

# 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 exponent of 0.75 and 1.37 at melt fraction 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 contain 0.5 to 1 vol.% of melt, which is consistent with the durable presence of melt at depths over millions years while the oceanic plate spreads apart the mid-ocean ridge. A minimum permeability may allow the rise of Mid-Ocean Ridge Basalts where melt is likely to be present up to 4 vol.% beneath the ridges.

## Keywords (6 max)

Electrical conductivity; upper mantle; Low Velocity Zone; melt interconnectivity; olivine aggregate; basalt.

## Highlights

- We measured the electrical conductivity (EC) of the melt-bearing olivine aggregate
- We note an melt interconnectivity threshold at a melt fraction of 0.5 vol.%
- We model EC according to T°C and melt fraction using the conventional Archie's law
- The LVZ & MORB production regions are explained by <1 and < 4% of melt respectively
- Low melt fraction (<1%) is consistent with durable presence of melt at the LVZ

## One sentence summary

We performed *in situ* electrical conductivity measurements on partially-molten olivine aggregate to check the mixing law models at low, realistic melt fraction potentially existing in the upper mantle.

## 44 1. Introduction

45 One of the most striking geophysical anomalies identified in the upper mantle is the Low  
46 Velocity Zone (LVZ, e.g. [Holtzman, 2016](#)) characterized by low seismic velocities and high  
47 attenuation and located in the asthenosphere near the Lithosphere-Asthenosphere Boundary  
48 (LAB); under oceanic plates, the LVZ appears to coincide in some regions with a 20 to 50 km  
49 thick layer that possesses a high electrical conductivity (EC) (up to  $\text{Log } \sigma = -0.3$ ;  $\sigma$  in S/m)  
50 relative to overlying and underlying layers (e.g. [Evans et al., 2005](#); [Baba et al., 2006](#); [Naif et al.,](#)  
51 [2013](#); [Sarafian et al., 2015](#)).

52 Several factors that might enhance EC have been invoked to explain these anomalies, such as  
53 anisotropy in mineral conductivity (e.g. [Poe et al., 2010](#)), water dissolved in nominally  
54 anhydrous minerals (e.g. [Dai & Karato, 2014](#)), or the presence of melt (e.g. [Gaillard et al.,](#)  
55 [2008](#); [Yoshino et al., 2010a](#); [Ni et al., 2010](#); [Sifré et al., 2014](#)). However, conductivity  
56 anisotropy in olivine aggregates appears to have an insufficient effect on EC to account for the  
57 observed mantle anomaly ([Poe et al., 2010](#); [Yang, 2012](#)). In addition, water dissolved in  
58 olivine is unlikely to produce the conductivity anomalies observed in the upper mantle  
59 ([Gardés et al., 2014](#)) because the concentration of water in minerals required to reach upper  
60 mantle conductivities (100 to 1000 ppm; e.g. [Dai & Karato, 2014](#)) would lead to partial  
61 melting of the mantle rocks, accompanied by partitioning of significant proportions of water  
62 into a melt phase rather than minerals ([Hirschmann, 2006](#)). Anisotropic distribution of the  
63 melt may also be a further factor enhancing the EC ([Caricchi et al., 2011](#); [Zhang et al., 2014](#);  
64 [Pommier et al., 2015a](#)). For these reasons, it seems that the presence of melt is the most likely  
65 explanation for the EC anomalies in the upper mantle, supported by melt-solid viscosity and  
66 density contrast ([Sakamaki et al., 2013](#)).

67 Large differences in transport properties between silicate minerals and melt mean that the EC  
68 of silicate melts is orders of magnitude higher than mineral phases (e.g. [Tyburczy and Fisler,](#)  
69 [1995](#)). As a consequence, the bulk EC of partially molten rocks (minerals + melt) varies with  
70 the relative fraction of solid and liquid phases, but also with their respective distribution  
71 ([Glover, 2010](#) and references therein). A liquid phase should form an interconnected network  
72 in a solid aggregate whenever dihedral angles between the two phases are lower than  $60^\circ$ .  
73 Since, in olivine aggregates, basaltic melt is distributed as pockets, tubes and films with  
74 dihedral angles as low as  $\sim 10^\circ$ , melt is expected to be interconnected and thus contributes to  
75 a significant increase of the EC even at melt fractions lower than 1% ([Cmíral et al., 1998](#);  
76 [Yoshino et al., 2009](#); [Faul & Scott, 2006](#); [Garapić et al., 2013](#)).

