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.

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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 decompression 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...
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, \( \delta_d \). 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 \( \delta_d \), 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 \( \delta_d \), 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 \( \gamma = 3.5 \) 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, \( \delta_d \), 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 \( \mu m \) for olivine and 2 \( \mu m \) for chromite. During hot-pressing, the olivine grain size grew to ~8 \( \mu m \).

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 \( \tau_{\text{max}} = 90 \) MPa to an angular displacement corresponding to a shear strain at the outer radius of \( \gamma_{\text{max}} = 2 \). 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 \( \mu m \) 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 Al2O3, 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

(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.
was then loaded into separate sample assemblies similar to that used for the deformation experiment. The three portions were then annealed separately for 1, 10, and 50 h at 1200 °C and 300 MPa. After annealing, the samples were polished following the same procedure used for the quenched sample. To make the melt and grain boundaries more visible in reflected light images, samples were then etched with a weak solution of HF and HCl, which preferentially etches the quenched melt phase and the grain boundaries. Mosaic images of tangential sections of the as-deformed and annealed samples are presented in Fig. 2. The large cracks visible in these images, particularly in Fig. 2c, formed during decompression and, thus, contain no melt.

2.3. Image analysis

To quantitatively analyze changes in the distribution of melt with increasing anneal time, strips of optical micrographs were taken of portions of each tangential section and stitched together into a mosaic image at least 1.5 mm long and ~0.4 mm wide with a resolution of 1.3 μm/pixel. A threshold was then applied to the image to create a binary image representing the distribution of the quenched melt as illustrated in Fig. 3. The area fraction of melt in the binary images corresponds with the volume fraction of MORB that was initially put into the sample (0.04) within 0.002. The images were then smoothed by centering a 2-D Gaussian filter matrix on each pixel of the image. The filter was convolved with the overlapping region of the image and then divided by the number of pixels in the smoothing matrix. Because one of the goals of this analysis was to determine the peak melt fraction within the bands, it was important to use a smoothing filter with a diameter less than the width of the bands. As reported in King et al. (2010), band thickness in a suite of similar deformation experiments is typically ~20 μm, similar to the thickness observed in the quenched sample. A filter diameter of 16 μm was determined to be an appropriate size. A filter with a 32-μm diameter yielded significantly lower values for the peak melt fractions in the bands.

![Fig. 2](image_url) Mosaic images of longitudinal tangential sections of portions of the sample depicting the overall melt distribution after (a) quench, (b) 1 h anneal, (c) 10 h anneal, and (d) 50 h anneal.
After a smoothed image was created, five profiles were extracted from each image similar to the profiles displayed in Fig. 3c, f, i, and l. Peak melt fractions were tabulated for each band in each profile, with bands defined as a peak in melt fraction above the overall average melt fraction of 0.04. This method is different from that used by Parsons et al. (2008) in which three profiles were averaged together to create one average profile for the image. Because not all the bands are precisely parallel, averaging the profiles leads to broadening of the peaks in melt fraction associated with the bands, under-estimation of the peak melt fraction within bands, and over-estimation of the melt fraction in non-band regions. The method used here of tabulating a large number of data points from within band and non-band regions accounts for variation in melt fraction along the trace of each individual band and within non-band regions without needing to define an average band angle.

2.4. Model formulation

Annealing of melt-rich bands was modeled by solving the partial differential equations governing mass and momentum conservation of the matrix and the melt. Nondimensionalized versions of these equations are Eqs. (24)–(26) of Takei and Hier-Majumder (2009). See their article for a description of the nondimensionalization scheme and boundary conditions. The initial melt distribution was prescribed by a background melt fraction of 0.05 and a peak melt fraction of 0.12. The governing partial differential equations were discretized in a one dimensional grid with finite volume discretization. Once the velocities were determined by solving Eqs. (25) and (26) of Takei and Hier-Majumder (2009), the melt fraction was updated by integrating Eq. (24) in time, using an Eulerian forward integration. Length of time steps for the time integration was adjusted at each step using the Courant criterion. Three sets of numerical experiments were carried out for reference viscosities of $4 \times 10^{11}$, $4 \times 10^{12}$, and $4 \times 10^{13}$ Pa·s, respectively.

