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Experimental determination of melt interconnectivity and electrical conductivity in the upper mantle

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ABSTRACT

The presence of a small fraction of basaltic melt is a potential explanation for mantle electrical conductivity anomalies detected near the top of the oceanic asthenosphere. The interpretation of magnetotelluric profiles in terms of the nature and proportion of melt, however, relies on mathematical models that have not been experimentally tested at realistically low melt fractions (<0.01). In order to address this, we have performed *in situ* electrical conductivity measurements on partially molten olivine aggregates. The obtained data suggest that the bulk conductivity follows the conventional Archie's law with the melt fraction exponents of 0.75 and 1.37 at melt fractions greater and smaller than 0.5 vol.% respectively at 1350 °C. Our results imply multiple conducting phases in melt-bearing olivine aggregate and a connectedness threshold at ~0.5 vol.% of melt. The model predicts that the conductive oceanic upper asthenosphere contains 0.5 to 1 vol.% of melt, which is consistent with the durable presence of melt at depths over millions years while the oceanic plates spread apart at the mid-ocean ridge. Beneath ridges a minimum permeability may allow mid-ocean ridge basalts to rise out of the mantle, where our model indicates that melt is present in proportions of up to 4 vol.%.

1. Introduction

One of the most striking geophysical anomalies identified in the upper mantle is the Low Velocity Zone (LVZ, e.g. Holtzman, 2016) characterized by low seismic velocities and high attenuation and located in the asthenosphere near the Lithosphere–Asthenosphere Boundary (LAB). Under oceanic plates, the LVZ appears to coincide in some regions with a 20 to 50 km thick layer that possesses a high electrical conductivity (EC) (up to Log $\sigma = -0.3$; σ in S/m) relative to overlying and underlying layers (e.g. Evans et al., 2005; Baba et al., 2006; Naif et al., 2013; Sarafian et al., 2015).

Several factors that might enhance EC have been invoked to explain these anomalies, such as anisotropy in mineral conductivity (e.g. Poe et al., 2010), water dissolved in nominally anhydrous minerals (e.g. Dai and Karato, 2014), or the presence of melt (e.g. Gaillard et al., 2008; Yoshino et al., 2010; Ni et al., 2011; Sifré et al., 2014). However, conductivity anisotropy in olivine aggregates appears to have an insufficient effect on EC to account for the observed mantle anomaly (Poe et al., 2010; Yang, 2012). In addition, water dissolved in olivine is unlikely to produce the conductivity anomalies observed in the upper mantle (Gardés et al., 2014) because the concentration of water in minerals required to reach upper mantle conductivities (100 to 1000 ppm; e.g. Dai and Karato, 2014) would lead to partial melting of the mantle rocks, accompanied by partitioning of significant proportions of water into a melt phase rather than minerals (Hirschmann, 2006). Anisotropic distribution of the melt may also be a further factor enhancing the EC (Caricchi et al., 2011; Zhang et al., 2014; Pommier et al., 2015a, 2015b). For these reasons, it seems that the presence of melt is the most likely explanation for the EC anomalies in the upper mantle, supported by melt-solid viscosity and density contrast (Sakamaki et al., 2013).

Large differences in transport properties between silicate minerals and melt mean that the EC of silicate melts is orders of magnitude higher than mineral phases (e.g. Tyburczy and Fisler, 1995). As a consequence, the bulk EC of partially molten rocks (minerals + melt) varies with the relative fraction of solid and liquid phases, but also with their respective distribution (Glover, 2010 and references therein). A liquid phase should form an interconnected network in a solid aggregate whenever dihedral angles between the two phases are lower than 60°. Since, in olivine aggregates, basaltic melt is distributed as pockets, tubes and films

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Table 1
Chemical compositions and standard deviations (italic grey font) of the starting materials (Olivine & Synthesis, whereby the nominal and the analyzed composition of the latter are reported) and melt compositions after experiments. All analyses were normalized to 100 wt.%, and the total (*) shows the sum of oxides before correction. The number of analyses performed is indicated after the name of each experiment.

