Chemical differentiation of rocky planets occurs by melt segregation away from the region of melting. The mechanics of this process, however, are complex and incompletely understood. In partially molten rocks undergoing shear deformation, melt pockets between grains align coherently in the stress field; it has been hypothesized that this anisotropy in microstructure creates an anisotropy in the viscosity of the aggregate. With the inclusion of anisotropic viscosity, continuum, two-phase-flow models reproduce the emergence and angle of melt-enriched bands that form in laboratory experiments. In the same theoretical context, these models also predict sample-scale melt migration due to a gradient in shear stress. Under torsional deformation, melt is expected to segregate radially inward. Here we present torsional deformation experiments on partially molten rocks that test this prediction. Microstructural analyses of the distribution of melt and solid reveal a radial gradient in melt fraction, with more melt toward the center of the cylinder. The extent of this radial melt segregation grows with progressive strain, consistent with theory. The agreement between theoretical prediction and experimental observation provides a validation of this theory.

Significance

Partially molten regions of Earth link mantle convection with surface volcanism. We present laboratory experiments and theory that are at the heart of understanding the connection between these interior and surface processes. The theory proposes that the presence of melt fundamentally changes the style of deformation, making it anisotropic with leading-order, testable consequences. The laboratory results are in agreement with theoretical predictions. These results are novel at a foundational level and profoundly surprising. Together they make the case that the creep rheology of partially molten rocks is more than the sum of its parts. Moreover, this article sets forth a framework that will guide a broad swath of future research in rock mechanics and mantle flow.
approximation, we assume that, at each point in the domain, the imposed shear direction lies in the plane containing \( \sigma_1 \) and \( \sigma_2 \); this plane is perpendicular to the imposed shear plane (figures 3 and 5 of ref. 13). This leaves only one angle to be determined, the angle \( \Theta \) between the shear plane and the \( \sigma_3 \) direction. The magnitude of anisotropy is parameterized with two scalars: \( \alpha \) specifies the viscosity reduction in the \( \sigma_3 \) direction; \( \beta \) specifies the viscosity increase in the \( \sigma_1 \) direction. When either \( \alpha \) or \( \beta \) or both \( \alpha \) and \( \beta \) are nonzero at a point in the continuum, the viscosity at that point is anisotropic. The associated tensor then has nonzero off-diagonal terms that couple shear stress to normal strain rate (and vice versa). It is these terms that give rise to base-state segregation (13, 14).

To clarify the physical mechanism of base-state segregation, consider a cylindrical sample in a sealed chamber, deformed in torsion at a constant twist rate (Fig. 1C). Before any deviatoric stress is applied, the grain/melt microstructure is isotropic and the rate of (de)compaction is zero everywhere within the sample. With initiation of twisting, as a consequence of the deviatoric stress, a MPO develops and the viscosity becomes anisotropic. The imposed strain rate, aligned melt pockets, and consequent pattern of stress are shown schematically in Fig. 1B and C. The disparity between \( |\sigma_1| \) and \( |\sigma_3| \) gives rise to a net compression that, because \( \sigma_1 \) and \( \sigma_3 \) are everywhere tangent to the cylinder, is a compressive hoop stress. This compressive hoop stress pushes the solid grains radially outward and causes a pressure gradient that drives melt radially inward (13) (details provided in SI Appendix 2). This differential motion is the base-state melt segregation under torsional deformation.

To test this prediction and hence the hypothesis that viscosity is anisotropic, we imposed a constant twist rate on cylindrical samples of partially molten rock that initially had uniform melt fraction (Table 1). In tangential sections of quenched samples that were deformed in torsion (Fig. 2), we observe aligned melt pockets and low-angle, melt-enriched bands. Melt-enriched bands are also evident in transverse sections (Fig. 3). More importantly, analyses of optical micrographs of transverse sections reveal a gradient in melt fraction in the radial direction, with melt concentrated toward the axis of the cylinder. This gradient in melt fraction corresponds to the base-state melt segregation predicted if viscosity is anisotropic. Our observations of MPO, melt-enriched bands, and radial melt segregation are detailed in subsequent paragraphs.

Results and Discussion

MPO. The rose diagram in Fig. 2B demonstrates that at a local shear strain of \( \gamma = 4.6 \), melt pockets are aligned at \( \sim 29^\circ \) to the shear plane, antithetic to shear direction. In contrast, the expected \( \sigma_3 \) direction, based on cylindrical simple shear flow with isotropic viscosity, is \( 45^\circ \) to the shear plane. The observed low angle of melt alignment means that, at this shear strain, either melt pockets are not normal to the \( \sigma_3 \) direction (17) or \( \sigma_3 \) has rotated counterclockwise. The reason for this alignment is unknown; it might be due to the emergence of chains of melt pockets (18) (Fig. 2C) or to the anisotropic viscosity itself. In the theory of two-phase flow with viscous anisotropy, elaborated in SI Appendix 1, it is generally assumed that melt pockets align perpendicular to \( \sigma_3 \), as suggested by deformation experiments on an analog material at small strains (\( \gamma < 0.2 \)) (19). The observed MPO, therefore, may represent a subtle but important discrepancy between observation and theory that we return to below. Despite this possible discrepancy, the observed, strong MPO demonstrates the microstructural anisotropy that hypothetically causes viscous anisotropy.