We also compare the decay rate of perturbations using the linear stability analysis outlined by Takei and Hier-Majumder (2009). Here we summarize the key parameters that determine the growth rate $\lambda$ of the initial perturbation and that determine whether interfacial tension driven flow is dominated by compaction/decompaction or by dissolution/diffusion/precipitation. These two mechanisms are depicted schematically in Fig. 4. The material parameters are summarized in Table 1.

The critical nondimensional parameters are $Pe$, which is the ratio of the rate of advection to the rate of diffusion, and $W$, which is the ratio of the driving force for dissolution of a component in a two-component phase arising from nonequilibrium (surface tension) effects to that arising from equilibrium effects. When $W=0$, surface tension does not influence the chemical concentration of that component in the melt phase. These parameters are defined as

\[
\begin{align*}
Pe &= \frac{L v_0}{D_L} \\
W &= \frac{\gamma_{sl} \Omega}{d E}
\end{align*}
\]

where $E$ is a constant, $d$ is the grain size, $\gamma_{sl}$ is the surface energy of a solid/liquid interface, $D_L$ is the diffusion coefficient, and $\Omega$ is the molar
volume of the solid phase component. The characteristic length scale \( L \) and the characteristic velocity \( v_0 \) are defined as

\[
L = \left( \frac{\nu_b \left( \xi_0 + \frac{4}{3} \eta_0 \right) \phi_0}{\eta_b} \right)^{1/2}
\]

\[
v_0 = \frac{\gamma_d f}{\nu_b}
\]

where \( \xi_0 \) and \( \eta_0 \) are given below in Eq. (4), \( k_0 \) is the reference permeability, \( \eta_b \) is the reference viscosity of the matrix, and \( \eta_0 \) is the reference viscosity of the liquid (see Table 1).

When \( W \to 0 \) and/or \( Pe \to \infty \), dissolution/diffusion/precipitation is negligible and interfacial tension driven fluid flow is accommodated by matrix compaction/decompaction. In this end-member case, the nondimensional growth rate is given by

\[
N_{c/d} = \left( \frac{1}{\phi_0} \frac{1}{\phi_b} \right)^{1/2} \left( \frac{\xi_0 + \frac{4}{3} \eta_0}{\eta_b} \right) \left[ 1 + \frac{1}{(1-\phi_0) d p \phi_b k^*} \right]^{-1}
\]

(3)

where \( k^* \) is the non-dimensional wave number. The non-dimensional bulk and shear viscosities for a reference melt fraction \( \phi = \phi_0 \) are given by

\[
\eta_b^* = e^{-\lambda_0}, \quad \xi_0^* = \frac{1}{\phi_0}.
\]

(4)

The function \( f(\theta) \) is given by

\[
f\left( \frac{\pi}{3} \right) = \left[ 8 \cos \theta \frac{\theta}{2} \right. \left. \left[ \frac{\theta}{2} \right] - 2 \sqrt{3} \left( \frac{\theta}{3} - \frac{\theta}{2} \right) \right] \frac{1}{2}
\]

(5)

where \( \theta \) is the dihedral angle. Typical dihedral angles observed in olivine aggregates at upper mantle conditions of \( 25 - 31^\circ \) are well within this range, and there is some evidence that dihedral angles decrease with increasing pressure (Mei et al., 2002; Yoshino et al., 2007).

