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The stress dependence of olivine creep rate: Implications for extrapolation of lab data and interpretation of recrystallized grain size

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ABSTRACT

Based on measured values for the stress exponent, $n \approx 3.5$, combined with the empirically determined relationship between dislocation density and stress ($\rho \propto \sigma^{1.37}$) and an analysis of diffusion kinetics in olivine, we conclude that silicon pipe diffusion limits strain rate in the dislocation creep regime. Furthermore, assuming that steady state recrystallized grain size is set by a dynamic balance between strain energy density (associated with dislocations) and surface energy density (associated with grain boundaries), the resulting dependence of recrystallized grain size on stress accurately describes experimental observations when the empirical dislocation density versus stress relationship is accounted for ($d \propto 1/\sigma^{1.37}$). The improved physical understanding of the stress dependence of creep rate provides justification for incorporation of experimentally derived flow laws into models of geodynamical process and grain size evolution. These lab constraints combined with independent analyses of the stress dependence of mantle viscosity based on geophysical data provide bounds on rheological properties such as the yield stress of the lithosphere.

1. Introduction

Successful application of laboratory constraints on mantle viscosity requires both accurate determination of the stress dependence of creep rate and detailed understanding of the micromechanical processes that limit the creep rate. For example, the stress dependence of creep has important implications for interpreting the spatial response and processes responsible for visco-elastic relaxation during post-seismic creep (e.g., Freed et al., 2012) – which in turn provide geophysical tools to estimate mantle viscosity. The stress dependence of dislocation creep is also an important parameter in models for grain size evolution (e.g., de Bresser et al., 2001; Austin and Evans, 2009); microstructural observations of dynamic recrystallized grain size provide a powerful tool to investigate rheological properties of the lithosphere. An understanding of processes that control grain size is also critical for interpretation of a wide range of geodynamic processes, from the attenuation of seismic waves, fluid and melt transport, and strain localization at plate boundaries.

Experimental data on the high temperature creep behavior of olivine single crystals, dunites and peridotites are all well fit with a power law relationship between strain rate ($\dot{\varepsilon}$) and differential stress (σ),

$$\dot{\varepsilon} \propto \sigma^n. \tag{1}$$

For $30 \lesssim \sigma \lesssim 300$ MPa, reported values of the stress exponent, n, lie in the range 3 to 5.

To apply laboratory creep data to high-temperature mantle flow, constitutive equations must be extrapolated approximately two orders of magnitude in differential stress. Consequently, relatively small differences in n result in dramatically different predictions for mantle viscosity. In the illustrative example shown in Fig. 1, extrapolation of lab data from 100 MPa to a differential stress of 1 MPa with $n = 5$ predicts an effective viscosity approximately three orders of magnitude greater than that estimated with $n = 3.5$. This example illustrates extrapolation of lab data to mantle conditions beneath oceanic spreading centers; in this case, only extrapolation in stress is required because the experiments are conducted at the same pressure and temperature as those estimated for this region of the mantle. Given estimates and measurements for grain size in the mantle of 1–10 mm (e.g., Ave Lallemant et al., 1980; Behn et al., 2009; Evans et al., 2001), the relatively high effective viscosity predicted for dislocation creep with $n = 5$ indicates that diffusion creep would be the dominant deformation mechanism in the upper

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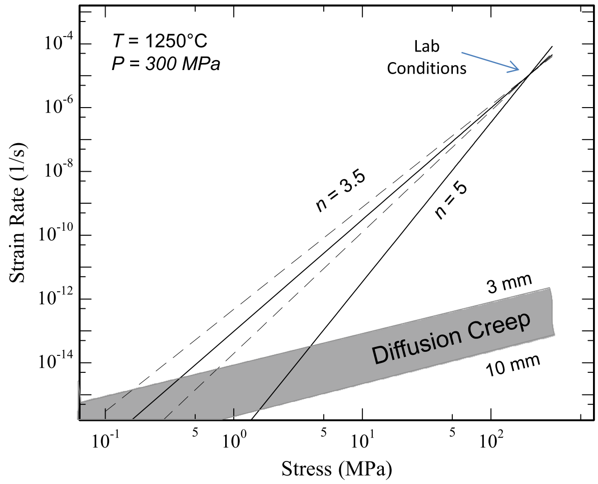

