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On the importance of viscous anisotropy in shear-induced melt segregation and organization

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Mechanical and transport properties of solid-liquid two-phase systems strongly depend on the detailed geometry of the liquid phase. In the 1980s-90s, the microscopic geometry of melt in partially molten rocks that are texturally equilibrated under hydrostatic stress was assessed experimentally; based on the results of these studies, viscosity, seismic wave velocity, and permeability of partially molten mantle were predicted quantitatively. Concurrently, geochemical studies were concluding that melt compositions indicate small degrees of texturally equilibrated melt (implying small melt fractions of about 1%). However, such small fractions of texturally equilibrated melt could not explain the large reductions in shear wave velocity and viscosity in the asthenosphere obtained from seismological and geodynamical studies. Nor could it explain rapid ascent of melt indicated from significant radioactive disequilibrium in basalts.

One possible key that has been considered to resolving these difficulties is the effect of shear stress on melt geometry. Experimental studies by Holtzman et al. (2003, 2007) on shear-induced melt segregation demonstrated a significant effect of shear stress on large scale melt distribution. In order to simulate melt distribution in realistic geological settings and its interaction with mantle flow, the underlying physics of this process should now be clarified. We investigated this process by using a two-phase flow theory into which an internal state variable describing the microstructural process was introduced. Our results demonstrate an important role of viscous anisotropy in shear-induced melt segregation.

Our approach consists of (1) deriving viscous constitutive relations of solid matrix as functions of a microstructural state variable, and (2) solving them together with the mass and momentum conservation equations for the two-phase system under a given boundary condition. Contiguity, which describes grain-to-grain contact geometry, is the essential microstructural factor determining the mechanical properties of granular media (Takei, 1998; Takei and Holtzman, 2009). Hence, contiguity provides an appropriate internal state variable for partially molten rocks. Recent experimental studies on partially molten rock (Daines and Kohlstedt, 1997) and partially molten rock analogue (Takei, 2005, 2009) demonstrate the development of microstructural anisotropy under stress, which is well described in terms of contiguity. The constitutive relations predict that a significant softening occurs in the direction of the least compressive stress (sigma3) and that, because of this anisotropy, strong coupling occurs between shear and isotropic components of stress. An important consequence of this coupling is significant enhancement of the interaction between shear deformation and melt migration: melt migrates up the stress gradient in the solid, and melt spontaneously segregates into the melt-rich bands which form at a low-angle to the shear plane (Takei and Holtzman, 2009). Both of these phenomena have important geological implications because they can significantly reduce viscosity and shear wave velocity even with a small amount of melt and develop high permeability channels for the melt ascent. These results were obtained for rotary shear and uniform simple shear systems. For more realistic geological settings, the effect of viscous anisotropy on melt migration was roughly estimated by using the corner flow ridge and subduction models of Spiegelman and McKenzie (1987). It was demonstrated that the melt phase is attracted to the position of high stress in the plate boundary. The attracted melt will significantly soften the matrix, change the stress concentration pattern, and hence change the melt flow pattern. Therefore, the next important step will be a numerical approach to simulate such interactive evolution between mantle flow and melt migration. This study has developed basic tools for such simulation.