In the other end-member case where \( Pe \to 0 \), dissolution/diffusion/precipitation is the dominant mechanism. The nondimensional growth rate is now given by

\[
N_{d/p} = -k^* \frac{1}{Pe} \frac{1}{\phi_0} \frac{1}{\phi_b} \frac{1}{d \phi_b} = \lambda_{c/d}^* + \lambda_{d/p}^*.
\]

(6)

When both mechanisms are active (finite \( W \) and \( Pe \)), the growth rate of a perturbation in melt fraction is given by

\[
\lambda^* = \frac{1-2 W b W \phi_b^{-1/2}}{1-b W \phi_b^{-1/2}} N_{c/d}^* + N_{d/p}^*.
\]

(7)

Because \( b W \phi_b^{-1/2} < 0 \), \( \lambda^* \) is almost equivalent to the sum of \( \lambda_{c/d}^* \) and \( \lambda_{d/p}^* \). The dimensional growth rate is calculated from this value as \( \lambda^* = \lambda_0 V_0 / L \). Both \( \lambda_{c/d}^* \) and \( \lambda_{d/p}^* \) are negative for \( \theta > 60^\circ \) and positive for \( \theta < 60^\circ \).

Because \( \lambda_{c/d}^* \) and \( \lambda_{d/p}^* \) depend differently on \( k^* \), the dominant mechanism depends not only on the material parameters but also upon the perturbation wavelength. The diffusion length \( \lambda_0 \) is defined as...
the wavelength at which \( \lambda_{c/d} = \lambda_{d/p} \) for \( \phi = \phi_0 \). It is given in dimensional form by

\[
\delta_d = 2\pi \left( \frac{d \omega}{\gamma_d} \frac{W \delta_0^{-1/2}}{1 - W \delta_0^{-1/2}} \right) \left( \frac{\xi(\phi_0) + \frac{4}{3} \gamma(\phi_0)}{2(1 - \phi_0) f(\theta) \phi_0^{-3/2}} \right)^{1/2}.
\]

To illustrate the regions of parameter space in which the different mechanisms of interfacial tension driven flow dominate, the log of the homogenization rate \( (\lambda) \) is plotted in Fig. 5 as a function of perturbation length scale for two representative grain sizes (10 \( \mu m \) and 1 mm). The compaction length \( (\delta_c) \) and diffusion length scale \( (\delta_d) \) are plotted for each grain size. The plot demonstrates that the combined homogenization rate is controlled by the faster mechanism (compaction/decompaction or dissolution/diffusion/precipitation) and that \( \delta_d \) represents the length scale at which the dominant mechanism switches.

3. Results

3.1. Formation of melt-rich bands

Consistent with prior studies on the same materials (Holtzman and Kohlstedt, 2007; Holtzman et al., 2003; King et al., 2010) and other multiphase systems with two phases of contrasting viscosity (Hustoft and Kohlstedt, 2006; Kohlstedt et al., 2010), when the sample is sheared, melt pockets first align at an angle \( \sim 20^\circ \) to the shear plane, antithetic to the shear direction. With increasing shear strain \( (\gamma > 1) \) for the materials and deformation conditions in this study), the melt segregates into distinct melt-rich bands of approximately the same orientation as the melt pockets leaving behind lenses of material depleted in melt. Such segregation of melt associated with deformation was previously predicted by the model of Stevenson (1989). For more details of observations of melt segregation in a suite of samples deformed in a torsional geometry see (King et al., 2010).

3.2. Evolution of melt-rich bands during static annealing

Results from image analyses of the quenched and annealed samples are presented in Table 2. The average melt fraction in the melt-rich bands after deformation is 0.34, with some of the most melt-rich bands reaching a maximum melt fraction of 0.50 over a small portion of the band. Other quenched torsion samples from King et al. (2010), which were polished on multiple tangential sections, revealed that on average the melt distribution is identical at a given radius around the whole sample. On this basis, we conclude that the properties observed in the quenched sample represent the starting microstructure for the subsequently annealed portions of the deformed sample.

