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**Experimental Investigation of the Electrical Behavior of Olivine
during Partial Melting under Pressure
and Application to the Lunar Mantle**

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Abstract

Electrical conductivity measurements were performed during melting experiments of olivine compacts (dry and hydrous Fo₇₇ and Fo₉₀) 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 $T_{\text{solidus}} + 75^{\circ}\text{C}$ (+/-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 lack 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 Fo₇₇ composition and ~92-97 in the quenched samples with an initial Fo₉₀ 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 Fo₇₇ samples and 45 (+/-5) S/m for the Fo₉₀ sample. Comparison of our results with electromagnetic sounding data of the deep interior of the Moon support 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 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 ($\text{Mg, Fe})_2\text{SiO}_4$ 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 et al., 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 (Fo₇₇ and Fo₉₀) 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 in order to test the hypothesis of partial melt in the present-day lower mantle of the Moon.

2. Experimental and analytical methods

2.1. Starting materials

Starting materials were hot-pressed polycrystalline olivine with different chemical compositions: $\sim\text{Fo}_{90}$ (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 microns (Table 2), with the bigger grains being close to the melt pool. Based on FTIR analyses at U of M, the wet Fo_{75} starting material contains $\sim 1100 \text{ H}/10^6 \text{ Si}$. These starting compositions have been chosen for two major reasons. First, petrological and geochemical evidence have shown olivine or high-pressure polymorphs of olivine are major phases in the interior of terrestrial bodies, representing $\sim 60 \%$ of the Earth's xenoliths (e.g., Mathias et al., 1970), $\sim 50\%$ of the lunar mantle (e.g., Khan et al., 2014), and 50-60% of the Martian mantle (Bertka and Fei, 1997). The Mg# (molar $\text{Mg}/(\text{Mg}+\text{Fe})$) 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 Figure 1, phase relations of the $\text{Mg}_2\text{SiO}_4\text{-Fe}_2\text{SiO}_4$ system under pressure do not present any solid state phase transitions when heating Fo_{90} and Fo_{77} at 4-6 GPa (Katsura and Ito, 1989; Ohtani et al., 1998). This pressure is too low to cross the stabilization field of spinel, and the only phase boundary is the solidus, located at 4 GPa at $\sim 1850^\circ\text{C}$ and 1650°C for dry Fo_{90} and Fo_{77} , respectively (after Ohtani et al., 1998). Therefore, the evolution of the electrical response of our samples during heating and partial melting will not be disturbed by the effect of mineralogical phase transformations, which was shown to affect bulk electrical properties of several silicate minerals (e.g. Bagdassarov and Delepine, 2004).

2.2. High-pressure cell assembly

Impedance spectroscopy experiments on olivine compacts were performed during partial melting at 4 and 6 GPa in the multi-anvil apparatus using tungsten carbide cubes with a corner-truncation edge length of 8 mm, in mullite or MgO /spinel octahedral pressure media with an edge length of 14 mm (Figure 2a). Graphite heaters were used, placed inside an outer zirconia sleeve for thermal insulation. Experimental samples were 1.2 to 1.5 mm in length, either cylindrical (2 mm in diameter) or square in cross section (1.6 mm in edge), and were placed at the center of the cylindrical heater inside an MgO sleeve. Depending on the geometry of the sample, two molybdenum disks (2 mm OD) or squares (1.6 mm edge length) were in contact with the sample, serving as electrodes. The temperature was

monitored with a $W_{95}Re_5$ – $W_{74}Re_{26}$ (C-type) thermocouple inserted within a 4-bore MgO sleeve with the junction in contact with the top of one of the molybdenum foils. A single lead wire was brought out from the other molybdenum disk. All MgO parts were fired at 1400°C at one atmosphere for a couple of hours and stored in an oven at 120°C overnight just before the experiment. Oxygen fugacity (fO_2) was not controlled during the experiments, but the presence of a graphite furnace implies a reducing environment with an oxygen fugacity ranging approximately between FMQ-3 and FMQ-4 at our experimental pressure (Stagno et al., 2013). These redox conditions are relevant to the Earth's upper mantle, the lunar mantle, and the martian mantle (e.g., Papike et al., 2005; Frost and McCammon, 2008).

2.3. Analytical technique

Longitudinal sections of the experimental charges were mounted and polished. Quenched samples were used for estimating the maximum melt fraction reached during the experiment as well as chemical analyses. Backscattered electron images, chemical composition maps and quantitative chemical analyses were obtained with a five spectrometer JEOL JXA-8530F electron microprobe using Wavelength Dispersive Spectrometry (WDS) and Energy-Dispersive Spectrometry (EDS) at the electron microprobe facility at ASU. Analyses were performed with a 15 kV accelerating voltage and a beam current of 10 nA. Mineral phases were analyzed with a focused beam and quenched melt analyses were analyzed with a 10 micron beam.

2.4. Electrical measurements

2.4.1. Cell calibration and experimental protocol

Electrical measurements were conducted using a 2-electrode method. In order to determine the effect of the resistance of the electrodes (molybdenum disks/squares, metallic wires and cables) on the bulk resistance measured in our experiments, we conducted a short-circuit experiment at 4 GPa and at temperature up to 1900°C. The measured resistance was ~ 7 ohm, and this value was deduced from all the bulk resistance measurements presented in this study. Our electrical cell has been calibrated using a hot-pressed polycrystalline olivine sample (wet Fo₇₇) by performing electrical experiments in the same conditions (same sample, pressure and temperature) in two different laboratories (ASU and BGI, Germany). The cell used at BGI was different from the one used at ASU, with differences in both materials and part dimensions. Electrical data were collected at 3 GPa and at temperatures up to 700°C. All data from both laboratories fit into a 3% error on $\log(\sigma)$, confirming that our cell was measuring the sample's response without significant interference from any other part of the cell assembly.