#Exp	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	Gd_2O_3	FeO	MgO	NiO	MnO	CaO	Na_2O	K_2O	Total*
Olivine (54)	39.78	0.01	0.02	0.04		8.21	51.37	0.38	0.12	0.06	0.01		
	0.75	*0.01*	*0.02*	*0.07*		*0.20*	*0.64*	*0.05*	*0.04*	*0.02*	*0.01*		
nominal	52		15		2	7.5	8.5			10	3	2	100
Synthesis (20)	52.00	0.01	15.34		1.88	6.81	8.68		0.02	10.20	3.10	1.96	98.71
	0.31	*0.01*	*0.19*		*0.23*	*0.17*	*0.17*		*0.02*	*0.13*	*0.10*	*0.04*	*2.71*
M480 – 100% (16)	48.27	0.01	14.38		1.80	6.15	13.58		0.01	10.43	3.28	2.09	97.75
	0.40	*0.02*	*0.35*		*0.14*	*0.17*	*0.96*		*0.01*	*0.32*	*0.16*	*0.13*	*0.53*
M484 – 10% (15)	48.86	0.03	12.19		1.64	9.59	11.34		0.15	10.98	3.02	2.19	97.98
	0.73	*0.02*	*0.82*		*0.24*	*0.56*	*1.62*		*0.05*	*0.55*	*0.22*	*0.23*	*0.48*
M477 – 4% (11)	50.21	0.04	15.28		2.18	7.31	8.77		0.19	10.67	3.17	2.19	96.69
	1.10	*0.02*	*2.62*		*0.16*	*0.86*	*0.93*		*0.03*	*0.39*	*0.06*	*0.10*	*0.63*
M486 – 2% (14)	49.75	0.07	11.65		1.40	9.76	11.14		0.19	10.82	3.18	2.06	98.48
	0.52	*0.02*	*0.79*		*0.17*	*0.50*	*0.83*		*0.04*	*0.65*	*0.36*	*0.27*	*0.52*
M487 – 1% (8)	48.65	0.11	11.43		1.18	9.50	13.45		0.15	10.79	3.00	1.73	95.90
	2.40	*0.05*	*0.76*		*0.25*	*0.64*	*1.23*		*0.06*	*2.59*	*0.43*	*0.32*	*1.10*
M488 – 0.5% (29)	49.90	0.01	14.15		1.76	8.45	8.81		0.08	12.48	2.67	1.69	97.21
	0.62	*0.01*	*0.33*		*0.24*	*0.38*	*0.69*		*0.03*	*0.67*	*0.17*	*0.14*	*0.91*
M501 – 0.5% (4)	52.09	0.05	13.54		1.25	9.57	10.93		0.00	8.77	2.47	1.34	98.45
	1.10	*0.02*	*0.67*		*0.14*	*0.28*	*2.50*		*0.00*	*1.35*	*0.19*	*0.12*	*0.59*
M510 – 0.25% (11)	51.45	0.05	10.78		1.14	7.83	15.20		0.15	9.31	2.97	1.10	97.42
	1.13	*0.03*	*0.70*		*0.24*	*1.16*	*2.22*		*0.04*	*0.69*	*0.37*	*0.07*	*0.49*

with dihedral angles as low as ~10°, melt is expected to be interconnected and thus contributes to a significant increase of the EC even at melt fractions lower than 1% (Cmíral et al., 1998; Yoshino et al., 2009; Faul and Scott, 2006; Garapić et al., 2013).

The conductivity of a partially molten assemblage is generally calculated based on a mathematical model with an assumed mineral and melt geometry. The applicability of such models has, to date, not been experimentally investigated, particularly at very low (<1%) melt fractions, which are likely realistic for the upper mantle. Amongst the numerous mixing laws summarized and described by Glover (2010) and ten Grotenhuis et al. (2005), the conventional and modified Archie's laws appear very suitable for calculating the EC of upper mantle materials in which both solid and liquid phases contribute to the bulk conductivity according to defined exponents. Other models, such as the tubes, cubes, and sphere + models (Grant and West, 1965; Waff, 1974) texturally reproduce a melt-bearing aggregate with a melt fraction >0.05 where pockets (pools) and films wetting grain boundaries are the dominant features of the melt network (Miller et al., 2014). At melt fractions lower than 0.02, the melt principally forms channels residing along grain edges, and can still be interconnected down to very low melt fractions resulting in a potentially poor fit to these models (Garapić et al., 2013; Holtzman, 2016). In spite of the proposed interconnectivity threshold (e.g. Holtzman, 2016), it is expected that the melt raises the bulk conductivity at these low (<0.01%) melt fractions.

Estimates for the amount of melt potentially present in the upper mantle is still quite uncertain due to a lack of experimental verification of models relating the degree of partial melt to the resulting EC, particularly at very low (<1%) melt fractions. In order to find the most adequate mixing law for mantle rocks containing low melt fractions, we have performed *in situ* electrical conductivity measurements on olivine aggregate with melt fraction varying from 0 to 100 vol.% at pressures and temperatures up to 3 GPa and 1430 °C respectively. From the results, we build a model based on the conventional Archie's law, which is valid over a large range of temperature and melt fraction. Then, we discuss the amount of melt potentially existing in the upper mantle, and its mobility. In addition, we estimate the temperature distribution in the asthenosphere without melt based on the present conductivity measurements of melt-free olivine aggregates.

2. Experimental procedure

2.1. Starting materials and sample preparation

Natural olivine from a Lanzarote peridotite (Canary Islands, Spain) and synthetic basalt were employed as solid and liquid starting materials respectively. The Lanzarote olivine consists of a single chemically homogeneous population of Fo92 (Table 1). Optical impurity-free olivine grains were crushed and sieved to obtain a maximum grain size of 100 µm. Olivine was used without further treatment (e.g. annealing under special conditions) so as to remain close to natural mantle materials. The basaltic glass was produced by mixing reagent grade oxides and carbonates and fusing the mixture twice in an iron-enriched platinum crucible at 1450 °C and 1 atm for 3 h. The resulting homogeneous glass had a composition similar to that of a Mid-Ocean Ridge Basalt (termed "synthesis", Table 1). Gadolinium was added to the melt (a very incompatible element that concentrates exclusively in the liquid) for neutron tomography observations that are not reported here. The same batch of basalt was used for all experiments. Its liquidus temperature was estimated to be approximately 1270 °C at 1.5 GPa from the melting temperature during synthesis and from EC measurements with the sample with 100% of melt. The glass was then cored to provide starting samples of basalt i.e. for 100% melt fraction experiments, while the rest of the glass was crushed into a fine powder (~5 µm grain size). This powder was mechanically mixed with olivine grains in order to distribute the glass as homogeneously as possible within the olivine aggregate. Each component was accurately weighed (precision of 0.1 µg) to achieve the desired melt fraction, assuming very little density variation between room and