The melt distributions in samples annealed for different lengths of time are compared in the reflected light and binary images of representative bands in Fig. 6. During 50 h of anneal time, the mean peak melt fraction in the bands decreased from 0.34 to 0.14, with the final melt fraction in the bands still more than three times the average starting melt fraction before deformation. The background melt fraction in the non-band regions increased during the 50 h anneal from 0.005 to 0.03, as expected since the width of bands (see below) and the overall melt fraction in the sample remain constant throughout the experiment. The peak melt fraction, plotted as a function of anneal time in Fig. 7a, drops more rapidly with increasing anneal time at the beginning of the anneal than later in the anneal.

The thickness of bands, defined as the full width at half maximum of a peak in melt fraction, within each of the annealed samples was measured, and the mean thickness is presented in Fig. 7b. The data suggest a very small but systematic increase in band thickness with increasing anneal time. The images from annealed samples in Fig. 6 were chosen as typical melt-rich bands from each of the samples. These images visually demonstrate the approximately consistent band thickness with increasing anneal time.

3.3. Grain size

Because grain size is an important parameter in the permeability and a critical length scale in the model, it is important to determine if the grain size evolved significantly during the long-anneal experiment. Grain size was obtained by a linear intercept method. Several lines were drawn across optical reflected light images of polished sections that had been etched with a weak acid solution. The distance was then measured between each intersection of a line with grain boundaries. At least 100 measurements were used for each sample. The measurements were multiplied by a factor of 1.5 to determine the average grain diameter (Giffins, 1970). As illustrated in the histograms of grain diameter plotted in Fig. 8 and the plot of grain size as a function of anneal time in Fig. 9, the mean grain size increases systematically with increasing anneal time but only by 1 \( \mu m \) during the 50 h anneal. The minimal grain growth may be a result of chromite pinning olivine grain boundaries.

3.4. Model results

Model runs were performed to explore surface tension driven flow accommodated by matrix compaction/decompaction with and without dissolution/diffusion/precipitation. Results of numerical simulations for three different reference shear viscosities are plotted as differential melt

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \phi_{\text{max}} )</th>
<th>( \phi_{\text{min}} )</th>
<th>grain size (( \mu m ))</th>
<th>FWHM (( \mu m ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quench</td>
<td>0.34 ± 0.11</td>
<td>0.0053 ± 0.0025</td>
<td>7.8 ± 3.1</td>
<td>17.7 ± 5.7</td>
</tr>
<tr>
<td>1 h</td>
<td>0.27 ± 0.09</td>
<td>0.015 ± 0.0052</td>
<td>8.0 ± 3.1</td>
<td>18.5 ± 4.4</td>
</tr>
<tr>
<td>10 h</td>
<td>0.19 ± 0.08</td>
<td>0.018 ± 0.0095</td>
<td>8.7 ± 3.6</td>
<td>19.2 ± 5.8</td>
</tr>
<tr>
<td>50 h</td>
<td>0.15 ± 0.06</td>
<td>0.027 ± 0.0051</td>
<td>9.0 ± 3.4</td>
<td>20.0 ± 6.6</td>
</tr>
</tbody>
</table>

Fig. 5. Perturbation homogenization rate \( (\lambda) \) plotted as a function of perturbation length scale \( (2\pi/k) \) for compaction/decompaction, dissolution/diffusion/precipitation, and both processes combined for grain sizes of 10 \( \mu m \) and 1 mm. The diffusion length \( (\delta_d) \) and compaction length \( (\delta_c) \) are plotted for each grain size as vertical dashed lines. At length scales shorter than \( \delta_d \), dissolution/diffusion/precipitation is the dominant mechanism of surface tension driven flow, while at length scales longer than \( \delta_c \), compaction/decompaction dominates. (Modified from Takei and Hier-Majumder (2009) Fig. 3).
fraction versus anneal time in Fig. 10. The three reference viscosities are $4 \times 10^{11}$, $4 \times 10^{12}$, and $4 \times 10^{13}$ Pa s with a Pe of $9 \times 10^{-3}$. Differential melt fraction is defined as the difference between the peak melt fraction in the bands ($\phi_{\text{max}}$) and the minimum melt fraction in the non-band region ($\phi_{\text{min}}$) normalized to the initial difference between peak and background melt fraction:

$$\Delta \phi = \frac{\phi_{\text{max}} - \phi_{\text{min}}}{\phi_{\text{max}} - \phi_{\text{min}}} \quad (9)$$

