Earth and Planetary Science Letters 425 (2015) 242–255

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Experimental investigation of the electrical behavior of olivine during partial melting under pressure and application to the lunar mantle

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ARTICLE INFO

Article history:
Received 8 December 2014
Received in revised form 26 May 2015
Accepted 28 May 2015
Available online 8 June 2015
Editor: J. Brodholt

Keywords:
electrical conductivity
partial melting
lunar mantle

ABSTRACT

Electrical conductivity measurements were performed during melting experiments of olivine compacts (dry and hydrous Fo_{77} and Fo_{90}) at 4 and 6 GPa in order to investigate melt transport properties and quantify the effect of partial melting on electrical properties. Experiments were performed in the multi-anvil apparatus and electrical measurements were conducted using the impedance spectroscopy technique with the two-electrode method. Changes in impedance spectra were used to identify the transition from an electrical response controlled by the solid matrix to an electrical response controlled by the melt phase. This transition occurs slightly above the solidus temperature and lasts until $T_{solidus} + 75\,^{\circ}C$ (±25). At higher temperature, a significant increase in conductivity (corresponding to an increase in conductivity values by a factor ranging from ∼30 to 100) is observed, consistent with the transition from a tube-dominated network to a structure in which melt films and pools become prominent features. This increase in conductivity corresponds to an abrupt jump for all dry samples and to a smoother increase for the hydrous sample. It is followed by a plateau at higher temperature, suggesting that the electrical response of the investigated samples lacks sensitivity to temperature at an advanced stage of partial melting. Electron microprobe analyses on quenched products indicated an increase in Mg# (molar $Mg/(Mg + Fe)$) of olivine during experiments (∼77–93 in the quenched samples with an initial Fo_{77} composition and ∼92–97 in the quenched samples with an initial Fo_{90} composition) due to the partitioning of iron to the melt phase. Assuming a respective melt fraction of 0.10 and 0.20 before and after the phase of significant increase in conductivity, in agreement with previous electrical and permeability studies, our results can be reproduced satisfactorily by two-phase electrical models (the Hashin and Shtrikman bounds and the modified brick layer model), and provide a melt conductivity value of 78 (±8) S/m for all Fo_{77} samples and 45 (±5) S/m for the Fo_{90} sample. Comparison of our results with electromagnetic sounding data of the deep interior of the Moon supports the hypothesis of the presence of interconnected melt at the base of the lunar mantle. Our results underline that electrical conductivity can be used to investigate *in situ* melt nucleation and migration in the interior of terrestrial planets.

1. Introduction

Partial melting is induced from different major processes that shape the interior of terrestrial bodies and contributes to their differentiation, evolution, and dynamics. For instance, upwelling in the Earth's mantle carries peridotite across the solidus and the melt produced percolates and migrates upward due to density contrast, contributing significantly to the activity of tectonic zones (e.g., Schmerr, 2012). Several studies also suggested the presence of melt at the base of the lower mantle of some terrestrial bodies, such as the Earth (e.g., Garnero and McNamara, 2008) and the Moon (e.g., Weber et al., 2011; Khan et al., 2014), that may indicate a remnant global magma ocean, remained partially molten due to the presence of trapped heat-producing elements. Partial melting experiments on silicate systems under pressure are needed

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http://dx.doi.org/10.1016/j.epsl.2015.05.052

to understand melt migration and extraction in the mantle. These experimental investigations are also required to investigate differentiation processes related to global melting and crystallization of planetary interiors, and to test the likelihood of hypotheses suggesting that the base of the mantle of some terrestrial bodies is currently partially molten.

Olivine $(Mg, Fe)_2SiO_4$ and its high-pressure polymorphs are major phases in the mantle of terrestrial bodies, and investigating their melting properties is key to understand melting processes in planetary interiors. Several phase relation studies of olivine have been conducted under pressure (e.g., Davis and England, 1964; Akimoto et al., 1967; Katsura and Ito, 1989; Ohtani et al., 1998; Liebske and Frost, 2012). However, these studies do not allow the investigation of partial melting in real time, which is necessary to understand melt nucleation, percolation, and extraction at mantle conditions. To do so, one possibility is to perform electrical conductivity measurements and to use the bulk electrical response of the sample as a probe to investigate melt transport during partial melting in real time. Because partially molten rocks consist of low-conductivity minerals and a more conductive liquid phase, their bulk conductivity is very sensitive to melt interconnectivity and melt distribution (e.g., Sato and Ida, 1984; Roberts and Tyburczy, 1999; Partzsch et al., 2000). Most electrical studies of partial melting were conducted at low pressure (<1 GPa) on volcanic rocks (e.g., basalts (Rai and Manghnani, 1977; Tyburczy and Waff, 1983); andesite (Waff and Weill, 1975)) and mixtures of olivine + a defined amount of basalt (Wanamaker and Duba, 1993; Roberts and Tyburczy, 1991, 1999; Caricchi et al., 2011; Yoshino et al., 2010). At atmospheric pressure, Rai and Manghnani (1978) and Partzsch et al. (2000) respectively measured the conductivity of granulite and ultramafic rocks (peridotite and eclogite) during partial melting, and attributed the observed strong increase in conductivity to the formation of an interconnected melt network. Partzsch et al. (2000) suggested that complete interconnection was reached at a melt fraction of ∼8 vol.%. All these electrical studies observed that the bulk conductivity of rocks increases by a few orders of magnitude during melting.

