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Experimental quantification of permeability of partially molten mantle rock

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ABSTRACT

Melt percolation in mantle rocks is currently poorly constrained, especially at low melt fractions. At mid-ocean ridges, for example, geochemical and geophysical observations produce divergent estimates of how much melt is present in the mantle and how quickly it moves. Accurate estimates of permeability and grain-scale melt distribution in mantle rock are necessary to reconcile these observations. We present three-dimensional (3-D), 700 nm-resolution images of olivine–basalt aggregates, containing nominal melt fractions (ϕ_n) between 0.02 and 0.20. Samples were prepared from a powdered mixture of San Carlos olivine and high-alumina basalt and hot-pressed in a solid-medium piston–cylinder apparatus at 1350 °C and 1.5 GPa. Images were obtained using synchrotron X-ray microtomography (SXμT) from the Advance Photon Source at Argonne National Laboratory. Stokes flow simulations, conducted using the digital melt volume as the numerical domain, determine that the permeabilities of experimental charges range from 2×10^{-16} to 5×10^{-13} m^2 for $\phi_n = 0.02$ to 0.20, respectively. The simulation results are well represented by the power-law relation between permeability (k) and melt fraction (ϕ), $k = \phi^n d^2/C$, where $n = 2.6 \pm 0.2$, and assuming a grain size of 35 μm in the experiments, $C = 58^{+36}_{-22}$. These results place important new constraints on rates of melt migration and melt extraction within partially molten regions of the mantle.

1. Introduction

At mid-ocean ridges, the divergence of lithospheric plates causes an upwelling of hot mantle. The pressure relief during ascent carries peridotite across its solidus and induces partial melting. The melt, which is less dense than the surrounding mantle, separates from the solid and percolates towards the surface via porous and possibly channelized flow (e.g. Kelemen et al., 1997). The melt extraction rate is governed by the permeability of the mantle, which is highly influenced by the amount of melt present as well as the topology and connectivity of the melt network. Despite its importance for understanding melt transport in the mantle, the permeability of partially molten mantle rock is poorly constrained. The aim of this study is to provide better permeability estimates through the quantification of grain-scale melt distribution.

At textural equilibrium, the relationship between permeability and the grain-scale melt distribution in a partially molten rock takes the form of a power law (Cheadle, 1989; Connolly et al., 2009; McKenzie, 1984; Ricard et al., 2001; von Bargen and Waff, 1986; Wark and Watson, 1998),

$$k = \frac{\phi^n d^2}{C} \tag{1}$$

where d is grain size, n is the power law exponent, and C is a geometric factor influenced by the dihedral angle. For an isotropic system with uniform grain size and shape, $n = 2$ (McKenzie, 2000; von Bargen and Waff, 1986). For more complex systems, where the effects of crystal anisotropy and grain-scale heterogeneity are no longer negligible, higher vales of n should be used. For example, a value of $n = 3$ represents well porous flow through a non-uniform network of packed tetrakaidekahedral grains (Zhu and Hirth, 2003). These model results have been corroborated by permeability experiments conducted on analogue systems composed of quartzite + H_2O and calcite + H_2O where grain size distribution is non-uniform, grain shapes are anisotropic, and $n \sim 3$ (Wark and Watson, 1998).

Mineralogy plays an important role, through its influence on surface free energy, in determining the minimum-energy configuration of the system. Therefore, experiments conducted on partial melts with chemistry similar to the mantle must be considered.

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Some permeability experiments (Connolly et al., 2009; Renner et al., 2003) have been conducted for olivine partial melts. They find that the permeability of partially molten olivine basalt at high melt fractions ($\phi > 0.02$) is consistent with a power law where $n \sim 3$. However, permeametry of partially molten aggregates in these experiments is technically challenging. Consequently, the results of such studies are subject to considerable uncertainty.

Grain-scale melt distribution is typically studied by examining backscattered electron images from two-dimensional (2-D) cross-sections of isostatically pressed samples (e.g. Cmíral et al., 1998; Faul and Fitz Gerald, 1999). By assuming a model about the three-dimensional (3-D) connectivity of the melt network, it is possible to infer and estimate sample permeability using the 2-D data. However, those estimates are innately ambiguous, since permeability is an intrinsic property of the 3-D microstructure (Zhu et al., 2011). Therefore, a fully 3-D approach must be employed in order to accurately determine sample permeability. Two methods may be employed for characterizing microstructures in three dimensions: serial cross-sectioning (Garapić et al., 2013; Wark et al., 2003) and synchrotron X-ray microtomography (SXμT) (Watson and Roberts, 2011; Zhu et al., 2011). This study focuses on the latter.

