ANISOTROPIC VISCOSITY OF OLIVINE-CHROMITE-MORB AGGREGATES.

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Introduction: The anisotropic viscosity (AV) of deformed mantle rocks significantly effects the outcome of large-scale geodynamic models. Specifically, AV impacts the development of Rayleigh-Taylor instabilities [1], a process strongly connected to lithospheric foundering [e.g., 2], Mars-like mantle convection [3], and planetary core formation [4]. While networks of partial melt are proposed to influence the AV of planetary interiors [1,5,6,7], insufficient experimental data exist to fully quantify this effect.

In this study, we build on previous work [6,8,9,10] in which it was demonstrated that as a partially molten rock deforms, melt segregates and organizes into melt-rich bands oriented ~20° antithetic to the shear direction [6]. Similar to materials with strong crystallographic-preferred orientations, the viscous response of melt-rich material may depend on the orientation of the applied stress relative to the melt-bands.

The viscous deformation of an anisotropic rock can be described through the relationship between the stress, strain-rate, and viscosity tensors. This relationship can be significantly simplified by assuming the deformation is isochoric and the material is transversely isotropic [5,11], which yields

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{xz} \end{Bmatrix} = \begin{bmatrix} \eta_{xxxx} & \eta_{xxxz} \\ \eta_{xzxx} & \eta_{\mathrm{xzxz}} \end{bmatrix} \begin{Bmatrix} \dot{\varepsilon}_{xx} \\ \dot{\varepsilon}_{xz} \end{Bmatrix}$$

where σ_{xx}, and η_{xxxx} refer to the normal stress, and normal viscosity, and σ_{xz}, and η_{xzxz}, the shear stress, and shear viscosity. A common measure of the degree of anisotropy, δ, is the ratio of the normal and shear viscosities. To determine the value of δ for rocks with a segregated melt phase, we performed deformation experiments in torsion and triaxial compression to estimate the shear and normal viscosities, respectively.

Methods: Experiments were performed in a gas-medium deformation apparatus [12] using a method similar to that of previous studies on olivine+MORB samples [13,14,15]. We performed one series of experiments in which the sample was deformed in torsion, followed directly by triaxial compression. Microstructural analyses followed each deformation stage to monitor the growth, and evolution of melt networks.

Powders of olivine, chromite, and MORB (76:20:4) were cold pressed into a Ni can at 100 MPa uniaxial pressure. The sample was then hot-pressed in a gas-medium deformation apparatus [12] at 1523 K and 300 MPa for ~4 hours. The sample was then immediately deformed in torsion at the same conditions. Torsional deformation served to induce melt segregation and produce an anisotropic microstructure. Once sufficient strain was accumulated to ensure melt segregation, strain rate stepping tests were performed to characterize the shear stress dependence of the shear viscosity. Subsequent to torsional deformation, the sample was removed from the apparatus and tangential sections were polished and optically investigated in reflected-light. Melt bands were observed within the outer 3.2 mm of the sample consistent with previous work [16]. We then cut a rectangular parallelepiped from the outer portion of the sample with relatively homogeneous microstructure and rejacketed this smaller sample in a nickel can. The rejacketed sample was then deformed in triaxial compression at 1523 K and 300 MPa such that the maximum compressive stress was parallel to the torsion axis. Load stepping was carried out to characterize the stress dependence of the normal viscosity. Subsequent to deformation, polished sections were prepared for microstructural analysis.

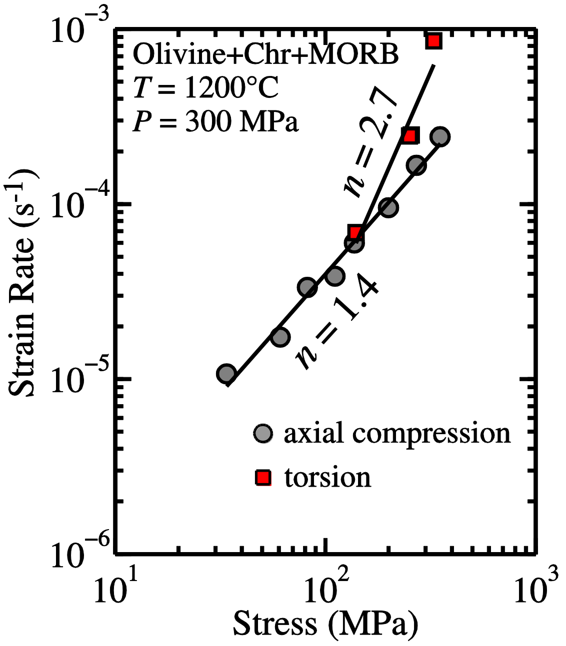

Figure 1. Mechanical data from both torsion and axial compression experiments. Solid lines are fits to the individual data sets, and the best-fit stress exponent, n, is given. Note that the largest difference in

strength is observed at higher stresses, and there is possibly a crossover in strength at ~130 MPa.