High-pressure electrical conductivity measurements in the laboratory are also of direct interest to electromagnetic field and modeling studies that probe the electrical response of planetary interiors and can detect the presence of partially molten areas (e.g., Key et al., 2013; Khan et al., 2014). Combined with petrological constraints and laboratory experiments, the interpretation of these electromagnetic data can provide information about the amount of melt, its geometry, interconnectivity, and storage conditions. In particular, several electromagnetic and seismic studies suggested the hypothesis of the presence of partial melt at the base of the lunar mantle (e.g., Nakamura, 2005; Weber et al., 2011; Khan et al., 2014). Experimental work is requested to test further this hypothesis and demonstrate whether or not bulk physical properties (elastic and electrical) of the lunar interior can be reproduced in the laboratory using partially molten materials at conditions relevant to the lunar mantle.

In this paper, we present an electrical investigation of dry and hydrous polycrystalline olivine compacts (Fo_{77} and Fo_{90}) at 4 and 6 GPa during partial melting. Our results present new experimental constraints on the electrical properties of partially molten olivine at high pressure. Two-phase electrical models are used to estimate the conductivity of the melt phase. Our conductivity data are then compared with the electrical profile of the deep lunar mantle, assuming that our experiments correspond to a chemical end-member for a lunar lowermost partially molten mantle, in order to test the hypothesis of partial melt in the present-day lower mantle of the Moon.

Table 1
Olivine starting compositions (in wt%).

	Fo_{77}	Fo_{90}
SiO_2	36.67	38.90
FeO_{tot}	22.09	9.67
MnO	0.10	0.12
MgO	40.54	50.80
CaO	–	–
K_2O	–	–
NiO	0.44	0.39
Total	99.85	99.87
Mg#[a]	0.77	0.90

[a] Mg# = Mg/(Mg + total Fe).

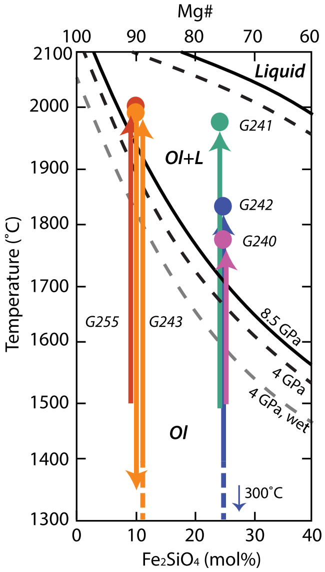

Fig. 1. Phase relations of the Mg_2SiO_4–$(Mg_{0.6}, Fe_{0.4})_2SiO_4$ system at 4 GPa. Solidi and liquidi are after Ohtani et al. (1998) and Katsura and Ito (1989). Dots represent the quench temperature for each experiment (Table 1) and arrows indicate the temperature range of electrical measurements during heating and cooling cycles.

2. Experimental and analytical methods

2.1. Starting materials

Starting materials were hot-pressed polycrystalline olivine with different chemical compositions: $\sim Fo_{90}$ (San Carlos olivine), Fo_{77}, and hydrous Fo_{77}, all synthesized at University of Minnesota (U of M) at a confining pressure of 0.3 GPa and a temperature of 1200–1250 °C in a gas-medium apparatus. Starting compositions are listed in Table 1. The olivine grain size in quenched samples ranges from ∼50 to 150 μm (Table 2), with the bigger grains being close to the melt pool. Based on FTIR analyses at U of M, the wet Fo_{77} starting material contains ~ 1100 H/10^6 Si. These starting compositions have been chosen for two major reasons. First, petrological and geochemical evidence has shown olivine or high-pressure polymorphs of olivine are major phases in the interior of terrestrial bodies, representing ∼60% of the Earth's xenoliths (e.g., Mathias et al., 1970), ∼50% of the lunar mantle (e.g., Khan et al., 2014), and 50–60% of the Martian mantle (Bertka and Fei, 1997). The Mg# (molar Mg/(Mg+Fe)) of the Earth's upper mantle is around 90 (Hart and Zindler, 1986) while it is lower and closer to 75–85 for the lunar mantle (e.g., Khan et al., 2007; Grimm, 2013) and around 75 for the iron-rich martian mantle (e.g., Dreibus and Wänke, 1985). Our olivine samples are therefore representative of the range of average olivine compositions present in the mantle of these three terrestrial bodies. Second, as shown in Fig. 1, phase relations of the Mg_2SiO_4–Fe_2SiO_4 sys-