Fig. 1. Plot of differential stress versus strain rate illustrating how the mantle strain rate (effective viscosity) predicted by extrapolation of the dislocation creep flow law depends strongly on the stress exponent (n). The lines labeled $n = 3.5$ show predicted strain rates and uncertainty (dashed lines) for a dislocation creep flow law with $n = 3.5 \pm 0.3$. The field labeled diffusion creep shows predicted strain rates for the olivine diffusion creep flow law with mantle grain sizes from 3 to 10 mm (Hirth and Kohlstedt, 2003). Dislocation creep (with $n = 3.5$) is predicted to be the dominant deformation at mantle stresses of ∼1 MPa, consistent with geophysical observations. In contrast, with $n = 5$ diffusion creep dominates at mantle stresses.

mantle (Fig. 1). This prediction is inconsistent with both geological and geophysical observations that demonstrate microstructural (e.g., fabric) and physical properties (e.g., seismic anisotropy) consistent with dislocation creep (e.g., Mainprice and Silver, 1993; Karato et al., 2008).

The dependence of strain rate on stress for dislocation creep under dry conditions is constrained from experiments on coarse-grained (up to ∼1 mm) natural dunite and olivine single crystals. Analyses of individual data sets for coarse-grained natural samples give $n = 3.6 \pm 0.1$ (Keefner et al., 2011) and $n = 3.6 \pm 0.2$ (Chopra and Paterson, 1984). Similarly, olivine single crystals deformed in orientations to produce slip on one or two of the major slip systems exhibit $3.3 \le n \le 3.9$ for wide ranges of temperature, oxygen fugacity and silica activity ($n = 3.6 \pm 0.3$ (Durham and Goetze, 1977); $n = 3.5 \pm 0.1$ (Bai et al., 1991); $n = 3.5 \pm 0.2$ (Jin et al., 1994)).

In contrast, a "global inversion" of dry dislocation creep data by Korenaga and Karato (2008) resulted in a significantly larger value of $n = 4.9$. These authors limit their evaluation of dry dislocation creep to studies on hot-pressed olivine aggregates. Experiments on hot-pressed aggregates, which have relatively small grain sizes, are conducted at conditions at the transition between dislocation creep and grain size sensitive deformation mechanisms (dislocation-accommodated grain boundary sliding (GBS) or diffusion creep). In this case, accurate determination of the stress dependence of strain rate (i.e., n) requires simultaneous analysis of the grain size dependence of creep rate. Under such conditions olivine creep rates are well fit with a constitutive relationship with the form (Hirth and Kohlstedt, 2003; Hansen et al., 2011)

$$\dot{\varepsilon}_{tot} = \dot{\varepsilon}_{diff} + \dot{\varepsilon}_{gbs} + \dot{\varepsilon}_{disl}, \tag{2}$$