The conductivity cell (Figure 2a) was connected to a 1260 Solartron Impedance/Gain-Phase Analyzer for electrical impedance measurements. Our run conditions are presented in Table 2. The cell assembly was compressed to the target pressure (either 4 or 6 GPa) and then temperature was increased in ~ 20 min to 1500°C for all samples except the hydrous Fo₇₇ sample, for which temperature was increased quickly to 300°C only. Impedance spectra were recorded regularly during heating, starting at 1500°C for the dry samples and 300°C for the hydrous Fo₇₇

sample. Temperature was maintained for time-series measurements at defined T when a change in the shape of the impedance spectra was observed (see Section 2.4.2.) and electrical measurements were repeated until a stable value of the electrical resistance R was reached (generally rapidly, within a few minutes and in all cases less than 20 min). Temperature was then increased again until a plateau in resistance value is reached. Electrical measurements during cooling and second heating were performed for one run (run G243, Fo₉₀ sample, Table 2). All samples were quenched at the highest temperature (Table 2) by shutting off the electric power supply to the furnace before starting decompression in order to preserve the partially molten texture of the final state.

2.4.2. Impedance spectra and data reduction

Impedance spectroscopy measurements consisted of recording the electrical impedance of the sample at variable frequency (ranging between a maximum of 5 MHz and a minimum of ~100-1000 Hz), with an applied voltage of 1 V. This complex impedance Z is the sum of a real part (Z') and an imaginary part (Z''), with the real part corresponding to the electrical resistance R of the sample. Because the contribution of the electrodes to the measured impedance is small enough compared to the sample's contribution, the electrical conductivity of the sample σ (S/m) can be deduced from the value of R (ohm) by using the following relation:

$$\sigma = 1/(G \cdot R) \quad (1)$$

With G the geometric factor (m). For our conductivity cell

$$G = A/l \quad (2)$$

With A the surface area of the Mo electrode (m^2) and l the thickness of the sample (m). For each measurement, the electrical response of the samples was directly observed in the (Z' , Z'') plane, and the value of R was obtained from the intersection of the sample's response with the real impedance axis (Z'). For typically resistive systems like polycrystalline olivine, inductive effects are negligible compared to R and our data (semiarcs) are best fit with a RC or R-CPE (constant phase element) parallel circuit, as observed by previous studies of olivine aggregates (e.g., Yoshino et al., 2009; Farla et al., 2010). Relative errors on values of σ (Table 2) were calculated considering errors on the geometrical factor (i.e., considering errors on A and L) as well as propagated errors on each measured value of resistance R .

As shown in Figure 2b-d, the shape of impedance spectra changed with temperature, and three types of spectra were observed for each sample during partial melting experiments:

1) at low temperature (i.e., below the solidus temperature), an impedance arc was observed in the high-frequency part; the highest frequency part of the arc (>0.1 MHz) was not accessible, as previously observed on other studies of olivine under pressure (e.g., Yoshino et al., 2012), but the clear part of the arc at lower frequencies allowed us to identify the resistance value (Figures 2b and 2c). At low-temperature, impedance spectra of the hydrous Fo_{77} sample consisted of a first impedance semi-circle in the plane where $Z'' < 0$ followed by a smaller semi-circle in the plane where $Z'' > 0$ (Figure 2b). Previous electrical studies have observed a similar shape of impedance spectra and interpreted the first semi-circle as a conductive loop, and the second semi-circle as an inductive loop related to relaxation processes due to

chemical reactions (e.g., Bai and Conway, 1991; Lee and Pyun, 1999; Kriaa et al., 2009; Wang et al., 2013). The conductivity of the sample can be determined from the first half-circle (Wang et al., 2013). The electrical resistance of the sample is determined as the intersection of the first semicircular pattern with the Z' axis (real part of the complex impedance).

2) Slightly above the predicted solidus temperature and until $T = T_{\text{solidus}} + 75^{\circ}\text{C}$ (+/- 25), with T_{solidus} based on phase equilibria studies of olivine by Ohtani et al. (1998) and Katsura and Ito (1989), the impedance arc became noisy and the resistance value was still identified by the intersection of the sample's response with the Z' axis.

3) At higher temperature (Figure 2d), the sample's resistance is low (<200 ohm) and the electrical response at high frequencies was dominated by induction effects derived from electrode and W-Re wires. A vertical line replaces a semi-circle shape, as commonly observed with melt (e.g., Pommier et al., 2010) and with low-resistance solid minerals (e.g., Yoshino et al., 2012), and the electrical resistance is determined as the intersection of the sample response with the real axis.

3. Results

3.1. Interaction processes between sample and cell parts

SEM images and electron microprobe analyses were used to characterize chemical interaction processes between sample and parts of the conductivity cell

directly in contact with it (Mo electrodes and MgO sleeve). Figure 3 presents SEM images and chemical composition maps of some samples after partial melting experiments. Because of density contrasts, melt migrated upward. In the multi-anvil, the cell is oriented such that it has an inclination of $\sim 35^\circ$ compared to its vertical position in Figure 2a, and the top of the conductivity cell is actually located close to the MgO sleeve, where melt migrated and eventually pooled (Figure 3a). This observations underlines the fact that in our experiments, melt migration is gravity-driven and not governed by thermal gradient, in which case the melt would pool in the equator of the sample on both sides of its cylindrical shape. Thermal gradients in our samples are expected to be small (10 degrees or so) and are mostly sideways because the sample is thin and well centered in a symmetrical furnace. At the highest temperatures, when melt was interconnected and its migration was significant, melt infiltrated and reacted with the MgO sleeve, as underlined by a visible front reaction of magnesiowüstite (ferropericlase) formation in the MgO sleeve from the experiment on hydrous Fo₇₇ (Figure 3c) and the EDS map of the Si distribution (Figure 3d).

In most samples, a few iron-rich metallic spheres (diameter < ~ 50 microns) were observed, mostly disseminated in areas close to the electrodes (Figure 3b and 3g). Energy-dispersive spectrometry (EDS) spot analyses detected the presence of MoO₂ in the spheres close to the electrodes, suggesting a chemical interaction between iron-rich melt and Mo electrodes at the highest temperatures. An interaction with electrodes may also be supported by the irregular surface of the Mo electrodes in some areas in contact with the sample (Figures 3a and 3c), though this

may also be caused by polishing. Because of their low abundance and scattered repartition in the sample, we consider that these spheres, possibly sinking during the heating cycle, did not contribute to the measured bulk conductivity in our experiments. The analysis of melt vein (Table 3) shows that if MoO₂ is present in the silicate melt, not in a quantity that is significant enough to control melt conductivity.

