How does melt influence the seismic anisotropy of partially molten upper mantle?

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Introduction

We have demonstrated that the presence of melt has a significant effect on the rock fabrics, or lattice preferred orientations (LPO), in olivine-rich rocks deformed in the laboratory. The question, as always, is how to extrapolate these results to the mantle. Here, we show further results that demonstrate that the transition between fabric types appears to depend on the length scale of melt segregation, a result that will provide a strong constraint on the scaling problem as we come to understand it better. However, we also ask to what extent the LPO or the melt itself will dominate the measured anisotropy. We are in the beginning stages of a project to measure 3-D anisotropy beneath the East African rift in Ethiopia.

1. How does melt affect an olivine rock fabric?

We reported transitions in olivine LPO in the presence of melt (Holtzman et al., 2003), (1), below): a typical high T a-slip on b-plane fabric with no melt, (2) grids in a- and c- plane figures in the presence of aligned melt pockets (in samples of olivine+MORB); (3) an apparent c-slip on b-plane fabric when melt segregates into networks (in samples of olivine+chromite+MORB). Subsequently, we have found that the olivine + MORB system also develops the same transition but at higher strain than in samples with long wavelength networks, confirming our hypothesis that the chromite plays no direct role in causing the fabric transition. All samples were deformed in a Paterman gas medium deformation apparatus at 330 MPa and 1250°C. The shear stresses and strains are listed for each sample below.

Observations at grain- and dislocation- scale

SEM images (secondary electrons) of samples decorated by oxidation of dislocation cores and grain boundaries.

<table>
<thead>
<tr>
<th>olivine MORB</th>
<th>olivine+MORB</th>
<th>olivine+chrome+MORB</th>
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<td>1. The grain size in the two samples appears similar.</td>
<td>2. There do not appear to be stress concentrations (i.e. high dislocation density) in olivine adjacent to chromite grains. However, chromite grains probably pin grain boundaries.</td>
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Rheology:

Normally, the LPO patterns to the left would be interpreted as indications of the dominant dislocation slip system (e.g. Katayama et al., 2005), if so, the correspondence between rheological behavior and LPO/microstructural observations must be explained.

At right, single crystal data show the strength of the two dominant slip systems, with the yellow box indicating the conditions of our experiments. (010)[001] is stronger than [010][001]. However, in the effective rheological data for these shear experiments, the opposite trend is observed: samples with [010][001] are weaker than those with [010][001], suggesting that the dislocation slip system is not controlling the strength of the composite. We suggest that strain partitioning between deformation mechanisms at different scales is controlling the strength of the samples, as discussed below.

Interpretation:

1. The usual high-temperature olivine fabric, no melt present, a-slip dominates.

2. In the presence of an oriented melt fabric, homogeneous at the grain scale, diffusion creep (along grain boundaries) becomes very easy in the shear plane, but leaves a residual stress field to be accommodated by (a- and c-) dislocations randomized because they are accommodating local grain interactions, not the dominant simple shear.

3. When melt segregates to length scales larger than the grain size, stress in "lenses" reflects back-rotation (see Katz model) and sideward elongation of lenses, both due to partitioning of shear strain in bands. The fact that olivine+MORB develops the a-c flip suggests (but more slowly) that the rate of the rotation process increases with increasing length scale of melt segregation (for a constant stress).

Further questions: many...

2. How does melt directly cause seismic anisotropy?

With Mike Kendall, we are developing a simple model for the effect of melt on seismic anisotropy. We calculate several contributions of melt to anisotropy, including isotropic melt rich layers (b) and oriented pockets (d), each calculated with a flavor of effective medium theory (e.g. Kendall, 1994) and superimposed on a background LPO, oriented with fast direction either vertically or horizontally. Each is plotted as a function of “S” or the degree of melt segregation. In (e), we plot % anisotropy. If S varies spatially, as shown in the schematic drawing, we would predict an increase in anisotropy towards the flanks of a melt-rich region, maximum at the lithosphere-asthenosphere boundary.

3. The East African Rift as testing ground

Extensive seismic studies of the East African Rift in Ethiopia have already been performed. The results show strong shear wave splitting with fast directions parallel to the volcanic centers on the surface, suggesting that the alignment of melt is causing the splitting (e.g. Kendall et al., 2005). Furthermore, the magnitudes of delay times (shear wave splitting) are strongest near the flanks of the rift, defined by both the tomography and the surface expression of the rifting (e.g. Bastow et al., 2005). The gradients in the magnitude of delay times are similar to our predictions above. These results suggest that melt is dominating the seismic signal, overwhelming the contribution from LPO.

Next:

To try to constrain the melt distribution beneath the rift and also the orientation and magnitude of the LPO, we (with Jim Gaherty) will analyze surface waves measured with three arrays of broadband stations at different densities. We will build a 3-D velocity model constrained with both the shear wave splitting results (good horizontal resolution) and the surface waves (good vertical resolution).