For the compaction/decompaction end-member, the model predicts a more gradual decrease in differential melt fraction with increasing anneal time than in the model runs incorporating dissolution/diffusion/precipitation. With decreasing reference viscosity for the melt-free solid, the bands drain more rapidly. Model runs that include the effects of dissolution/diffusion/precipitation predict more rapid draining of the bands than compaction/decompaction alone.

Along with the model results, $\Delta \phi$ versus anneal time is plotted for this study and for Parsons et al. (2008). In Fig. 10a, $\phi_{\text{max}}^0$ and $\phi_{\text{min}}^0$ are taken from the quenched sample, while in Fig. 10b they are taken from the 1 h anneal. For the Parsons et al. (2008) data set a value for $\Delta \phi$ at 1 h is projected by a linear interpolation between the values for the quenched sample and the 10 h anneal. The significance of this comparison in Fig. 10a and b is discussed below.

4. Discussion

4.1. Comparison of model results with experimental data

4.1.1. Predicted mechanism of surface tension driven flow

As discussed in the Methods section, the predicted dominant mechanism of surface tension driven flow (compaction/decompaction or dissolution/diffusion/precipitation) depends upon viscosities of the solid and fluid, the permeability of the aggregate, solid–liquid interfacial energy, kinetics of dissolution and precipitation (taken to be infinite in this formulation), diffusivity of the solid component through the melt, grain size and the wavelength of the perturbation in melt fraction. In Fig. 11a, $\delta_t$ is plotted as a function of grain size for $\phi_0 = 0.01$. The dashed box on the plot indicates the range of $\delta_t$ for the grain size and melt fraction in the experimental sample. The model of Takei and Hier-Majumder (2009) predicts that interfacial tension driven fluid flow is dominated by compaction/decompaction of the matrix for melt perturbations with wavelengths longer than $\delta_k$, while dissolution/diffusion/precipitation is the dominant mechanism for perturbations with wavelengths shorter than $\delta_k$. The value of $\delta_t$ calculated for the sample is significantly longer than the thickness of and spacing between melt-rich bands. Therefore, the dissolution/diffusion/precipitation mechanism is predicted to be dominant.

4.1.2. Evolution of differential melt fraction

Although the absolute measurements of melt fraction are significantly different between this study and that of Parsons et al.’s (2008), the differential melt fraction records similar patterns in the evolution of melt distribution. In both studies, the rate of decrease in differential melt fraction decreases with increasing anneal time. Comparison of the evolution of $\Delta \phi$ with anneal time measured from the samples with the model results indicates that the incorporation of the dissolution/diffusion/precipitation mechanism is important to accurately represent the experimental data. When $\Delta \phi$ is calculated using reference values from the quenched sample, as in Fig. 10a, no single model result fits the data. However, when $\Delta \phi$ is calculated using reference values from the 1 h anneal (Fig. 10b) the model results for a reference viscosity of $\eta = 4 \times 10^{13}$ Pa s fit the experimental data quite well. As discussed in more detail below, the melt distribution in the 1 h anneal may be the most appropriate starting condition when comparing the results to the model because different processes may be acting at short anneal times compared to anneal times $> 1$ h due to the particularly high melt fraction ($>0.5$) in portions of the bands immediately after quenching. Though the best fit is with the model incorporating dissolution/diffusion/precipitation at the highest reference viscosity, the fit from the model results that do not incorporate dissolution/diffusion/precipitation is nearly as good at the lowest reference viscosity ($4 \times 10^{11}$ Pa s). Another line of evidence using flow laws based on experimental data from melt-free olivine suggests that the higher reference viscosity (and therefore the model incorporating dissolution/diffusion/precipitation) is more
appropriate. Using the Hirth and Kohlstedt (2003) flow law for a grain size of 8 μm and a temperature of 1200 °C, the effective viscosity is $8 \times 10^{12}$ Pa s for melt-free diffusion creep of dry olivine. This value is within the range of modeled reference viscosities for which the incorporation of dissolution/diffusion/precipitation provides the better fit.