Constraints on mantle permeability come from both geochemical and geophysical observations. Analyses of uranium-series isotopes in mid-ocean ridge basalts (MORB) (Lundstrom et al., 1995; McKenzie, 2000, 1985; Sims et al., 2002; Stracke et al., 2006), have shown a measureable degree of secular disequilibrium between ^{238}U and its shorter-lived daughter nuclides ^{230}Th and ^{236}Ra. Preservation of secular disequilibrium at the surface implies a low melt fraction retained by the mantle, $\phi < 0.01$, with a relatively fast upwelling velocity at $\sim$1 m yr^{-1} (Kelemen et al., 1997). By contrast, geophysical observations imply higher melt fraction. For example, seismic and magnetotelluric data (Evans et al., 1999; The MELT Seismic Team, 1998) from the East Pacific Rise 17°S give evidence that the melt fraction in the mantle is 0.01 to 0.02, implying that melt extraction is inefficient at lower melt fractions. In a more recent study, Key et al. (2013) reported a melt fraction close to 0.10 under the East Pacific Rise 9°N using magnetotelluric inversions. Accurate estimates of permeability of partially molten rocks are needed to reconcile the apparent contradiction in melt fraction.

In this study, we utilize high-resolution SXμT to digitally capture the 3-D melt distributions of olivine–basalt aggregates isostatically pressed in a piston–cylinder apparatus at 1350 °C and 1.5 GPa. Nominal melt fractions (ϕ_n) of samples ranged from 0.2 to 0.20 (Zhu et al., 2011). To demonstrate textural equilibrium of these experimental charges, we also conducted time series experiments at nominal melt fraction of 0.05 (refer to the Online Supplement). For each sample, we selected several representative subvolumes and characterized their permeability, grain size distribution, and melt interconnectivity. The permeability of each subvolume was calculated by numerically solving the Stokes fluid questions for the velocity and pressure fields within the digital melt microstructure. Permeability was plotted as a function of the measured melt fraction (ϕ_m) in the corresponding subvolume and an empirical relation between permeability and melt fraction was obtained. Our results provide new experimental constraints on the permeability and melt distribution of partially molten rocks.

2. Experimental methods

2.1. Sample preparation

Experimental charges were prepared from a powder mixture of natural, high-alumina basalt (Mg # = 0.705) and San Carlos olivine ($\sim$Fo$_{90}$) (Zhu et al., 2011). Olivine grains were sorted using a sieve to a maximum grain size of 10 μm. The nominal melt fraction desired for each sample was obtained by varying the basalt content of the mixture, which was then homogenized with ethanol for six hour-long cycles in an automatic agate mortar and pestle. The homogenized mixtures were pressed into cylindrical pellets under a 1-ton press, placed into graphite capsules (Fig. 1A), and dried overnight at 400 °C to remove water. The whole assembly was centered in a straight-walled graphite furnace using crushable MgO spacers. The pressure medium for all experiments consisted of a CaF_2 sleeve.

Experiments were conducted using 1.27 cm assemblies (Boyd and England, 1960). Pressure was initially applied using the cold piston-in technique (Johannes et al., 1971). The friction correction for the assemblies was calibrated against the Ca-tschermakite breakdown reaction at 1.2 to 1.4 GPa and 1300 °C (Hays, 1966) and determined to be less than the pressure uncertainty, so no correction has been applied to the reported pressures. Temperature was measured and controlled using a $W_3Re_{97}/W_{25}Re_{75}$ thermocouple; no correction for the effect of pressure on thermocouple EMF has been applied to the reported temperatures. N_2 was flowed over the thermocouple wires to minimize thermocouple oxidation over the course of an experiment. Temperatures are estimated to be accurate to ±10 °C and pressures to ±50 MPa. The temperature difference over the capsule was determined to be less than 5 °C using offset thermocouples. Experiments were terminated by shutting off the power. Upon completing each experimental run, the graphite capsule was sawed open to expose the surface of the experimental charge (Fig. 1B). The exposed surface was polished and reflected light photomicrographs were taken. A cylindrical $\sim$0.9 mm diameter samples was then cored from each charge to be used for SXμT analysis (Fig. 1C).

Two suites of experiments were conducted (Table 1). The first suite was a time series, which was conducted to determine the minimum time required for a sample to reach textural equilibrium. All of the time series samples have a nominal melt fraction of 0.05 and the sintering time varied systematically from 42 to 336 hours (see Online Supplement). The second suite of samples consisted of nominal melt fractions of 0.02, 0.05, 0.10, and 0.20. The sintering time for each sample was sufficiently long to ensure textural equilibrium (Zhu et al., 2011).

3. Analytical methods

3.1. Synchrotron X-ray microtomography

Microtomography was conducted at 2-BM of the Advanced Photon Source at Argonne National Laboratory, Argonne, IL. A multilayer monochromator was used to select a narrow band (27 keV) of X-rays. Those photons were then passed through the olivine–basalt sample (Fig. 2). On the opposite side of the sample, the X-rays were transmitted to a LuAg:Ce scintillator, converting them into visible light. A CCD camera was used to detect the visible light, and the light intensity was recorded. The sample was rotated 180° in 0.12° increments to build a digital volumetric representation of the sample in about 20 min (Fig. 2). For each sample, the raw intensity data was processed using GRIREC (Dowd et al., 1999) into a stack of image slices. Each slice is a grayscale image whose constituent pixels have values that are functions of X-ray attenuation, which is in turn, a function of material density. In this way, SXμT is used to differentiate phases, so long as the density contrast between the phases is substantial.

Silicate melt samples pose a unique problem in that the density contrast between olivine and basalt is not sufficient to differentiate the phases using standard phase contrast techniques. To circumvent this issue, we employed diffraction-enhanced imaging (Fitzgerald, 2000) to improve the contrast between olivine