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An experimental study of the effects of surface tension in homogenizing perturbations in melt fraction

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ABSTRACT

Static annealing experiments were conducted on fine-grained samples of a partially molten, olivine-rich rock to explore the role of interfacial tension driven flow in redistributing melt within the sample. A sample of fine-grained olivine + 20% chromite was prepared with an initially homogeneously distributed melt fraction of 0.04. When this sample was deformed in torsion, the melt segregated into distinct melt-rich bands uniformly spaced throughout the sample, as demonstrated in prior studies. Portions of this sample were then statically annealed for different lengths of time to observe the homogenization of the melt distribution. The evolution of the melt distribution in experimental samples was compared to numerical models based on formulations for interfacial tension driven flow that do or do not incorporate the effects of dissolution/precipitation coupled with diffusive mass transfer of components of the solid phase through the liquid phase (dissolution/diffusion/precipitation). The results indicate that, at the grain size and perturbation length scales in these samples, dissolution/diffusion/precipitation in response to the chemical potential gradient arising from the curvature of solid–liquid phase boundaries at triple junctions plays a significant role in accommodating interfacial tension driven flow. These experiments provide a valuable test for theory and allow us to place constraints on the homogenization rate of perturbations in melt fraction in rocks with a relatively simple composition. The results contribute to increasing our understanding of the nature of melt-rich, high-permeability pathways that may facilitate melt extraction from the upper mantle.

1. Introduction

Interfacial tension is a critical factor in determining the distribution of melt in a multiphase aggregate. Melt distribution and grain-scale pore geometry (controlled by surface energies at grain and phase boundaries) are primary controls on melt interconnectivity and permeability (e.g., Wark and Watson, 1998), which in turn control the mechanisms and rates of melt transport in the lower crust and mantle. A small amount of melt can also significantly influence the rheological properties of a partially molten rock (Hirth and Kohlstedt, 1995a,b; Kohlstedt and Zimmerman, 1996). The effects of the melt can be especially pronounced if the melt distribution is inhomogeneous and/or anisotropic (Holtzman and Kohlstedt, 2007; Holtzman et al., 2003; King et al., 2010). Depending upon the dihedral angle, interfacial tension can either amplify or homogenize perturbations in melt fraction (Hier-Majumder et al., 2006). Improved constraints on interfacial tension driven flow are of fundamental importance to improving our understanding of the mechanisms that drive melt extraction and the formation of Earth's chemical and mechanical boundary layers.

Several formulations for multi-phase flow have been implemented to model the coupled matrix deformation and fluid flow during interfacial tension driven flow (e.g., Hier-Majumder et al., 2004; Hier-Majumder et al., 2006; Riley and Kohlstedt, 1991; Riley et al., 1990; Stevenson, 1986; Takei and Hier-Majumder, 2009). Riley and Kohlstedt (1991) developed a model for melt transport in partially molten rocks driven by capillary forces in which melt transport is accommodated by coupled compaction and decompaction of the rock matrix. Riley and Kohlstedt (1991) also conducted experiments on melt migration from a melt-rich source to a melt-poor sink as a calibration of this model. Parsons et al. (2008) employed another experimental approach to explore melt migration in which partially molten samples were statically annealed after they had been deformed in direct shear to produce melt-rich bands. In these annealing experiments, the melt fraction within the bands decreased significantly, and the width of the band increased moderately. Analysis of the experimental results from the static annealing experiments using the equations from Riley and Kohlstedt (1991) yielded the permeability of the aggregate and the viscosity of the matrix that best fit the experimental data. More recently Takei and Hier-Majumder (2009) extended existing models of surface tension flow to include the effects of

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dissolution, diffusive transport of components of the solid phase through the fluid phase, and precipitation driven by a chemical potential gradient at solid–liquid phase boundaries arising from the curvature of the interface. In their analysis, Takei and Hier-Majumder (2009) identify a diffusion length scale, δ_d. The diffusion length scale defines the boundary between two regimes of coupled fluid flow and matrix deformation with an important distinction in the rate controlling processes. For perturbations at a length scale longer than δ_d, the homogenization rate is controlled by mechanisms not involving mass transfer between solid and liquid (i.e., fluid flow and viscous matrix deformation), yielding results similar to those of Riley and Kohlstedt (1991). The set of mechanisms involved in this process is referred to as compaction/decompaction. For perturbations at length scales shorter than δ_d, the homogenization rate is controlled by processes involving mass transfer between solid and liquid. The set of mechanisms involved in this process is referred to as dissolution/diffusion/precipitation.