3.2. Effect of melt nucleation and migration

SEM images of quenched samples showed that a large degree of partial melting has been achieved during the electrical experiments, with a melt phase representing up to ~40%. Microprobe chemical analyses for the different phases are listed in Table 3. For each sample, EDS and WDS analyses showed that the melt phase is iron-rich. The quenched texture of the melt pool observed in one sample (Figure 3a and 3b) is composed of iron-bearing olivine (Mg # = 92.8), ferropericlase, and metallic iron (Table 3). Several olivine grains present a chemical zonation, with iron-rich edges. The increase in Mg# of the olivine matrix during experiments (~77-93 in the quenched samples with an initial Fo₇₇ composition and ~92-97 in the quenched samples with an initial Fo₉₀ composition) also confirms the partitioning of iron to the liquid phase and the zoning indicates the fact that chemical equilibrium was not attained during the experiments. Ferropericlase was observed in all quenched Fo₇₇ samples, mostly under the form of well-defined grains along the interface with the MgO sleeve, but also as a few crystals inside the sample. Rare occurrences of ferropericlase were observed as symplectic exsolution in olivine. Mg # of ferropericlase ranges from ~76 to 88 (Table 3). A significant potential for the

formation of ferropericlasite from a solid solution of MgO and FeO could arise from the partitioning of a portion of Si into the melt phase. Incongruent melting with the formation of ferropericlasite is observed for the bulk composition of Fo₇₇ at these pressure conditions (4-6 GPa). This differs from the case for higher Mg content olivine (Fo₉₀), where ferropericlasite is not observed until ~9 GPa (Ohtani et al., 1998).

Only the hydrous sample presented a nearly continuous ~20-100 micron thick layer of ferropericlasite (~50 micron on average) at the interface between the sample and the MgO sleeve (Figure 3c). The contribution of ferropericlasite to the measured bulk conductivity was calculated using previous electrical data of ferropericlasite under pressure (Yoshino et al., 2011) extrapolated to our temperature of quenching (1860°C). Since the ferropericlasite layer and the partially molten olivine sample arrangement corresponds to a parallel circuit, the measured electrical resistance (effective resistance R_{eff} , in ohm) of the circuit can be written as follow (Glover et al., 2000; Pommier et al., 2008):

$$\frac{1}{R_{eff}} = \frac{\chi_{ferropericlasite}}{R_{ferropericlasite}} + \frac{1-\chi_{ferropericlasite}}{R_{partially\ molten\ olivine}} \quad (3)$$

with χ the volume fraction of ferropericlasite (considering a 50 micron thick layer, its value is 0.0975). At the quenching temperature, our calculations show that the ferropericlasite layer only contributes to ~6% to the bulk conductivity, underlining that the partially molten olivine sample is the dominant electrical contributor over the entire T range.

Heating paths and corresponding advancements of partial melting as probed by the sample's electrical resistance are shown for each sample on Figure 4.

345 Electrical conductivity values are presented in Figure 5. The scatter in the
346 conductivity data points during the first 10-20 min of heating of the dry samples
347 (Figure 4) may be the result of relaxation processes inside the sample that were not
348 completed during the fast initial heating phase until 1500°C. As shown in Figure 5,
349 below the solidus temperature, our electrical data are in general agreement with
350 measurements on Fo₇₀, Fo₈₀, and Fo₉₀ olivine aggregates under pressure (Xu et al.,
351 2000; Dai et al., 2010; Yoshino et al., 2012).

352 The transition in spectra from typical impedance arc (Figures 2b and 2c) to
353 induction-dominated spectra (Figure 2d) was initially recorded after reaching
354 temperatures up to 100°C above the solidus temperature, consistent with the fact
355 that melt needs to reach higher temperature (and therefore higher melt fraction)
356 than the solidus condition in order to be interconnected (Partzsch et al., 2000) and
357 thus, lower significantly the bulk resistance with induction effects dominating the
358 measured complex impedance. The presence of a plateau value observed in each
359 experiment (Figures 4 and 5a) underlines that the electrical response of the
360 investigated samples lack sensitivity to temperature at an advanced stage of partial
361 melting. It might be interpreted as electrical equilibrium, for which steady state
362 electrical conductivity values are achieved due to the fast diffusion of charge
363 carriers (e.g., defects, ions) at very high temperature (1700-1900°C). The absence of
364 a significant dependence of bulk conductivity on temperature was observed on a T
365 range starting at 1700°C for Fo₇₇ at 4 GPa, at ~1830°C for Fo₇₅ at 6 GPa and hydrous
366 Fo₇₇ at 4 GPa, and at 1900°C for Fo₉₀ at 4 GPa.

Our conductivity values are consistent with the ones obtained for olivine+basalt systems (Roberts and Tyburczy, 1999; Yoshino et al., 2010; Carrichi et al., 2011), though a detailed comparison is hampered by the fact that these studies were conducted at lower pressure and temperature. The amplification in conductivity during partial melting of our olivine samples is smaller than the one measured on different types of peridotites at atmospheric pressure (Rai and Manghnani, 1978). In our study, the significant increase in conductivity corresponds to a factor ranging from ~ 30 to 100 in conductivity values. This increase is abrupt for all dry samples whereas it is smoother for the hydrous sample. At atmospheric pressure, Rai and Manghnani (1978) measured a significant jump in the conductivity of their partially molten peridotite samples, corresponding to an increase of a factor of $\sim 3 \times 10^5$. The smaller amplitude of the conductivity jump in our samples can be attributed to the combination of the effect of pressure and sample chemistry. Heating conditions may also contribute to different amplitudes in conductivity: in Rai and Manghnani (1978), heating and cooling rate was as slow as 300K/h, with a 15 min step at each temperature, supporting the attainment of equilibrium morphology in their samples.