77  
78 The conductivity of a partially molten assemblage is generally calculated based on a  
79 mathematical model with an assumed mineral and melt geometry. The applicability of such  
80 models has, to date, not been experimentally investigated, particularly at very low ( $< 1\%$ )  
81 melt fractions, which are likely realistic for the upper mantle. Amongst the numerous mixing  
82 laws summarized and described by [Glover \(2010\)](#) and [ten Grotenhuis et al. \(2005\)](#), the  
83 conventional and modified Archie's laws appear very suitable for calculating the EC of upper  
84 mantle materials in which both solid and liquid phase contribute to the bulk conductivity  
85 according to defined exponents. Other models, such as the tubes, cubes, and sphere+ models  
86 ([Grant & West, 1965](#); [Waff, 1974](#)) texturally reproduce a melt-bearing aggregate with a melt  
87 fraction  $> 0.05$  where pockets (pools) and films wetting grain boundaries are the dominant  
88 features of the melt network ([Miller et al., 2014](#)). At melt fractions lower than 0.02, the melt  
89 principally forms channels residing along grain edges, and can still be interconnected down to  
90 very low melt fractions making those models misfit ([Garapic et al., 2013](#); [Holtzman, 2016](#)). In  
91 spite of the proposed interconnectivity threshold (e.g. [Holtzman, 2016](#)), it is expected that the  
92 melt raises the bulk conductivity at these low ( $< 0.01\%$ ) melt fractions.

93

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

105

## 106 **2. Experimental procedure**

### 107 **2.1. Starting materials and sample preparation**

108 Natural olivine from a Lanzarote peridotite (Canary Islands, Spain) and synthetic basalt were  
109 employed as solid and liquid starting materials respectively. The Lanzarote olivine consists of  
110 a single chemically homogeneous population of Fo92 (Table 1). Optical impurity-free olivine  
111 grains were crushed and sieved to obtain a maximum grain size of 100 micrometers. Olivine  
112 was used without further treatment (e.g. annealing under special conditions) so as to remain  
113 close to natural mantle materials. The basaltic glass was produced by mixing reagent grade  
114 oxides and carbonates and fusing the mixture twice in an iron-enriched platinum crucible at  
115 1450°C and 1 atmosphere for 3 hours. The resulting homogeneous glass had a composition  
116 similar to that of a Mid-Ocean Ridge Basalt (termed "synthesis", Table 1). Gadolinium was  
117 added to the melt (a very incompatible element that concentrates exclusively in the liquid) for  
118 neutron tomography observations that are not reported here. The same batch of basalt was  
119 used for all experiments. Its liquidus temperature was estimated to be approximately 1270°C  
120 at 1.5 GPa from the melting temperature during synthesis and from EC measurements with  
121 the sample with 100% of melt. The glass was then cored to provide starting samples of basalt  
122 i.e. for 100% melt fraction experiments, while the rest of the glass was crushed into a fine  
123 powder (~ 5 micrometers grain size). This powder was mechanically mixed with olivine  
124 grains in order to distribute the glass as homogeneously as possible within the olivine  
125 aggregate. Each component was accurately weighed (precision of 0.1 micrograms) to achieve  
126 the desired melt fraction, assuming very little density variation between room and  
127 experimental conditions (Sakamaki et al., 2013). The mixtures are named according to the  
128 volume fraction of added basaltic glass (see also section 4.1). The mixtures and the olivine-  
129 only aggregate were cold-pressed using a hydraulic press and jig to provide samples 3 mm in  
130 diameter and 1.0 to 1.4 mm in length.