4.1.3. Perturbation wavelength

Using the first-order growth rate of a perturbation

$$\Delta \phi = e^{\lambda^* t^*},$$

where $t^*$ is nondimensional time dimensionalized by $t = t^* \frac{L}{v_0}$ (homogenization rate for $\lambda^*<0$) for $\lambda^*$ (given in Eq. (7)) corresponding to a variety of perturbation wavelengths, it is possible to determine the perturbation wavelength that best fits the experimental data (Fig. 11b). That is, we can test if the fit of the model to our data corresponds with an identifiable length scale within the system (e.g., band thickness or band

Fig. 7. (a) The mean peak melt fraction in the bands plotted versus anneal time for the samples in this study. Error bars of one standard deviation are plotted. (b) The mean band thickness as measured by the full width at half maximum of the bands for different lengths of anneal.

Fig. 8. Histograms of grain size measured by the linear intercept method of the sample following the (a) quench, (b) 1 h anneal, (c) 10 h anneal, and (d) 50 h anneal. Grain size does not change significantly during the long anneal time, presumably due to the presence of chromite grains as a pinning phase.
spacing, grain size, or sample size). A least squares fit of perturbation wavelength to the experimental data yields $4 \times 10^{-4}$ m. This best-fit value for perturbation wavelength is very close to the average band spacing in the sample of $2 \times 10^{-4}$ m, suggesting that the spacing rather than the thickness of the melt-rich regions determines the mechanism and rate of homogenization. In other words, this result implies that the rate-limiting step is the flow of melt through the melt-depleted non-band regions. The implication of this result is that the value of $\phi_{d}$, which gives the length scale that separates the two regimes of surface tension flow, should be calculated for the melt fraction in the non-band region. The value of $\phi_{d}$ in the non-band region, indicated by the dashed box in Fig. 11a, is close to $2 \times 10^{-3}$ m. The fact that the best-fit perturbation wavelength is less than the estimated value of $\phi_{d}$ is consistent with the results of the model fit to the experimental data. This result is consistent with the conclusion from Holtzman and Kohlstedt (2007) and King et al. (2010) that the spacing of melt-rich bands that form from stress-driven melt segregation is controlled by the compaction length within the non-band regions.

4.1.4. The disaggregation melt fraction

The model may provide a better fit to the data normalized to $\Delta \phi$ in the sample annealed for 1 h than to the data normalized to $\Delta \phi$ in the quenched sample because the physical mechanism that allows rapid draining of melt at very high melt fractions early in the early stage of the anneal differs from the mechanism that takes over at lower melt fractions. Above the disaggregation melt fraction, the geometry of the melt phase changes from tubes connected along triple junctions to sheets of melt along interfaces between grains. The theoretical disaggregation melt fraction $\phi_{d}$ for hexagonal grains from Takei and Hier-Majumder (2009) is given by

$$\phi_{d} = \left[ \frac{f(0)}{4 \sin \left( \frac{\pi}{6} - \frac{\pi}{2} \right)} \right]^{2}. \quad (11)$$