The effect of successive cooling and heating cycles has been measured for Fo₉₀ and results are presented in Figure 5b. Electrical conductivity is initially low ($\sigma \sim 0.03$ -0.08 at 1500°C), in agreement with previous electrical studies on polycrystalline Fo₉₀ samples under pressure (Xu et al., 2000; Dai et al., 2010; Yoshino et al., 2012). An abrupt increase in conductivity of about 1 log unit is observed during the first heating between 1850° and 1900°C, corresponding to the

T range following the solidus temperature (e.g., Ohtani et al., 1998), whereas the cooling cycle is characterized by a smoother decrease in conductivity. Melt crystallization processes may explain the non-linear behavior of conductivity with inverse temperature during cooling. On the investigated temperature range, the difference in conductivity values between the different cycles ranges between 0.4 and ~0.8 log unit. This difference may result from a lack of equilibrium between the solid and liquid phases, or disorder-order transitions in the crystal structure (e.g., Rai and Manghnani, 1978).

3.3. Effect of pressure and water on conductivity during partial melting

The effect of pressure on the electrical response of Fo₇₇ compacts during partial melting was observed between 4 and 6 GPa (Figure 4a, 4b, and 5a). In both cases, the abrupt increase in conductivity, corresponding also to a change in the shape of impedance spectra, is observed after crossing the solidus, at a temperature of ~1650°-1700°C at 4 GPa and ~1850°-1900°C at 6 GPa. If an effect of pressure is observed initially on conductivity, with lower conductivity values measured at 6 GPa than at 4 GPa, no effect of pressure is observed on the plateau value (for both experiments, $\sigma_{\text{plateau}} \sim 14$ (+/-2) S/m). The melt phase being more conductive than the solid matrix, these similar σ_{plateau} values are possibly the result of the presence of a higher melt fraction in the experiment at 6 GPa than at 4 GPa, therefore compensating for the effect of pressure.

The experiment on hydrous Fo₇₇ (Figures 4d and 5a) presents a non-linear increase in conductivity during heating from 300° to 1300°C, contrasting with an

Arrhenian behavior (dashed blue line, Figure 5a). In particular, conductivity increased rapidly between 600° and 1000°C, identified as possible hydrogen escape from olivine grains, which is consistent with previous observations (Yoshino et al., 2009). From ~1500° to 1650°C, the electrical conductivity is higher than the one of the dry Fo₇₅ compact, suggesting that some hydrogen is still present in the sample at that time. No significant jump in conductivity is observed as for the dry samples. Conductivity increased significantly, but its evolution with increasing temperature is smoother than for dry samples, possibly due to the effect of hydrogen escaping the sample. The conductivity value of the plateau is similar to the one of the dry sample (~12 S/m, Figure 5a) suggesting that the sample lost hydrogen through the non-welded cell assembly. Microprobe analyses also support the hypothesis of the loss of water, and no hydrous phases have been identified in the quenched melt phase (where hydrogen would preferentially partition). Water contents in hydrous phases can be estimated using the summation deficit from the electron microprobe analysis (difference between original analytical total and a sum of 100 wt% gives H₂O content of the mineral) and our analytical totals did not show any deficit (Table 3). Qualitative EDS identification and electron microprobe WDS analyses did not detect the presence of any hydrous phases in the quenched products, including in the quenched melt where hydrous quench phases would be expected.

4. Discussion

4.1. Melt interconnectivity

Our *in situ* electrical measurements probed partial melting processes and melt segregation through changes in the bulk electrical properties of the samples. The evolution of melt texture was not directly observed, requiring therefore to compare electrical results with experimental studies of partial melting in order to interpret electrical changes in terms of melt interconnectivity.

From previous experimental studies on geological systems at lower pressure (e.g., Laporte, 1994; Yoshino et al., 2010; Miller et al., 2014), it may be inferred that at low melt fraction (<0.10), the distribution of melt in our olivine aggregate samples is characterized by a pervasive network of channels along grain edges. This first stage of melting that initiates melt interconnectivity is consistent with the slight decrease in electrical resistance observed at T slightly above the solidus (Figure 6) together with an increased noise in the electrical response. The X-ray microtomography study by Miller et al. (2014) showed that for a mixture of olivine and basalt at 1.5 GPa, the transition from a tube-dominated network to a structure in which melt films and pools become prominent features occurs at a melt fraction of 0.10. Partzsch et al. (2000) observed that the jump in conductivity measured for granulite at atmospheric pressure indicates an interconnected network and occurred at a melt fraction of ~ 0.08 , which is in good agreement with the 0.10 melt fraction from Miller et al. (2014). This second stage of melting is in agreement with the jump in conductivity observed in our experiments, which also corresponds to a change in the electrical response, from semi-circle impedance spectra to vertical lines (Figure 2). The observations of Miller et al. (2014) point out that grain boundaries are completely wetted at a melt fraction of 0.20. Therefore, we assume

that the jump in conductivity corresponds to an increase in the melt fraction from about 0.10 to 0.20.

The electrical plateau following the conductivity jump is consistent with melt pooling, as imaged by SEM pictures of quenched samples (Figure 3). As previously investigated in partial melting studies (e.g., McKenzie, 1985; Wolf and Wyllie, 1991), the liquid morphology (controlled by crystallography) enhances the permeability of the aggregates and may promote liquid segregation. Melt pooling is enhanced by increased permeability, k (k for connected tubes $>$ k for channels in a medium composed of pockets and disconnected tubes). The movement of melt is enhanced through these well-connected pathways, leading to the formation of a melt pool. This increase in permeability is detected using electrical monitoring and corresponds to a stage of significant increase in conductivity (Figure 6).

