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The influence of melt on olivine fabrics and rheology

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In the past three years, we have been exploring the phenomena of shear stress-driven melt segregation in partially molten rocks at high temperature and pressure. During deformation of rocks with small degrees of melt, the melt spontaneously segregates into melt rich bands that organize into networks of melt rich shear zones. We have demonstrated in experiment and theory that the basic physics of the segregation can be approximately described by two-phase non-dilatent flow (i.e. no cracking necessary; compaction theory suffices for now), which allows us to predict length scales of melt-rich networks to mantle and lower crustal conditions with reasonable confidence. Still, many questions remain, including 1) the dynamic interactions of deformation mechanisms involved in the organization of melt-rich networks from the grain-scale upwards, 2) ways of measuring and calculating effective viscosities of system with pervasive strain partitioning over a range of length scales, and 3) the implications for the seismic, transport, and rheological structures of natural systems with much more complex and variable boundary conditions than in experiments.

The olivine lattice preferred orientation data from experiments provides information relevant to all three questions. In direct shear experiments, we have found that small degrees of aligned and segregated melt profoundly affect the LPO. In melt-free systems at experimental conditions (T=1250 C, P=300 MPa, shear stress=25-150 MPa), it is well established that the dominant (easiest) slip system is a-slip on b-plane, i.e. (010)[100]. When a few percent melt is added, the a-and c-axis concentrations break down to form girdles and then, by a shear strain of about ¥gamma=2, the a-axes concentrate orthogonal to the shear direction, in the shear plane. In samples with a second fine-grain solid phase present to reduce the permeability, melt segregates into networks of melt rich bands. In these samples, the a-axis rotation occurs more quickly, at shear strains of ¥gamma¥approx 1. We have recently reproduced these results in torsional deformation geometry, in which no flattening occurs normal to the shear plane.

Normally, this pattern would be interpreted as a change in the dominant slip system. With no thermodynamic reason for such a change to occur, we offer an alternative hypothesis. The a-axis rotation occurs because the anisotropic alignment of melt causes a spatial partitioning of deformation between diffiusion-accommodated (and dislocation-accommodated?) grain boundary sliding in the melt-rich plane (about 20 degrees to the shear plane). Dislocations are driven by the resultant stress field in the crystal whose shear normal tensional components (parallel to the observed a-axis alignment) are exaggerated relative to the shear parallel components. Thus the anisotropic partitioning of strain into two or more different deformation mechanisms at the grain scale causes any tensional components in the boundary conditions to be exaggerated in the local grain-scale stress field. Because the difference in strength between the (010)[100] and (010)[001] slip systems is very small, the a-axis rotation may occur with only a small component of overall outward flow. We present a results from a 3-D grain-scale grain boundary diffusion creep model which illustrates the effect of aligned melt on the local stress field in a grain, which would drive dislocations. Further theoretical development of this process is required to test the hypothesis against experimental data. These efforts are underway. Extrapolating to upper mantle conditions will require a good understanding of the critical deformation mechanisms interacting in the experimental samples and a more complete physical model for their interaction.