Melt Distribution. Two-phase flow theory with anisotropic viscosity (13) also predicts the emergence of sheets of high-melt fraction that appear as bands in 2D sections (3). In Fig. 3, these features appear as radial lines of high-melt fraction where sheets cross the transverse section. For the sample deformed to an outer-radius shear strain of \( \gamma = 5.0 \) (Fig. 3A and C), the melt-enriched bands are distributed uniformly around the cylinder, whereas at a larger strain of \( \gamma = 14.3 \) (Fig. 3B and D), the

Table 1. Experiments summary

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \gamma (R) )</th>
<th>( K_{eq} ) s(^{-1} )</th>
<th>( \sigma_{eq} ), MPa</th>
<th>( \phi_{max}/\phi_{min} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P0767</td>
<td>11.1</td>
<td>2.29 \times 10^{-4}</td>
<td>187</td>
<td>1.6</td>
</tr>
<tr>
<td>P0811</td>
<td>5.6</td>
<td>1.84 \times 10^{-4}</td>
<td>237</td>
<td>1.2</td>
</tr>
<tr>
<td>P0812</td>
<td>5.8</td>
<td>1.84 \times 10^{-4}</td>
<td>163</td>
<td>1.4</td>
</tr>
<tr>
<td>P0817</td>
<td>5.0</td>
<td>2.35 \times 10^{-4}</td>
<td>197</td>
<td>1.3</td>
</tr>
<tr>
<td>P0839</td>
<td>7.3</td>
<td>1.84 \times 10^{-4}</td>
<td>237</td>
<td>1.7</td>
</tr>
<tr>
<td>P0891</td>
<td>14.3</td>
<td>2.04 \times 10^{-4}</td>
<td>179</td>
<td>2.0</td>
</tr>
</tbody>
</table>

\( \gamma (R) \) is the outer-radius shear strain, \( R \) is the radius of a sample with \( R = 6 \) mm.

\( K_{eq} \) The equivalent strain rate and stress, \( \sigma_{eq} \), respectively, are calculated from shear strain rate and stress, using the Cauchy stress tensor.

\( \phi_{max}/\phi_{min} \) is the ratio of maximum to minimum melt fraction in the profile of azimuthally averaged melt fraction.
azimuthal distribution of melt-enriched bands is inhomogeneous, dominated by several extraordinarily large bands. Because the total strain decreases toward the center of the cylinder, the region close to axial center exhibits less banding. More significantly, however, Fig. 3 C and D demonstrates a general increase in melt fraction toward the center of the cylinder, consistent with the predicted base-state migration of melt radially inward.

Radial profiles of the azimuthally averaged, normalized melt fraction are presented in Fig. 4A for seven experiments, each with a different final strain. The melt fraction in an experiment with no deformation (gray line) varies by less than 10% along a radius. In all deformed samples, the melt fraction increases toward the center of the cylinder—evidence for base-state segregation. For the three samples deformed to an outer-radius shear strain of $\gamma(R) = 5.5 \pm 0.5$, each radial profile of melt concentration reaches its peak at a radius of $r^{\text{peak}} \approx 1$ mm, corresponding to a shear strain of $\gamma(r^{\text{peak}}) \approx 1$. Melt fraction decreases from that point toward the axis of the cylinder; this behavior is expected because the low-stress/low-strain region at small radius has little or no MPO and hence has essentially isotropic viscosity ($\alpha = \beta = 0$). For samples deformed to higher outer-radius shear strains [$\gamma(R) = 7.3$, $11.1$, and $14.3$], peaks in melt fraction occur at a radius of $r^{\text{peak}} < 0.2$ mm. The sample with the highest outer-radius shear strain [$\gamma(R) = 14.3$] exhibits the largest ratio of maximum to minimum melt fraction $\phi_{\text{max}}/\phi_{\text{min}}$ (Table 1), a measure of the strength of base-state melt segregation. Except for the samples sheared to outer-radius shear strains of $\gamma(R) = 5.0$ and $7.3$, the maximum in melt fraction increases with increasing shear strain. In summary, the results presented in Fig. 4A demonstrate that, with increasing strain, the pressure gradient induced by anisotropic viscosity drives melt inward, increasing the maximum value of the azimuthally averaged melt fraction and decreasing the radius at which this maximum occurs.

