.N. and Paterson M.S. (1984) *JGR, 89,* 7861-7876. [11] Hirth G. and Kohlstedt D.L. (1995) in *Inside the Subduction Factory,* ed. Eiler J., AGU Monogr., *138*, 83-105. [12] Bai et al. (1991) *JGR,96,* 2441-2463.