For dihedral angles of $25 - 31^\circ$ as observed by Mei et al. (2002), the disaggregation melt fraction is expected to be 0.38–0.42. However, a dramatic change in rheological behavior of partially molten peridotite was observed at lower melt fractions of 0.25 to 0.30 by Scott and Kohlstedt (2006), suggesting that a significant change in the nature of the melt network occurs in this range of rheologically critical melt fraction. The disaggregation melt fraction based on Eq. (11) is plotted as a function of dihedral angle in Fig. 11c. The observed mean peak melt fraction in the bands of the quenched sample is marked with error bars representing one standard deviation. The average olivine–olivine-basalt dihedral angle observed in Mei et al. (2002) is also indicated on the plot. While the mean peak melt fraction in the bands is below the disaggregation melt fraction for the expected dihedral angle, some of the bands with the highest melt fraction are in the disaggregation regime. After 1 h of anneal time, all measurements of melt fraction within the bands were below the disaggregation melt fraction.

Predictions from numerical modeling are unclear regarding the pressure gradients that exist in association with a region of material above the disaggregation melt fraction. The formulation of Hier-Majumder et al. (2006) predicts that, above the disaggregation melt fraction, regions enriched in melt become low-pressure zones into which more melt flows, amplifying the perturbation in melt fraction. However, numerical models of a deforming crystal suspension demonstrate a regime in which the yield strength of the material depends upon the crystal fraction, even when the crystal fraction is well below the rheologically critical melt.
fraction (Saar et al., 2001). This behavior results from the formation of load-bearing networks of solid grains within the crystal suspension. The experimental results presented here suggest that it may be important to incorporate such behavior into models of surface tension driven flow.

4.2. Implications

4.2.1. Formation and stability of melt-rich channels in Earth’s oceanic upper mantle

One question we can address with the results of this study is whether or not melt-rich conduits remain stable over geologically significant time scales without a continuous driving force to sustain them. In an analysis of the thickness of melt-rich bands formed from stress-driven melt segregation, Takei and Hier-Majumder (2009) determined a minimum band thickness below which the homogenization rate resulting from interfacial tension driven flow is greater than the segregation rate resulting from deformation. At a grain size of 1 mm and a differential stress of 10 MPa, this minimum band thickness is ~1 cm. But, over what time scales are thicker bands stable?

The model results can be scaled to the region of partial melting beneath an oceanic spreading center in peridotite upper mantle by extrapolating in grain size, perturbation wavelength, and viscosity using the first-order approximation of dissipation rate (Eq. 10). In Fig. 12, the rate if dissipation of $\Delta \phi$ with time is plotted for a grain size of 1 mm as a function of perturbation wavelength. This calculation is for a grain size of 1 mm and viscosity of $2.5 \times 10^{18}$ Pa s with other parameters given in Table 1.

![Fig. 12](image-url)

Fig. 12. The time for dissipation of differential melt fraction to 0.1 (left axis) and the homogenization rate (right axis) for dissolution/diffusion/precipitation (dashed line), compaction/decompaction (dotted line), and both mechanisms (solid line) as a function of perturbation wavelength. This calculation is for a grain size of 1 mm and viscosity of $2.5 \times 10^{18}$ Pa s with other parameters given in Table 1.

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The model results can be scaled to the region of partial melting beneath an oceanic spreading center in peridotite upper mantle by extrapolating in grain size, perturbation wavelength, and viscosity using the first-order approximation of dissipation rate (Eq. 10). In Fig. 12, the rate if dissipation of $\Delta \phi$ with time is plotted for a grain size of 1 mm as a function of perturbation wavelength. We define a value of $\Delta \phi = 0.1$ for which the perturbation in melt fraction is considered to be homogenized. The time to reach homogenization is plotted on the left axis of Fig. 12. Across a wide range of length scales (from 10 m to 100 m), the homogenization time is relatively constant at ~150 My; at longer wavelengths, the homogenization time is even greater. For these wavelengths, surface tension driven flow is very
small compared to the driving force for segregation. Even if the initial mechanism forming the bands (some combination of deformation-driven and reaction-driven infiltration) was relatively short-lived, surface tension driven flow would not homogenize these high-permeability pathways within the length of time they are at high temperature. For perturbations less than ~10 m, dissolution/diffusion/precipitation plays a significant role in homogenizing the melt distribution and the homogenization time depends strongly on the perturbation wavelength. Surface tension driven flow for perturbations at the shortest length scales (≤ 1 m) may compete with the driving force for segregation and prevent channels at this scale from developing.