where the subscripts *tot*, *diff*, *gbs*, and *disl* refer to total, diffusion, dislocation-accommodated grain boundary sliding, and dislocation creep. At constant pressure, P, temperature, T, and chemical environment, $\dot{\varepsilon}_{diff} = \dot{\varepsilon}_{diff}(\sigma, d)$, $\dot{\varepsilon}_{gbs} = \dot{\varepsilon}_{gbs}(\sigma, d)$, and $\dot{\varepsilon}_{disl} = \dot{\varepsilon}_{disl}(\sigma)$, where d is the grain size. In contrast to the global fit (i.e., Korenaga and Karato, 2008), analyses of individual data sets for hot-pressed aggregates using Eq. (2) consistently give values for n for dislocation creep and/or GBS in the range from 3.0 to 3.5; Hirth and Kohlstedt (2003) (who included a re-analysis of data from Mei and Kohlstedt, 2000) concluded that $n = 3.5 \pm 0.3$ for both GBS and dislocation creep, Wang et al. (2010) determined $n = 3.3 \pm 0.2$ for GBS, and Hansen et al. (2011) found $n = 2.9 \pm 0.3$ for GBS. At similar grain size/stress conditions as those used to identify GBS, Bystricky et al. (2000) obtained $n = 3.2$ to 3.3, while Karato et al. (1986) found $n = 3.5$. In contrast, a value of $n \approx 8$ has recently been reported from creep tests on fine-grained olivine aggregates synthesized from oxides (Faul et al., 2011), who also concluded that an exponential relationship provided a good fit to their data.

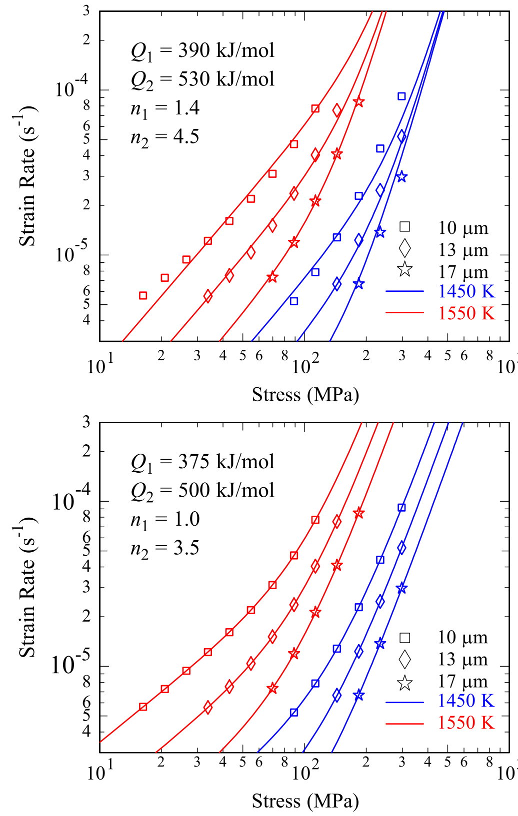

Fig. 2. Plots of differential stress versus strain rate showing influence of neglecting the grain size sensitivity of creep rate in the GBS regime on fits for the stress exponent. Synthetic data for both plots are created for two temperatures and three grain size using the diffusion creep and GBS flow laws reported in Hirth and Kohlstedt (2003). The lines show non-linear least squares fits (for A, n and Q) to the synthetic data using the relationship $y = A_1\sigma^{n1}\exp(-Q_1/R/T)/d^3 + A_2\sigma^{n2}\exp(-Q_2/R/T)/d^p$. In the top plot, $p = 0$ (i.e., there is no grain size dependence to strain rate in the high stress regime); in this case, the value of n_2 is significantly greater than that used to generate the data. In the bottom plot, $p = 2$ and the flow law parameters used to generate the data are returned by the fit.

We suggest that, in their global fit, Korenaga and Karato (2008) overestimated the value of n because they did not include the grain-size sensitive GBS regime in their analysis. At the time of their analysis, data constraining the GBS process were limited. Consequently, they interpreted data sets from both coarse-grained and fine-grained samples that reported $n = 3$–4 as lying within the dislocation creep regime and thus as having no grain size dependence. In Fig. 2 we illustrate why neglecting the grain size dependence associated with GBS can result in an overestimation of n. For this analysis, we plot a synthetic data set created using the diffusion creep and GBS flow laws from Hirth and Kohlstedt (2003) for ranges in temperature and grain size typical of those used for experiments on hot-pressed aggregates. The details of these flow laws are not the focus of this paper; we are only illustrating the effect of neglecting the grain size dependence of GBS. While the synthetic data set was generated with $n = 3.5$ in the