4.2. Comparison with two-phase conductivity models

Different electrical models have been proposed to model the conductivity of two-phase aggregates (e.g., Glover et al., 2000 and references therein), based on the geometry of the solid and liquid phases. The Hashin and Shtrikman bounds (HS+, HS-; Hashin and Shtrikman, 1962) and the modified brick layer model (MBLM; Schilling et al., 1997) are commonly used models that were introduced for isotropic spherical and cubic arrangements, respectively. In the Hashin and Shtrikman model, the HS+ bound (and HS- bound) corresponds to spheres of solid (or melt) are isolated from each other in a liquid (or solid) matrix, and the bulk conductivity (σ_{bulk}) is calculated as a function of melt fraction (X_{melt}) as follows

$$S_{bulk}|_{HS+} = S_{melt} + \frac{1 - X_{melt}}{\frac{1}{\sigma_{ol} - S_{melt}} + \frac{X_{melt}}{3S_{melt}}} \quad (4)$$

$$S_{bulk}|_{HS-} = S_{melt} + \frac{X_{melt}}{\frac{1}{\sigma_{melt} - S_{ol}} + \frac{1 - X_{melt}}{3S_{ol}}} \quad (5)$$

with σ_{melt} being the conductivity of the melt phase and σ_{ol} the one of the solid phase (olivine). In the MBLM, melts films are interconnected through the faces of solid cubes, and the bulk conductivity is calculated using

$$\sigma_{bulk} = \frac{\sigma_{melt}(\sigma_{melt}(X_{melt}^{2/3} - 1) - \sigma_{ol}X_{melt})}{\sigma_{ol}(X_{melt} - X_{melt}^{2/3}) + \sigma_{melt}(X_{melt}^{2/3} - X_{melt} - 1)} \quad (6)$$

The conductivities calculated using these models were shown to be in general good agreement with electrical laboratory data (e.g., Schilling et al., 1997; Roberts and Tyburczy, 1999; Partzsch et al., 2000; Caricchi et al., 2011). The MBLM model and the HS+ bound provide similar results when the melt phase conductivity is much higher than the conductivity of the solid phase. While these electrical models are relevant to model stages of interconnected melt veins in our samples, the last phase of the experiment where melt segregation occurs corresponds to an equivalent parallel model. In a parallel circuit, the reciprocal of equivalent resistance (R_{eq} , in Ohm) equals the sum of the reciprocals of the resistance values,

$$\frac{1}{R_{bulk}} = \frac{1}{R_{olivine}} + \frac{1}{R_{melt}} \quad (7)$$

The resistance R_{bulk} corresponds to our measured bulk resistance at the time of quenching. The bulk equivalent electrical conductivity is obtained using the relationship

$$\sigma_{bulk} = \frac{1}{R_{bulk} \times G} \quad (8)$$

The comparison of our experimental results with calculated bulk conductivities is shown in Figure 6 for the Fo₇₇ sample at 6 GPa. SEM analyses on the quenched material provide a melt content of about 40%, under the form of melt pooling (~35% of the sample) and melt interconnected in the olivine matrix (~5% of the sample) (Figure 3a). As explained above (Section 4.1), we assume as part of our calculations a melt fraction of 0.10 when the jump in conductivity occurs, and a melt fraction of 0.20 at the end of the conductivity jump phase.

The electrical conductivity of olivine was computed using laboratory-based Arrhenian equations from Yoshino et al. (2012) and Dai et al. (2010) obtained at similar pressure. Since iron partitioned to the melt phase, depleting olivine progressively in iron, we considered a Fo₇₅ matrix for a melt fraction of 0.10, a Fo₈₀ matrix for a melt fraction of 0.2, and a Fo₉₀ matrix for calculations at T_{quench} (X_{melt}~0.4), in agreement with microprobe analyses (Table 3). At the final temperature (1976°C), olivine conductivity is 0.28 S/m (Dai et al., 2010), and melt conductivity was calculated using a parallel model that involves the following relationships

- The geometry of the melt pool and wetted grains correspond to

$$\frac{1}{R_{bulk}} = \frac{1}{R_{melt\ pool}} + \frac{1}{R_{wetted\ matrix}} \quad (9)$$

with R_{bulk} being the measured resistance at T_{quench} (17 ohm), R_{melt pool} the resistance of the totally molten part of the sample, and R_{wetted matrix} the resistance of the wetted olivine grains;

- The resistance of the wetted matrix is estimated using

$$R_{\text{wetted matrix}} = \sigma_{\text{HS+}} \times G_{\text{wetted matrix}} \quad (10)$$

with $\sigma_{\text{HS+}}$ being the bulk conductivity of the wetted matrix using the HS+ bound (Equation 3), for which only σ_{melt} is unknown, and $G_{\text{wetted matrix}}$ being the geometric factor of the part of the sample that consists of wetted olivine grains (2.08×10^{-3} (+/- 1.35×10^{-4})m);

- Considering that the melt has the same conductivity throughout the sample, σ_{melt} can be written

$$\sigma_{\text{melt}} = \sigma_{\text{melt pool}} = \frac{1}{R_{\text{melt pool}} \times G_{\text{melt pool}}} \quad (11)$$

with $G_{\text{melt pool}}$ being the geometric factor of the part of the sample that represents the melt pool (5.42×10^{-4} (+/- 1.34×10^{-4})m). As a result, Equation 6 has only one unknown, $R_{\text{melt pool}}$. We obtain a resistance value for the melt pool of 23.9 (+/-2.5) ohm. Using Equation 8, a value of 78 (+/-8) S/m was obtained for the melt conductivity.

For calculations at lower melt fractions, where no large melt pool was present, we consider the HS bounds and the MBL model to reproduce the sample's response. The same melt conductivity was assumed (78 (+/-8) S/m), and therefore our conductivity calculations at slightly lower temperature (1810° and 1850°C) than the quench temperature may overestimate marginally the conductivity of the melt phase. Calculations using the HS and MBL models are in good agreement with our experimental data (Figure 6). At a melt fraction of 0.10, corresponding to $T \sim 1810^\circ\text{C}$ and with the conductivity of Fo₇₅ being ~ 0.10 S/m, the HS lower and upper bounds provide bulk conductivity values of 0.13 S/m (+/-0.01) and 5.5 (+/-0.6) S/m,

respectively. A conductivity value of 5.6 (+/-0.6) S/m is obtained using the MBL model. At a melt fraction of 0.20, corresponding to $T \sim 1850^\circ\text{C}$ and with the conductivity of Fo_{80} being 0.14 S/m, the HS upper bound provides bulk conductivity values of 11.3 (+/-1.0) S/m. A similar conductivity value of 11.6 (+/-1.2) S/m is obtained using the MBL model. The same approach has been applied to our other experiments in order to calculate melt conductivity. A similar melt conductivity range has been obtained for the other experiments on dry and initially hydrous Fo_{75} at 4 GPa, whereas a more resistive melt phase reproduces electrical data on Fo_{90} ($\sim 40\text{--}50$ S/m), suggesting that decreasing the iron content in melt decreases its electrical conductivity.