We present data from a set of annealing experiments similar to those of Parsons et al.'s (2008) but with refined experimental design and improved image analysis. In Parsons et al. (2008), three different samples (of the same material used in this study) 0.5 mm in height were deformed in direct shear to a shear strain of $\gamma \approx 3.5$ and either quenched or allowed to anneal after deformation. In this study, a sample of partially molten olivine-rich rock was deformed in torsion, resulting in segregation of melt into distinct melt-rich bands (King et al., 2010). Portions of the sample were then annealed for different lengths of time to explore the evolution of the perturbations in melt fraction. The larger sample size of torsion samples (~4.5 mm in height) compared to direct shear samples (0.5 mm in height) allowed (1) all of the annealing experiments to be performed on portions of the same deformation sample and (2) analysis of a larger area of the sample with more melt-rich bands than in the direct shear samples used in Parsons et al. (2008). We compare the observed homogenization of melt-rich bands with increasing anneal time in the experiments to the homogenization rate determined by the model of Takei and Hier-Majumder (2009). The primary goal of the comparison between experiments and model is to determine if incorporating mass transfer between solid and liquid and diffusive transport of material through the fluid phase leads to better representation of the experimental results than does a model of compaction/decompaction without these considerations. We also explore the relationship between the perturbation length scale of the melt-rich bands observed in experiments and the diffusion length scale, δ_d, to determine if the rate controlling process predicted by the model is consistent with observed length scales within the experimental samples.

2. Methods

2.1. Sample preparation and assembly

Samples were prepared by mechanically mixing olivine from San Carlos, Arizona (72 vol.%), chromite from the Semail Ophiolite, Oman (24 vol.%), and powdered MORB glass (4 vol.%) (Holtzman and Kohlstedt, 2007; Holtzman et al., 2003; King et al., 2010; Parsons et al., 2008). The mixture was cold pressed into a nickel capsule before hot isostatic pressing for 3 h at 1200 °C and 300 MPa in a gas-medium pressure vessel (Paterson, 1990). A portion of the starting material was then polished and examined by optical microscopy to verify the homogeneity of the phase distribution throughout the sample. The mean starting grain diameter of the powders was 6 μm for olivine and 2 μm for chromite. During hot-pressing, the olivine grain size grew to ~8 μm.

2.2. Experimental procedure

Experiments were performed in a gas-medium deformation apparatus equipped with a torsion actuator (Paterson and Olgaard, 2000). The initial deformation experiment was controlled at a constant torque as measured by a torque cell housed inside the pressure vessel. The rate of angular displacement to maintain this torque was controlled by a servomotor feedback loop and monitored by a rotational variable displacement transducer (RVDT) outside the pressure vessel. Temperature was monitored near the sample using a Pt–Pt/Rh thermocouple. Furnace calibrations confirm variation of <1 °C along the length of the sample. Methods for determining shear stress and shear strain rate from torque and angular displacement as a function of time have been described by Paterson and Olgaard (2000).

The experiments were designed to investigate the role of surface tension in homogenizing the melt distribution after the driving force for segregation has been removed. A cylindrical sample was deformed at a constant torque corresponding to a shear stress at the outer radius of $\tau_{max} = 90$ MPa to an angular displacement corresponding to a shear strain at the outer radius of $\gamma_{max} = 2$. After deformation, the sample was cut perpendicular to the sample-piston interfaces into four wedge-shaped quarters as illustrated in Fig. 1a. One quarter was polished on the radial section and on a longitudinal tangential section (Fig. 1b) using diamond lapping film of progressively finer grit sizes of 30, 15, 6, 3, 1 and 0.5 μm followed by 10 min of chemo-mechanical polishing with a colloidal silica suspension (30 nm particle size). The other parts of the sample were each wrapped with 0.1 mm nickel foil, and spacers of Al_2O_3 the same height as the sample were prepared to fill the missing three quarters of a cylinder (Fig. 1a). Each of these three portions of the sample

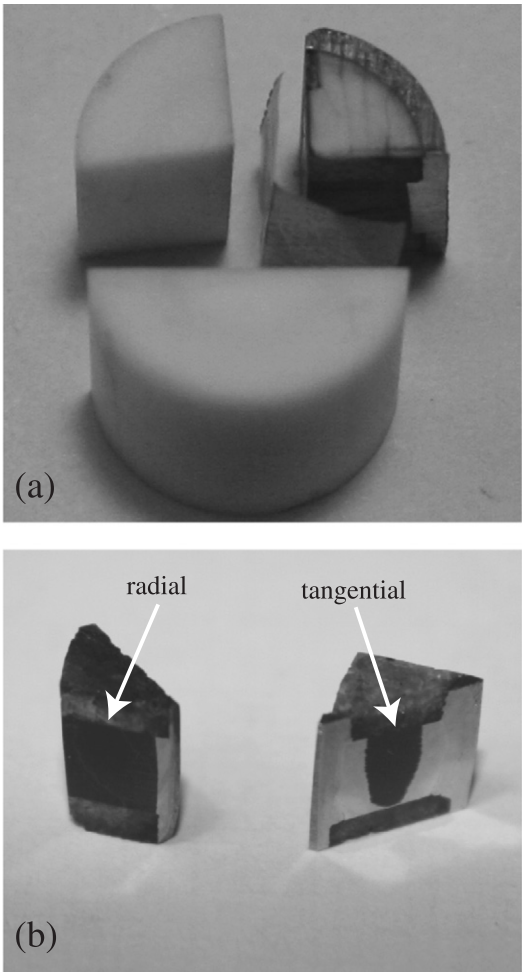

Fig. 1. After deforming a cylindrical sample in torsion, the sample was cut into quarters. (a) A photo of the setup for annealing each quarter separately. Exposed surfaces are covered with nickel foil and alumina spacers are used to recreate a cylinder. (b) After annealing a longitudinal radial (left) and tangential (right) sections are polished.