131

### 132 **2.2. In situ electrical conductivity measurements**

133 In every experiment, the sample was placed between two platinum foils (electrodes) in  
134 contact with two thermocouples forming the electrical cell (Fig. 1). An MgO sleeve chemically  
135 and electrically insulates the sample from the graphite furnace (see Fig. SI1). Crushable and  
136 hard alumina pistons were placed either side of the sample, which was positioned within the  
137 hot zone at the centre of the assembly. This zone extending over ~1.5 mm, and was  
138 determined by two thermocouples that measured the temperature ~0.3 mm away from each  
139 edge of the sample. Experiments where a temperature difference larger than 20°C between  
140 the 2 thermocouples was measured, were discarded to avoid EC uncertainties due to large  
141 temperature gradients. The furnace and inner parts of the assembly were inserted in a  
142 zirconia cylinder used as thermal insulator that was inserted in an unfired 12-mm edge length  
143 pyrophyllite cube. Because of the graphite furnace, the absence of a welded-shut capsule and  
144 the presence of olivine, oxygen fugacity is believed to approximate FMQ ( $\pm 1.5$  Log unit)

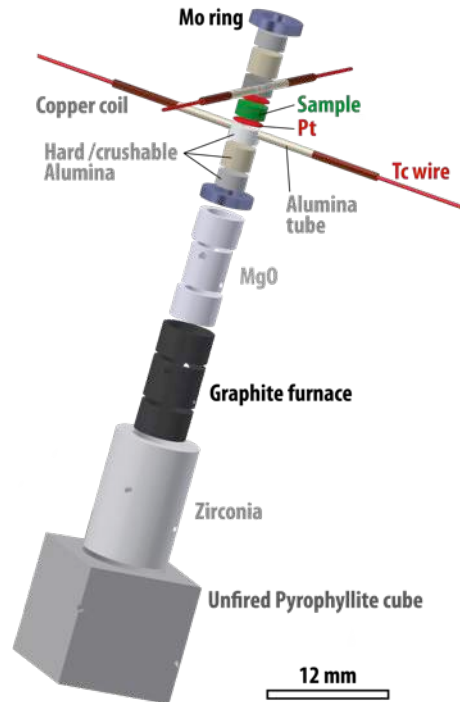
145 conditions Confining pressure was applied to the cube by a six-ram press (MAVO press,  
 146 Bayerisches Geoinstitute) employing second stage anvils with square truncations of 9-mm  
 147 edge length (Manthilake et al., 2012).  
 148

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

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

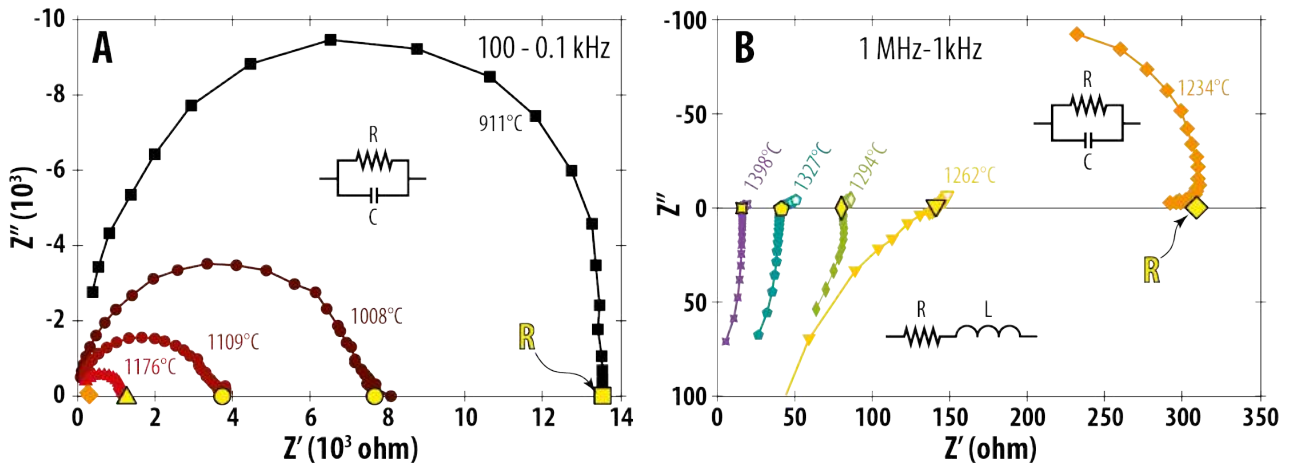
154 *In situ* EC measurements were performed using a Solartron impedance gain phase analyzer  
 155 connected to the 4 wires of the 2 thermocouples (see details about impedance spectroscopy in  
 156 Barsoukov & Macdonalds, 2005, for instance). The very low resistance of the liquid basalt  
 157 required the use of the 4-wire method for accurate EC measurements, as the internal  
 158 resistance of a 2-wire measurement is significant (see Fig. SI 2). The graphite furnace was  
 159 heated manually by controlling the electrical power and acted as a grounded Faraday cage,  
 160 causing only a minor amount of inductive interference in the frequency range 50 to 250Hz. In  
 161 a typical run the sample was pressurized for one hour, followed by a heating and cooling  
 162 cycle, during which impedance spectra were acquired. The 2 thermocouples were switched  
 163 between the temperature monitor and the impedance spectrometer to avoid interference.  
 164 After each increase or decrease in temperature the sample was allowed to reach a stable  
 165 temperature over a period ~1 minute before the sample resistance was measured. Impedance  
 166 spectra were typically acquired in a frequency range from 1 MHz to 10Hz depending on the  
 167 signal response of the sample and the temperature (Fig. 2). The temperature was monitored  
 168 before and after the resistance measurement and was generally found to have remained  
 169 constant. The measurement was repeated when the temperature was found to have deviated  
 170 by more than 5°C during the resistance acquisition. Uncertainties on the sample conductivity  
 171 arise from the sample geometry, temperature measurement and deviation during the  
 172 measurement and from the determination of the resistance. The total uncertainty calculated