Though these calculations reproduce our laboratory measurements satisfactorily, it is important to note that these electrical two-phase models consider a homogenous material with an equilibrated texture, whereas equilibrium texture and equilibrium melt distribution were not attained in our experiments. In particular, this may explain the difference of ~ 0.2 log unit in conductivity at 1810°C between our data and the HS lower bound (Figure 6). Partzsch et al. (2000) observed that the generation of an equilibrium texture for a granulite rock between mineral grains and melt at temperature up to 1100°C requires more than 200 h. As these authors predicted, if it were possible to measure the conductivity during partial melting at equilibrium morphology, the jump in conductivity should occur at lower temperature (i.e., at or slightly above T_{solidus}) due to the wetting behavior of the mineral–melt assemblages. However, petrogenesis is usually driven by non-

equilibrium and dynamic conditions, and therefore experiments involving
equilibrium texture may be limited to understand present-day geophysical data.

4.3. Application to the lunar interior

The presence of partial melt in the deep lunar interior has been suggested to
explain the presence of a seismic attenuation zone at the base of the mantle, from
~1250 to 1410 km depth (Nakamura, 2005; Weber et al., 2011; van Kan Parker et
al., 2012). Electromagnetic sounding data are also consistent with the presence of a
partially molten core-mantle boundary (e.g., Khan et al., 2014). In this hypothesis,
partial melt results from a lunar evolution in which dense cumulates led to mantle
overturn and settled at the base of the mantle (e.g., Hess and Parmentier, 1995),
remaining partially molten due to the presence heat-producing elements (de Vries
et al., 2010).

As illustrated in Figure 7, the potentially partially molten layer corresponds
to a pressure range of ~4.5-5 GPa. Several thermal studies suggest that the present-
day selenotherm implies temperatures ranging from ~1000 to 1700°C at the top of
the seismic attenuation zone and from ~1400 to 2100°C at its bottom (Hirschmann,
2000; Kuskov and Kronrod, 2009). Recently, Khan et al. (2014) proposed an
electrical model of the lunar interior, based on the inversion of lunar geophysical
data (mean mass and moment of inertia, tidal Love number, and electromagnetic
sounding data) in combination with phase-equilibrium computations. Their study
suggests that a partially molten layer deep in the lunar mantle is required to
reproduce the current geophysical dataset, and estimated a conductivity range of

3×10⁻² to 12.6 S/m in the uppermost low-velocity zone (Figure 7). The presence of a deep partially molten layer is also in agreement with the crossing present-day selenotherm with the mantle solidus below ~1100 km depth, considering a Taylor whole-Moon composition (Taylor, 1982) or the peridotite composition from Hirschmann (2000) (Figure 7).

Our run conditions are relevant to the storage conditions of the seismic attenuation layer at the base of the lunar mantle (in terms of pressure (depth), temperature, and oxygen fugacity (f_{O_2})). The composition of the lunar interior is still mainly unconstrained (e.g., Taylor, 2014). However, mineralogy estimates suggest that the lunar lower mantle is made principally of olivine (~50 vol.%, with a composition close to Fo₇₅), pyroxene (~40 vol.%), and garnet (~10 vol.%) (e.g., Khan et al., 2014). Spinel, ilmenite and anorthite are present in small amounts and their contribution to bulk conductivity is disregarded because it was shown that omitting the contribution of a mineral that is present at levels <10 vol.%, produces a difference in bulk conductivity of <0.02 log units (Khan et al., 2014). The bulk conductivity of a solid mantle with this mineralogy is not significantly different from the conductivity of an olivine solid matrix. Actually, bulk conductivity during partial melting is not noticeably affected by solid matrix chemistry, even at low melt fractions (Pommier and Garnero, 2014). Our experiments on Fo₇₇ represent an end-member for a lunar lowermost partially molten mantle. Because the chemistry of lunar melts at the base of the mantle is expected to differ from olivine melt, and in particular to contain high titanium contents (with TiO₂ >15 wt%; van Kan Parker et al., 2012; Khan et al., 2014), lunar melts are expected to be very conductive, and

possible more conductive than the iron-rich melt phase observed in our experiments. Therefore, we suggest that melt fraction estimates obtained from our experiments on olivine compacts are upper bounds of melt fraction in the lowermost lunar mantle.

As shown in Figure 7, a significant overlap exists between the conductivity at the base of the lower lunar mantle and with the conductivity region of interconnected melt from our experiments. The highest conductivity values estimated for the lowermost mantle ($\sigma > 10$ S/m) are consistent with a high olivine melt fraction (> 0.10), and possibly a lower melt fraction of denser and more conductive (Ti-rich) melt phase. For comparison, Delano (1990) suggested that partial melt in the low velocity layer is unlikely to exceed 10 vol.%, whereas Khan et al. (2014) argued that higher melt contents (< 40 vol. %) can be in equilibrium in the deep lunar interior. The overlap between our experimental conductivity results and conductivity computations is in agreement with the hypothesis of a partially molten layer at the base of the lunar mantle. Our results also indicate that complete melt interconnectivity and melt accumulation may occur in the most conductive part of the lowermost lunar mantle if the melt fraction is sufficiently high.

5. Conclusion

The electrical conductivity of dry and hydrous Fo₇₇ and Fo₉₀ polycrystalline compacts was measured at 4 and 6 GPa during partial melting. For all samples, a significant increase in conductivity and a change in the shape of impedance spectra

were observed above the solidus temperature, corresponding to a transition from melt tubes to a completely wetted solid matrix. Together with chemical analyses, SEM images, and previous studies on partially molten rocks, the electrical response of the sample was interpreted along with compositional and textural changes. Two-phase electrical models were used to estimate the electrical conductivity of the melt phase, which was found to be 78 (+/- 8) S/m for Fo₇₅ samples and 45 (+/-5) S/m for the Fo₉₀ sample. Finally, our results were compared with the electrical profile of the lunar mantle. A good overlap between our conductivity values of partial melt and the high electrical conductivities of the lunar lower mantle supports the hypothesis of a partially molten core-mantle boundary and underlines the need for further experimental work on lunar compositions to reproduce field electrical (and elastic) properties.

