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Viscous constitutive relations of partially molten rocks: effects of small amount of melt on shear and bulk viscosities

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Shear and bulk viscosities of partially molten rocks are derived theoretically as functions of grain boundary contiguity, based on the microstructural model of the grain boundary diffusion creep. The present theory is an extension of the Cooper and Kohlstedt (1989) model, by considering the microstructure in 3D and also by exactly solving the mechanical balance, reaction and diffusion kinetics, and mass conservations required at each grain. Also, the present formulation is an extension of the Takei (1998)'s formulation for elasticity to that for viscosity. Important implications of this study are as follows.

(1) Even with a small amount of melt (melt fraction less than 0.1%), shear viscosity is substantially (by a factor of 5) smaller than that without melt.

(2) Even with a small amount of melt (melt fraction less than 0.1%), bulk viscosity is nearly equal to shear viscosity, which does not support the relationship "bulk viscosity=shear viscosity / melt fraction" widely used in numerical simulations.

(3) Effects of grain-boundary contiguity and its anisotropy on the viscosities and viscous anisotropy are much stronger than those on the elasticities.

We consider a solid-liquid composite system which consists of solid grains making a framework through grain-to-grain contacts and the interstitial liquid phase. Grain boundary contiguity represents the area of the contacts relative to the total surface area of each grain. Anisotropy in contacts is described by contiguity tensor. Viscosities are derived by specifying the relationships between macroscopic and microscopic (less than grain scale) stresses, between macroscopic and microscopic strains, and also between microscopic stress and strain, where the last relationship is obtained by solving the governing equations for grain deformation. Using this model, the effects of contiguity on the shear and bulk viscoisities, effects of contiguity tensor on the viscosity tensor, and asymptotic behavior of the viscosities at small melt fraction are investigated analytically. Also, effects of diffusivities and reaction rates on viscosities are assessed quantitatively.