173 by propagating these errors is 0.2 Log units (Laumonier et al., 2015). At the end of the  
 174 experiment, the furnace power was switched off to quench the sample before slow  
 175 decompression.  
 176



177  
 178 **Figure 1: The 12-millimeter assembly employed for in situ electrical conductivity measurements with**  
 179 **the MAVO 6ram press. The sample (green) diameter is 3 millimeters before compression. The electrical**  
 180 **path (red) includes platinum foil electrodes which sandwich the sample and are in contact with 2 S-type**  
 181 **thermocouples connected interchangeably to a temperature monitor and a gain phase impedance**  
 182 **analyzer.**

183



184  
 185 **Figure 2: Impedance spectra in the Nyquist plane and equivalent electrical circuits (Huebner &**  
 186 **Dillenburg, 1995) obtained at low (A: T < 1200°C) and high (B: T > 1200°C) temperatures on the pure**  
 187 **basalt sample. R, C and L in electrical circuits stand for resistance, capacitance and inductance**  
 188 **respectively. The real resistance (yellow R) is shown by a yellow symbol.**

189 Electrical conductivity mechanisms for minerals and melts have been extensively described in  
 190 the literature (e.g. Roberts & Tyburczy, 1999; Gaillard, 2004; Yoshino et al., 2010b; Yoshino &  
 191 Katsura, 2013; Laumonier et al., 2015). It is worth to recall, however, the temperature  
 192 dependence of the electrical conductivity  $\sigma$  (S/m) according to the Arrhenius Law:

193 
$$\sigma = \sigma_0 \exp\left(-\frac{E_a + P\Delta V}{RT}\right) \quad (\text{Eq. 1})$$

194 where  $\sigma_0$ ,  $E_a$ ,  $P$ ,  $\Delta V$  and  $\mathfrak{R}$  are a pre-exponential term (S/m), the activation energy (J/mol), the  
 195 pressure (bar), the activation volume (cm<sup>3</sup>/mol) and the gas constant (J/mol/K) respectively.  
 196

### 197 2.3. Post-experiment analysis

198 Once recovered, the assembly was cut in the middle along an axial plane of the sample,  
 199 mounted in epoxy resin and polished for textural and chemical analyses. The distribution of  
 200 the melt and the sample dimensions were characterized by Scanning Electron Microscopy  
 201 (SEM) with a typical acceleration voltage of 20 to 22 kV. Crystal size distribution and  
 202 orientation were measured by Electron Backscatter Diffraction on a ZEISS SEM, Leo Gemini  
 203 1530 with a Schottky field emission gun employing an accelerating voltage of 20 keV and a  
 204 beam current of about 2.0 -2.5 nA using a 60 mm aperture (more details about the methods in  
 205 Supplementary Information).

