The role of melt on the dynamics of the upper mantle

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The processes that control the formation of oceanic crust, migration of melt to hot spots and volcanic arcs, and the dynamics of flow beneath oceanic spreading centers and the mantle wedge of subduction zones all depend on the mechanical and transport properties of partially molten mantle rocks. Our understanding of these regions is predominantly shaped by investigations of remotely collected geophysical data (e.g., seismic velocity) and geochemical analyses of the products and residues of melting. The interpretations of both types of data require an understanding of the relationships among deformation, melt topology and melt migration.

The effect of melt fraction on the viscosity of partially molten mantle rocks has been quantified through extensive deformation experiments in both the diffusion creep and dislocation creep regimes (e.g., Cooper & Kohlstedt, 1984; Hirth & Kohlstedt, 1995; Zimmerman & Kohlstedt, 2004). The effect is rather modest at low melt fractions, but a decrease in viscosity of approximately an order of magnitude is observed with an increase in melt content to $\sim 5-8\%$. These observations are well described by theoretical analyses that specifically account for the characteristics of melt topology observed from microstructural studies. The experimental data are also well fit by an empirical relationship in which the viscosity of the partially molten aggregate decreases exponentially with increasing melt fraction.

The mechanisms of melt migration in the upper mantle depend on the permeability and rheology of partially molten peridotite, which in turn, depend on both the amount and topology of the melt phase. Numerous theoretical studies have explored the effects of rheology and fluid mobility on melt migration processes in the upper mantle. These coupled processes have now been experimentally quantified in compaction experiments on partially molten dunite (Renner et al., 2003). The results of these experiments indicate that the permeability of partially molten aggregates is well described by a power law at melt contents between $\sim 3-20\%$ and that rheological properties under isostatic conditions are similar to those under deviatoric stress states.

The application of experimental data to natural conditions requires extrapolation in both time and scale. Experimentally based predictions for the rheology of the upper mantle compare well with both analyses of microstructures in naturally deformed rocks and geophysical estimates of mantle viscosity. However, for partially molten regions of the mantle, the scale of melt migration/melt redistribution may also play an important role on dynamics. For example, experimental studies indicate that melt rich channels form in response to pressure gradients arising from imposed deformation (Holtzman et al., 2003). In addition, significant changes in rheology may arise owing to variations in melt pressure during deformation (e.g., Renner et al., 2000; Evans et al., 2004; deMartin et al., 2004 (abs.)). Progress in these areas requires further quantification of transient deformation processes that arise owing to melt redistribution at scales ranging from $\sim$ 1 mm (i.e., individual melt pockets) to 0.1 to 10 km (i.e., the "compaction length" in the upper mantle). Finally, analyses of the effects of melt on the dynamics of the upper mantle must also incorporate our understanding of how melting changes other important properties; changes in water content and grain size are particularly important.