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Estimates of olivine–basaltic melt electrical conductivity using a digital rock physics approach

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A B S T R A C T

Estimates of melt content beneath fast-spreading mid-ocean ridges inferred from magnetotelluric tomography (MT) vary between 0.01 and 0.10. Much of this variation may stem from a lack of understanding of how the grain-scale melt geometry influences the bulk electrical conductivity of a partially molten rock, especially at low melt fraction. We compute bulk electrical conductivity of olivine–basalt aggregates over 0.02 to 0.20 melt fraction by simulating electric current in experimentally obtained partially molten geometries. Olivine–basalt aggregates were synthesized by hot-pressing San Carlos olivine and high-alumina basalt in a solid–medium piston-cylinder apparatus. Run conditions for experimental charges were 1.5 GPa and 1350 °C. Upon completion, charges were quenched and cored. Samples were imaged using synchrotron X-ray micro-computed tomography (μ-CT). The resulting high-resolution, 3-dimensional (3-D) image of the melt distribution constitutes a digital rock sample, on which numerical simulations were conducted to estimate material properties. To compute bulk electrical conductivity, we simulated a direct current measurement by solving the current continuity equation, assuming electrical conductivities for olivine and melt. An application of Ohm's Law yields the bulk electrical conductivity of the partially molten region. The bulk electrical conductivity values for nominally dry materials follow a power-law relationship $\sigma_{\text{bulk}} = C\sigma_{\text{melt}}\phi^m$ with fit parameters $m = 1.3 \pm 0.3$ and $C = 0.66 \pm 0.06$. Laminar fluid flow simulations were conducted on the same partially molten geometries to obtain permeability, and the respective pathways for electrical current and fluid flow over the same melt geometry were compared. Our results indicate that the pathways for flow fluid are different from those for electric current. Electrical tortuosity is lower than fluid flow tortuosity. The simulation results are compared to existing experimental data, and the potential influence of volatiles and melt films on electrical conductivity of partially molten rocks is discussed.

1. Introduction

At mid-ocean ridges, melt is thought to percolate over a broad, partially molten region through a grain-scale network of interconnected melt (Fig. 1). The capacity of the upper mantle to transport melt, which is ultimately responsible for the production of oceanic crust, strongly depends on the spatial distribution of melt in the upper mantle. The magnetotelluric (MT) method, which exploits the high conductivity of partially molten rock, is a valuable tool used to probe the melt content of the upper mantle. Though MT measurements are consistent with the presence of partial melt at mid-ocean ridges, they disagree on the shape of the melting region and on the local melt fraction, with estimates in the literature varying from as low as 0.01–0.03 (Evans et al., 1999) to as much as 0.10 (Key et al., 2013). Though much of this variation is likely due to the presence of melt anisotropy (e.g. Pommier et al., 2015a; Zhang et al., 2014; Caricchi et al., 2011 and references therein), which is typically not accounted for when transforming conductivity to melt fraction profiles, the first step towards reconciling MT survey estimates is to robustly link electrical conductivity of partially molten mantle rocks to the grain-scale morphology and interconnectivity of melt under hydrostatic stress. A microstructure-based approach to constraining electrical conductivity as a function of melt fraction will provide a baseline for extrapolating laboratory measurement to natural conditions and to assess the potential contributions of volatiles and melt anisotropy to bulk electrical conductivity.

Bulk electrical conductivity of partially molten rock strongly depends on interconnectivity of the highly conductive melt phase. For a monomineralic system, under hydrostatic melting conditions,

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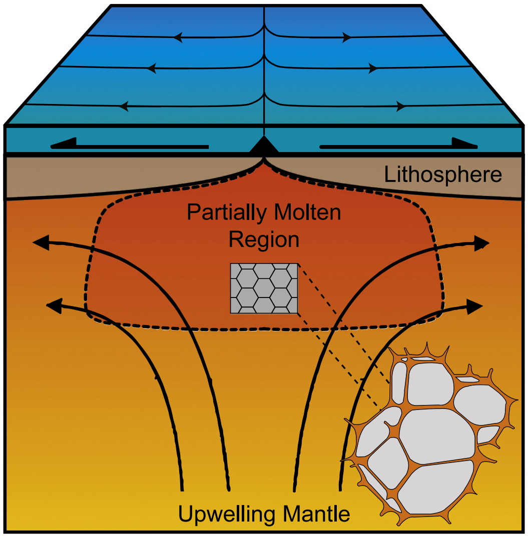

Fig. 1. Schematic diagram of a symmetrically spreading mid-ocean ridge. Surface arrows denote the spreading direction, curved arrows denote the upwelling direction of the mantle, blue region represents the ocean, brown represents the lithosphere, orange gradient represents the asthenosphere, and red represents the partially molten region beneath the ridge axis. Modified from Weatherley (2012). Pop-out figure is a depiction of an idealized, grain-scale melt geometry that is modified from Toramaru and Fujii (1986). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

melt settles into an equilibrium configuration that minimizes the total surface energy of the system (Fig. 1). The degree of interconnectivity can be assessed by the dihedral angle associated with its constituent solid–liquid phase boundaries (Bulau et al., 1979). For a dihedral angle greater than 60°, melt forms isolated pockets. In this case, the melt and solid phases are connected in series and the bulk electrical conductivity of the mixture is only marginally greater than that of the solid. However, for a dihedral angle less than 60°, as is the case for a partially molten olivine–basalt (Waff and Bulau, 1982), melt forms an interconnected network along grain edges (von Bargen and Waff, 1986). In this configuration, the melt conducts electricity in parallel with olivine and the bulk electrical conductivity for melt fractions greater than 0.01 increases by at least one order of magnitude (Roberts and Tyburczy, 1999; ten Grotenhuis et al., 2005; Yoshino et al., 2010).