206 Chemical compositions of melt and minerals (olivine) were quantified by an Electron Probe  
 207 Micro Analyzer with unfocused (10 micrometers) and focused (1 micron) beams respectively,  
 208 with an acceleration voltage of 15 kV and beam current of 150 nA. The water content was  
 209 measured using the Cameca IMS 1280HR at the Swiss SIMS laboratory of the University of  
 210 Lausanne (Switzerland) under a 10kV Cs<sup>+</sup> primary beam with a ~1.5 nA current, resulting in a  
 211 typical spot size of ~10  $\mu$ m. To minimize the water background in the machine, samples were  
 212 mounted in indium with a reference material. Before each measurement, the surface was  
 213 cleaned using a 25 $\mu$  rastered presputtering beam, for 240 seconds (more details about the  
 214 methods in Supplementary Information).  
 215

## 216 3. Results

217 **Table 2** shows the experimental conditions and fitting parameters for the eleven experiments  
 218 conducted with *in situ* EC measurements. One run was performed at a constant temperature  
 219 (M523) while all others followed similar heating and cooling cycles. All experiments were  
 220 carried out at a pressure of 1.5 GPa, except M501 that was conducted at 3 GPa in order to  
 221 investigate the effect of pressure on EC. The explored melt fraction, based on the initial  
 222 fraction of added basaltic glass, ranges from 0 (olivine-only) to 100 vol.% (basaltic melt only).  
 223

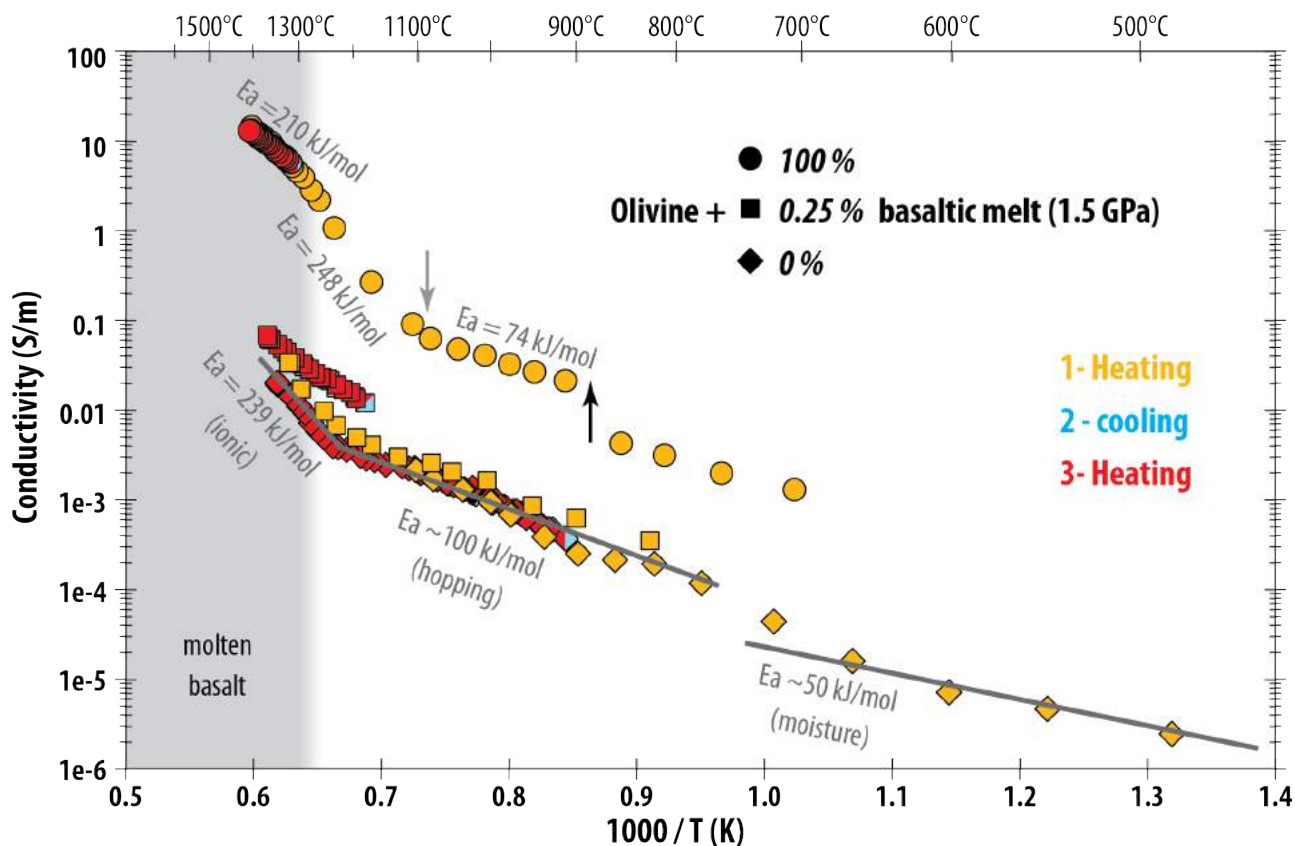
Exp #	Pressure (GPa)	Duration (min)	added basalt (vol.%)	Geometrical factor (10 <sup>-3</sup> )	T(°C) before quench	Duration before quench (min)	T(°C) max	T(°C) min	E <sub>a</sub> (kJ)	Log $\sigma_0$
M496	1.5	331	0.0	5.90	1348	16	1348	1192	239 (11)	5.84 (0.39)
M502	1.5	203	0.15	4.16	1307	23	1289	1164	163 (3)	3.66 (0.10)
M510	1.5	131	0.25	4.83	1354	21	1360	1182	177 (3)	4.41 (0.09)
M501	3.0	173	0.5	5.09	1299	31	1357	1121	170 (2)	4.60 (0.07)
M488	1.5	399	0.5	2.78	1373	35	1373	1205	162 (5)	4.54 (0.16)
M487	1.5	238	1.0	2.76	1346	102	1430	1292	195 (4)	5.70 (0.14)
M486	1.5	181	2.0	3.24	1373	15	1391	1266	191 (8)	5.80 (0.28)
M478	1.5	308	4.0	1.69	1395	25	1418	1214	207 (4)	6.52 (0.14)
M484	1.5	130	10	2.46	1425	20	1425	1298	206 (4)	6.71 (0.13)
M480	1.5	161	100	3.13	1405	19	1405	1317	210 (2)	7.67 (0.07)
M523	1.5	1690	0.25	6.16	1319	-	-	-	-	-