Acknowledgements

We are grateful to David Kohlstedt's lab at the University of Minnesota for providing the starting materials and for FTIR analyses on the hydrous Fo₇₇ starting sample. We thank Henrietta Cathey for her help with SEM images and microprobe analyses. AP acknowledges support from NSF-CSEDI grant EAR-1265428.

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Figure Captions

Figure 1: Phase relations of the $\text{Mg}_2\text{SiO}_4\text{-(Mg}_{0.6}\text{Fe}_{0.4})_2\text{SiO}_4$ 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.

Figure 2: Electrical measurements: experimental setup and observations. A) Cross section of the electrical conductivity cell (14/8 multi-anvil assembly). Electrodes are in W-Re and one electrode serves as thermocouple. See text for details. B-D) Examples of impedance spectra in response to a scan in frequency in the complex plane (Z' , Z''). The value of the resistance R (ohm) corresponds to the intersection of the sample's electrical response with the real axis (Z'). B) Hydrous Fo_{77} sample at 700°C and 4 GPa. The small arc in the negative Z'' values following the impedance arc corresponds to induction processes. C) Dry Fo_{77} at 1655°C and 6 GPa. Only the end of the impedance arc is observed. D) Electrical response of dry Fo_{77} samples at 4 and 6 GPa at temperatures above the solidus. The linear shape of the sample's response indicates dominant induction processes and is used as an indication of melt controlling the bulk electrical response of the sample. See text for details.

Figure 3: SEM microphotographs and qualitative maps of Si in quenched samples. A) Fo_{77} sample at 6 GPa, with visible melt veins and melt pooling. B) Zoom in from A). C) Hydrous Fo_{77} at 4 GPa. Partial melting is pointed out by the presence of melt veins and a front of formation of magnesiowüstite (Mgw). D) Zoom in from C) showing the repartition of Si. Yellow areas indicate a significant presence of Si, such as in olivine grains and melt veins in the magnesiowüstite layer. E) Melt pool-olivine matrix area in Fo_{90} sample at 4 GPa (run G255). The spherical white phase close to the electrode is Mo-Fe oxides, the Mo coming from the electrode. F) Melt pool-olivine matrix area Fo_{90} sample at 4 GPa (run G243).

Figure 4: Temperature path above 1500°C and corresponding electrical evolution as a function of time for dry Fo_{77} at 4 GPa, dry Fo_{77} at 6 GPa, dry Fo_{90} at 4 GPa and hydrous Fo_{77} at 4 GPa. Expected solidi are from Figure 1. Temperature was maintained when a change in impedance spectra was observed.

Figure 5: Temperature-dependence of electrical conductivity of the investigated samples during partial melting. A) In each experiment, a significant jump in conductivity indicates the transition from isolated melt tubes to a completely wetted olivine matrix. Comparison with previous studies: dry Fo_{90} from Xu et al. (2000), Dai et al. (2010); dry Fo_{70} from Yoshino et al. (2012); garnet peridotite and eclogite from Rai and Manghnani (1978); triangle from Caricchi et al. (2011); squares from Roberts and Tyburczy (1999); hexagons from Yoshino et al. (2010), vertical line from Ten Grotenhuis et al. (2005). B) Electrical conductivity of Fo_{90} sample at 4 GPa vs. temperature during heating and cooling cycles. Crosses

correspond to the electrical measurements during heating presented in Figure 7. See text for details.

Figure 6: Changes in electrical resistance and conductivity during partial melting: example of dry Fo₇₇ at 6 GPa. Drawings represent the sample at different steps of partial melting. Below the solidus, electrical properties are typical of dry polycrystalline olivine. A slight change in the dependence of R and σ to temperature is observed after the solidus is crossed, attributed to the nucleation and low interconnectivity of the melt phase. The jump in R and σ occurs at the same time as a change in impedance spectra (from an impedance arc to an induction-dominated response) and is consistent with a transition from interconnected melt tubes to a completely wetted olivine matrix. At this stage of partial melting, significant changes in olivine chemistry occur (increase in Mg#) caused by the partitioning of iron to the melt phase. Finally, a plateau in R and σ is reached and corresponds to melt migration and eventual melt pooling. Experimental conductivity data are satisfactorily reproduced by two-phase electrical models (Hashin and Shtrikman bounds, in red, the modified brick layer model, in blue). Numbers in *italic* are melt contents (%) in agreement with Partzsch et al. (2000) and Miller et al. (2014). Comparison with these models led to an estimate of melt conductivity of 70.5 (+/-14.5) S/m. See text for details.

Figure 7: Thermal (left side) and electrical (right side) profiles of the Lunar interior, after the study by Khan et al. (2014) based on the inversion of lunar geophysical data in combination with phase-equilibrium computations. **Dashed line corresponds to the solidus for the Taylor Whole Moon (TWM) composition (Taylor, 1982) and solid line corresponds to peridotite solidus (Hirschmann, 2000).** Experimental results from our study are highlighted in red and significantly overlap with the conductivity at the base of the lunar mantle.

FIGURES

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

A)

B)

Figure 6

Figure 7

TABLES

Table 1. Olivine starting compositions (in wt%).

	Fo ₇₇	Fo ₉₀
SiO ₂	36.67	38.90
FeO	22.09	9.67
MnO	0.10	0.12
MgO	40.54	50.80
CaO	-	-
K ₂ O	-	-
NiO	0.44	0.39
Total	99.85	99.87
Mg# ^a	0.77	0.90

a: $\text{Mg\#} = \text{Mg}/(\text{Mg} + \text{total Fe})$

Table 2. Summary of electrical experiments.