**Comparisons with Model.** Fig. 4B compares the azimuthally averaged profiles of normalized melt fraction from three samples deformed to $\gamma(R) = 5.5 \pm 0.5$ with those derived from numerical simulations. The data points in Fig. 4B, which are the mean values of the azimuthal averages at each radius, reach a maximum normalized melt fraction of $\approx 1.15$ at $r^{\text{peak}} \approx 1$ mm and a minimum of $\approx 0.95$ at $r \approx 4$ mm. For comparison, radial profiles of melt fraction from numerical simulations of samples deformed to $\gamma(R) = 5.5$ at an initial compaction length of $\delta_0 = 0.1$ R and a bulk-to-shear viscosity ratio of $\nu_s = 10$. In the simulations, two conditions are used for the angle of viscous anisotropy: (i) $\Theta = 45^\circ$, suggested by previous experiments (19), and (ii) $\Theta = 60^\circ$, suggested by Fig. 2. For both conditions, if an initial perturbation in melt fraction is incorporated into the simulation, melt-enriched bands develop. However, for $\Theta = 60^\circ$, the band angle is higher than observed in experiments (15); this inconsistency requires further investigation. The other variable in the simulations is the magnitude of viscous anisotropy. In all four simulations, $\alpha$ increases from zero at the center of the cylinder to $\alpha_{\text{max}} = 2$ at $r \approx 1$ mm and then remains constant at larger radii. In two of the simulations, $\beta$ mimics the behavior of $\alpha$. In the other two simulations, $\beta$ is zero at all radii. In the decompaction region (i.e., at small radii), profiles with $\Theta = 45^\circ$ exhibit higher melt fractions than
In this paper we presented experimental observations of the radial distribution of melt in partially molten rocks deformed in torsion to large strain. For this deformation geometry, the theory of melt segregation with anisotropic viscosity predicts a radial distribution of melt fraction. The inclusion of viscous anisotropy in the theory is a necessary and sufficient condition for the development of radially inward, base-state melt segregation. Our experiments test this prediction, and the results reported here are in general agreement with theory, validating the viscous-anisotropy hypothesis. This experimental validation of MPO-induced viscous anisotropy represents a significant advance in our understanding of the relationship between microstructure, microfracture, and rheology of partially molten rocks, and it also exposes details of the linkage between deformation, MPO, and viscosity that are not captured by the present model. Although questions remain concerning the influence of MPO-induced viscous anisotropy on large-scale mantle dynamics, this study emphasizes its importance to melt segregation and rheological behavior of partially molten rocks in laboratory experiments and mantle flow.

Materials and Methods

Samples were fabricated from mixtures of fine-grained powders of olivine from San Carlos, AZ, plus 10 vol% alkali basalt from Hawaii. Olivine powders were obtained by grinding San Carlos olivine crystals in a fluid-energy mill to produce a particle size of 2 μm. Before mechanically mixing with alkali basalt powders with a particle size of 10–100 μm, the olivine powders were dried at 1,373 K for 12 h at an oxygen partial pressure near the Ni-NiO buffer to remove water and carbon-based impurities introduced during the grinding process. Mixtures were uniaxially cold-pressed at 100 MPa into nickel capsules and then hydrostatically hot-pressed at 1,473 K and 300 MPa for 3.5 h in a gas-medium apparatus (21). After hot-pressing, samples were cut into thin cylinders with a diameter of 2R = 12 mm and a thickness of 3–5 mm. The cut sample was then placed into a nickel capsule with spacers coated from a coarse-grained natural dunite as end caps, thus providing nonreactive, impermeable boundaries during deformation (22). The sample, Al2O3 spacers and pistons, and ZrO2 pistons were enclosed in an iron jacket for deformation.

Torsion experiments were conducted at a shear strain rate of $10^{-5}$ to $10^{-4}$ s$^{-1}$, a temperature of 1,473 K, and a confining pressure of 300 MPa in a gas-medium apparatus fitted with a torsion actuator (21). After achieving the target strain, each sample was cooled rapidly (~2 K/s) to 1,300 K under the torque imposed at the end of the deformation experiment to preserve the deformation-processed microstructure and then cooled to room temperature with no torque applied. After deformation, with the iron jacket and the nickel capsule dissolved in acid, the deformed sample was cut in half perpendicular to the torsional axis, leaving two transverse sections for examination. Each transverse section was polished on a series of diamond lapping films down to 0.5 μm, followed by a final step using colloidal silica. The section was then examined by reflected-light optical microscopy after chemically etching with diluted HF to highlight melt pockets.

To map the whole transverse section with an area of $\sim 113 \text{ mm}^2$, a mosaic image consisting of 2,209 high-resolution (0.3 μm per pixel) optical micrographs was used. A binary image with melt appearing white was created from this mosaic image, using a combined image segmentation method, which includes edge detection (23–25) and a threshold of grayscale. Then a profile of melt fraction was calculated from the area fraction of the white pixels (22).

**Conclusions**