Results: Mechanical data are presented in Figure 1. From these data, we calculate stress exponents of $n = 1.4$ and $n = 2.7$ for compression and torsion, respectively. At the highest stress attained (~380 MPa), which corresponds to the biggest difference in viscosity between torsion and compression, we calculate a shear viscosity of 3.6×10^{11} Pa s and a normal viscosity of 1.3×10^{12} Pa s. These viscosities result in $\delta = 3.6$.

As illustrated in Figure 2a, microstructural investigations after torsion reveal melt-rich bands oriented 20° antithetic to the shear direction. This microstructure compares well with that observed by [17] and presented in Figure 2b. After axial compression, however, the melt distribution appears relatively homogeneous (Figure 2c).

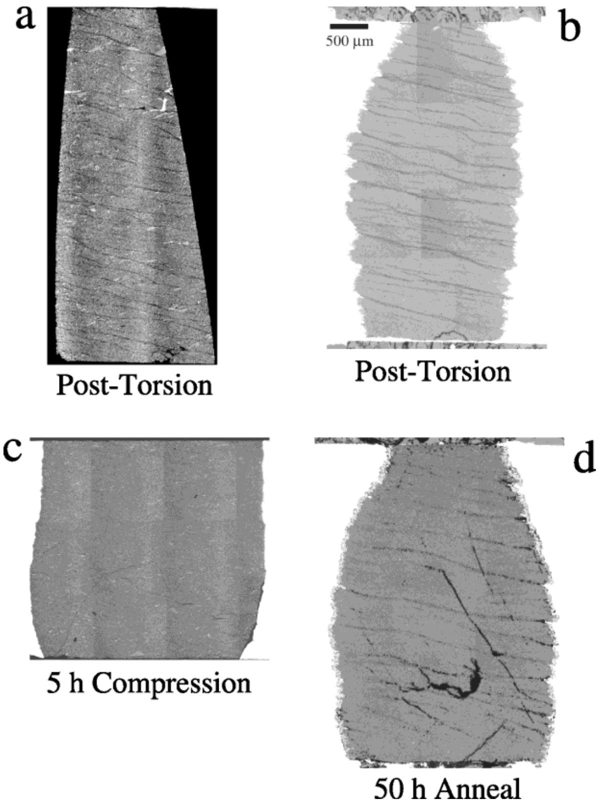

Figure 2. Mosaics of reflected-light photomicrographs from tangential sections of deformed Ol-Chr-MORB aggregates after torsion (a and b), compression (c), and annealing (d). (a) and (c) are from this study. (b) and (d) are from [17]. Note that melt-rich bands are still observed after 50 h of annealing but are absent after only 5 h of compression.

Discussion: For an olivine-chromite-MORB aggregate at 380 MPa, there is a half-order of magnitude difference between the shear and normal viscosities. This difference, however, is a strong function of the stress (or strain rate) because of the different stress exponents observed. The difference in stress exponents may be due to a change in dominant deformation mechanism associated with a change in stress orientation or, alternatively, associated with the difference in melt distribution as the melt desegregates during compression. Interestingly, the desegregation occurred over the duration of a 5 h compression experiment (Figure 2c), whereas static annealing experiments by [17] exhibit some band-like structures after 50 h (Figure 2d). Therefore, the melt distribution reacts quickly to changes in stress orientation such that the orientation of the viscosity tensor and the magnitude of its anisotropy quickly adjust to changes in the stress tensor.

The maximum magnitude of anisotropy observed in this study, $\delta = 3.6$, is significantly smaller than previously expected by theoretical treatments [e.g., 18]. We emphasize, however, that compression tests were not conducted normal to the band orientation but rather normal to the shear plane. Thus, our estimate of δ serves as a minimum presuming that compressive strength is greatest normal to the band orientation. These experiments provide constraints on both the magnitude of AV in partially molten rocks and insight into the evolution of both the melt distribution and the viscosity tensor with changing stress conditions.

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