Run #	Sample	Composition	Average grain size (μm)	Pressure (GPa)	T of jump in σ ($^{\circ}\text{C}$)	Quench Temperature ($^{\circ}\text{C}$)	Relative error on σ (%)	σ plateau (S/m)
G240	PI1769	Fo_{77}	50-100	4	1700	1784	3.23-9.04	12 (+/-2)
G241	PI1769	Fo_{77}	50-150	6	1815	1976	2.22-6.44	24 (+/-1)
G242	PI1723	Hydrous Fo_{77} *	30-100	4	1500	1864	1.68-4.49	16(+/-1)
G243	PI1543	Fo_{90}	50-100	4	1850	2000	1.81-7.23	-
G255	PI1543	Fo_{90}	50-150	4	1810	2007	3.80-16.1	5.5 (+/-0.5)

*Based on FTIR analyses, water content in starting material is $\sim 1100\text{H}/10^6\text{Si}$.

Table 3. Composition of the major phases in the samples after electrical melting experiments (in wt% of oxide).

Run #	P (GPa)	T quench (°C)	Phase	SiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	NiO	MnO	MgO	CaO	Total	Mg#								
G240	4	1784	Solid matrix																		
			Ol center sample (8) ^a	38.2	(17) ^b	0.06	(1)	0.14	(33)	20.6	(28)	0.52	(2)	0.11	(1)	39.7	(26)	0.06	(1)	99.4	77.5
			Ol close to MgO sleeve (2)	39.2	(7)	0.04	(3)	0.00	(0)	15.6	(51)	0.47	(4)	0.07	(1)	44.2	(31)	0.07	(1)	99.7	83.5
			Ol close to electrode (1)	39.5	-	0.07	-	0.01	-	16.6	-	0.41	-	0.06	-	43.8	-	0.07	-	100.5	82.4
			Quenched melt																		
			Mgw (1)	0.07	-	0.25	-	0.08	-	24.1	-	0.43	-	0.08	-	73.7	-	0.01	-	98.7	84.5
			Ol (1)	40.9	-	0.14	-	0.00	-	5.84	-	0.06	-	0.06	-	52.9	-	0.02	-	99.8	94.2
G241	6	1976	Solid matrix																		
			Ol close to melt (5)	41.1	(17)	0.04	(1)	0.00	(1)	6.55	(70)	0.10	(4)	0.06	(0)	52.6	(67)	0.02	(0)	100.5	93.5
			Ol center sample (5)	39.9	(31)	0.05	(1)	0.01	(1)	11.7	(89)	0.20	(3)	0.06	(2)	48.4	(95)	0.02	(1)	100.3	87.7
			Mgw (1)	0.10	-	0.18	-	0.14	-	34.9	-	0.69	-	0.15	-	63.5	-	0.01	-	99.6	76.4
			Quenched melt																		
			Ol (3)	41.1	(9)	0.08	(2)	0.00	(1)	7.9	(36)	0.03	(1)	0.06	(1)	51.9	(49)	0.03	(0)	101.1	92.8
			Mgw (10)	0.07	(10)	0.21	(3)	0.06	(2)	20.4	(100)	0.14	(4)	0.08	(1)	79.0	(126)	0.01	(0)	99.9	87.4
			Oxide (1)	1.10	-	4.42	-	0.16	-	54.8	-	0.06	-	0.09	-	6.7	-	0.04	-	67.3	-
			Quenched melt vein																		
Liq (1)	29.9	-	0.13	-	0.00	-	60.8	-	0.39	-	0.51	-	6.38	-	0.43	-	98.6	15.7			
G242	4	1864	Solid matrix																		
			Ol close to MgO sleeve (5)	40.3	(18)	0.06	(2)	0.00	(1)	11.53	(107)	0.30	(6)	0.09	(3)	48.74	(91)	0.06	(1)	101.1	88.3
			Ol center sample (5)	39.0	(25)	0.05	(2)	0.01	(1)	18.27	(68)	0.48	(5)	0.11	(2)	43.07	(68)	0.05	(1)	101.1	80.8
			Ol close to electrode - edge (3)	39.6	(51)	0.06	(1)	0.02	(4)	14.95	(253)	0.37	(4)	0.11	(2)	45.63	(202)	0.05	(1)	100.8	82.7
			Ol close to electrode - core (3)	39.0	(12)	0.04	(1)	0.04	(3)	18.19	(129)	0.44	(4)	0.11	(2)	43.03	(106)	0.05	(1)	100.9	82.6
			Interface sample-MgO sleeve																		
			Ol type 1 (4)	41.5	(14)	0.08	(2)	0.00	(0)	6.92	(55)	0.02	(1)	0.04	(1)	52.98	(43)	0.03	(2)	101.6	93.2
Ol type 2 (1)	40.3	-	0.08	-	0.00	-	10.30	-	0.20	-	0.06	-	50.12	-	0.07	-	101.2	89.7			
G243	4	2000	Solid matrix																		
			Ol close to melt (10)	39.9	(22)	0.03	(1)	0.00	(2)	5.11	(46)	0.22	(3)	0.07	(2)	53.8	(45)	0.04	(3)	99.1	94.9
			Ol center sample (7)	39.4	(18)	0.06	(2)	0.01	(2)	7.63	(63)	0.20	(1)	0.13	(2)	51.5	(54)	0.10	(2)	99.0	92.3
G255	4	2007	Solid matrix																		
			Ol close to melt (4)	42.4	(22)	0.03	(2)	0.00	(2)	2.89	(90)	0.12	(6)	0.04	(2)	55.8	(89)	0.04	(1)	101.3	96.4
			Ol center sample (3)	41.4	(60)	0.03	(1)	0.02	(36)	5.57	(99)	0.13	(3)	0.08	(3)	53.2	(110)	0.05	(2)	100.5	94.4
			Quenched melt																		
			Ol (3)	42.2	(12)	0.03	(0)	0.01	(0)	1.85	(12)	0.04	(1)	0.03	(1)	56.4	(20)	0.11	(7)	100.6	98.2

^a Number of microprobe analyses.

^b One standard deviation of replicate analyses in terms of least unit cited.