Since the electrical conductivity of rock strongly depends on the melt geometry, bulk conductivity versus melt fraction relationships have been derived for a number of idealized melt geometries, such as a Hashin–Shtrikman sphere pack. Though idealized geometries are useful for conceptualizing melt configurations, partially molten mantle rocks are heterogeneous and exhibit a range of melt features (e.g. Miller et al., 2014; Waff and Faul, 1992) depending on the melt fraction present. At melt fraction larger than ~0.01, melt mostly resides in triple junctions connected at four-grain junctions (Miller et al., 2014; Waff and Bulau, 1982; Zhu et al., 2011 and references therein) though melt films that wet two-grain boundaries have also been observed at low melt fraction (e.g. Cmíral et al., 1998; Faul et al., 1994). Melt pools exist with increasing frequency as melt fraction increases, leading to an increased degree of grain boundary wetting or spillover from triple junctions (e.g., Miller et al., 2014; Zhu et al., 2011). At melt fraction of 0.2, melt pools are the dominant feature of the melt network (Miller et al., 2014; Zhu et al., 2011). The coexistence of multiple geometries for a given melt fraction highlights the importance to consider realistic, three-dimensional (3-D) melt geometries when computing material properties like electrical conductivity.

Experiments conducted on partially molten olivine–basalts find that bulk electrical conductivity varies as a power law with melt fraction (i.e., Archie's Law):

$$\sigma_{\text{bulk}} = C\sigma_{\text{melt}}\phi^m \tag{1}$$

where σ_{bulk} is bulk conductivity, σ_{melt} is melt conductivity, and ϕ is melt fraction. C and m are empirical power law parameters that depend on the melt morphology and interconnectivity. Values $m = 0.89$ to 1.30 and $C = 0.73$ to 1.47 have been reported for olivine–basalt partial melts (Pommier et al., 2015b; Roberts and Tyburczy, 1999; ten Grotenhuis et al., 2005; Yoshino et al., 2010). Though experimentally assessing the bulk electrical conductivity of olivine aggregates is necessary for accurately interpreting EM data, empirical relationships alone do not provide much textural information about the partially molten rock.

Most studies (Roberts and Tyburczy, 1999; ten Grotenhuis et al., 2005; Yoshino et al., 2010) find that the data on partially molten samples overlap the upper Hashin–Shtrikman bound, which is intended to represent a loose pack of uniformly wetted spheres. We argue that this interpretation is inconsistent with microstructural observations of texturally equilibrated rocks. While experimental constraints on the electrical conductivity of partially molten rock as a function of melt fraction are essential to interpret MT data, a direct link between electrical properties and melt geometry is still missing.

In addition, the use of electrical conductivity to infer permeability of systems where direct permeability measurements could be challenging, such as partially molten rocks, has garnered significant interest. With the assumptions that pathways for both conductivity and permeability are linked to the microstructure of the rock, several studies have discussed the apparent formation factor, defined as the $\sigma_{\text{bulk}}/\sigma_{\text{melt}}$ and its relation to microstructure in various porous media (e.g. Avellaneda and Torquato, 1991; Johnson et al., 1986; Katz and Thompson, 1987). A self-consistent analysis of permeability and electrical conductivity using network (David, 1993) and laminar flow models on periodic pore spaces (e.g. Martys and Garboczi, 1992; Schwartz et al., 1993) conclude that these approaches produce comparable results in terms of extrapolating permeability from electrical conductivity. They may even work empirically to deduce fluid flow information from electromagnetic data. However, the physics of laminar flow and direct electric current – both the governing equations and boundary conditions – are different. For example, while highly conductive impurities on grain boundaries can significantly enhance bulk conductivity in polycrystalline olivine (Watson et al., 2010), they will not support fluid flow. Therefore, one should not expect that changes in the melt microstructure, in this case by means of changing the melt fraction, have the same effect on permeability as it does on electrical conductivity. With this in mind, it is important to assess whether a link between permeability and electrical conductivity is physically justified.

In this study, we compute the bulk electrical conductivity and permeability of digital rocks composed of olivine and basaltic melt with texture equilibrated at isostatic mantle pressure–temperature conditions. We digitized each sample using synchrotron-based X-ray micro-computed tomography (μ-CT) (Zhu et al., 2011). The resulting 3-D images constitute digital rocks, on which direct current and fluid flow simulations were conducted.

2. Methods

2.1. Sample preparation and imaging

The samples considered in this study are synthetic olivine–basalts aggregates representing partially molten rocks (Miller et al., 2014; Zhu et al., 2011). Experimental charges were prepared from a powered mixture of Fo_{90} San Carlos olivine and natural, high-alumina basalt (Mg # = 0.0705) mixed in proportion to achieve