By comparing this calculation with observations of the width distribution of dunites in natural ophiolites, we can determine if the wavelength dependence of homogenization rate appears in the geological record. Based on measured thicknesses of dunite bands in the Oman ophiolite, Braun and Kelemen (2002) determined a scale-invariant power law distribution across several orders of magnitude in band thickness. Though their observations span from 3 mm to 100 m, the power law distribution applies most robustly to band thickness of ~30 mm to 50 m. The calculated results plotted in Fig. 12 demonstrate that the significant effects of surface tension driven flow at short perturbation length scales could account for the deviation from the power law distribution at small length scales. This effect could also arise from truncation errors due to incomplete measurement at short length scales.

4.2.2. Lower crustal migmatisms

The same type of analysis described above could be extended to other systems, such as lower crustal granulites. Migmatisms record evidence for segregation of melt into layers of very high melt fraction (e.g., Brown, 2006). Consider an aluminous metapelite granulite for which many studies of pressure temperature paths exist (e.g., White and Powell, 2002). While melt generation depends upon many factors, most importantly the availability of H₂O, observations from natural rocks indicate that a significant amount of melt (>10 vol.%) is present only at temperatures above 800 °C (Brown, 2006). A typical clockwise P–T path for a granulite facies metapelite brings the rock above 850 °C at pressures ranging from 400 to 800 MPa (White and Powell, 2002). The solidsus temperature at which melt quenches (i.e., the temperature at which an assemblage indicative of melt would be preserved) depends upon the rate of melt loss during cooling. This solidsus is predicted to be 680 °C for a small amount of melt loss (less than 70% melt loss) and 740 °C for a higher amount of melt loss (White and Powell, 2002). We can use the model of surface tension driven flow to estimate the cutoff cooling rate between “fast cooling”, which would allow the preservation of evidence for melt-rich layers, and “slow cooling”, which would allow time for melt to be homogenized. While the material parameters for these complex lower crustal lithologies are not well constrained, we can illustrate a possible extension of the range of application of this model using the parameters from Table 1. We calculate that a perturbation at a 1-m length scale would homogenize in ~10 My. From this estimate, we can determine that migmatisite features would be preserved in rocks with low melt loss if they cool faster than 9 °C/My and in rocks with high melt loss if they cool faster than 9 °C/My. These rates are consistent with those for relatively fast cooling inferred to have occurred during exhumation (Thompson et al., 1997).

5. Conclusions

The experiments presented here demonstrate the nonlinear dissipation of differential melt fraction driven by surface tension during static annealing of samples in which melt distribution was inhomogeneous due to stress-driven melt segregation. At the grain size in the experimental samples and with the perturbation length scale of either the band thickness or the band spacing, the model of Takei and Hier-Majumder (2009) predicts that dissolution/diffusion/precipitation is the dominant and rate-controlling mechanism of surface tension driven flow. Numerical simulations of the formulation incorporating dissolution/diffusion/precipitation provide a much better fit to the data than does the formulation consisting of surface tension driven flow accommodated only by matrix compaction/decompaction. Extrapolation of the model to conditions appropriate for the upper mantle predicts that surface tension driven flow should not inhibit the preservation of melt-rich pathways with a wide range of perturbation length scales >1 m over geologically significant time scales. However, surface tension could prevent the formation of the smallest length-scale melt-rich channels.

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