224 **Table 2: Experimental conditions for EC measurements and fitted activation energy  $E_a$  and**  
 225 **preexponential factor  $\sigma_0$  (S/m), with standard deviations into brackets. T°C max to T°C min defines the**  
 226 **temperature interval for the fitting of  $E_a$  and  $\sigma_0$ .**

### 227 3.1. Electrical conductivity of melt-bearing olivine aggregates

228 The EC of the olivine-only sample (M496) for several heating-cooling cycles is shown in  
 229 **Figure 3**. During the first heating, the EC increased with temperature, corresponding to a low  
 230 activation energy ( $E_a \sim 50$  kJ/mol), likely due to the presence of moisture up to  $\sim 700^\circ\text{C}$ .  
 231 Between  $\sim 800$  and  $\sim 1230^\circ\text{C}$ ,  $E_a$  is a factor of two higher than at lower temperatures ( $E_a \sim 100$   
 232

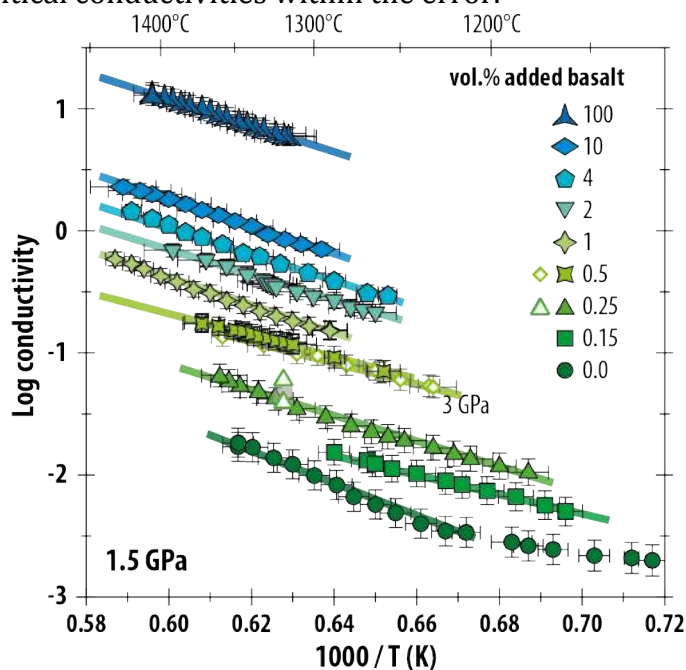
233 kJ/mol) due to hopping (also called small polaron) conduction and potential grain boundary  
 234 effects (Wannamaker & Duba, 1993; Sakamoto et al., 2002; Yoshino et al., 2009). At  
 235 temperatures above 1230°C, high  $E_a$  ( $239 \pm 11$  kJ/mol) indicates that ionic conduction (e.g.  
 236 Yoshino et al., 2009) is the dominant mechanism, although there may still be minor  
 237 contributions from other mechanisms (see also Gardés et al., 2014).  
 238 The conductivity of sample M510 that contained 0.25 vol.% of added basalt is similar to that  
 239 of pure olivine below the basalt liquidus temperature (1270°C), but it becomes significantly  
 240 higher than olivine at temperatures above 1300°C (Fig. 3). However, during the following  
 241 cooling and heating cycles, the conductivity remains higher than that for pure olivine,  
 242 probably due to the better wetting properties of melt once it has overshoot the liquidus  
 243 temperature and distributed through the solid matrix. The effect of crossing the solidus  
 244 temperature of the basalt is not visible in the experiment involving 0.25 vol.% of added basalt,  
 245 probably due to the low amount and initial distribution of melt (Fig. 3).  
 246 In the case of the sample composed of basaltic melt only (M480), the jump observed around  
 247 880°C during the first heating can be explained by improved contact between sample and  
 248 electrodes upon relaxation of the glass once the glass transition temperature has been  
 249 crossed. Around 1090°C (grey arrow on Fig. 3), the slope suddenly increases from  $74 \pm 9$   
 250 to  $248 \pm 10$  kJ, probably coinciding with the solidus temperature of the basalt. The value of 248  
 251 kJ has no physical meaning because the basaltic glass may have partly crystallized, and the  
 252 formed crystals may have gradually melted at these temperatures. The very good  
 253 reproducibility of the conductivity measurements during the different heating and cooling  
 254 cycles attests to the accuracy of the measurements and the limited loss of melt from the  
 255 sample chamber (see also section 4.1).  
 256



257  
 258 **Figure 3: Reciprocal temperature versus electrical conductivity of samples containing 0, 0.25 and 100%**  
 259 **of basaltic melt at 1.5 GPa. The activation energy ( $E_a$ ) is indicated for the pure olivine sample, with**  
 260 **probable conduction mechanisms. Black and grey arrows correspond to feature most likely caused by**  
 261 **the glass transition and the solidus of the basalt respectively. The conductivity values obtained during**  
 262 **cooling are superimposed by the last heating path. The error in temperature is smaller than the symbols**  
 263 **while the maximum error in EC is 0.2 log unit.**

264

265 The logarithmic EC of the pure olivine aggregate and of olivine aggregates containing various  
266 fractions of basaltic melt are displayed as a function of reciprocal temperature in Fig. 4. For all  
267 melt fractions investigated, the EC increases with the temperature but is clearly very sensitive  
268 to the fraction of melt: the higher the melt fraction, the higher the conductivity. For instance,  
269 at 1300°C, the addition of 0.5 vol.% of basaltic melt increases the EC by one order of magnitude  
270 compared to the pure olivine aggregate; the addition of 10 vol.% of melt increases  
271 the EC by 1.8 log unit, and the pure basalt liquid end-member is by 2.6 orders of magnitude  
272 more conductive. These relations are not affected by run duration: experiment M523 was  
273 performed at a single temperature of 1319°C for 27 hours, but the conductivity is consistent  
274 with data from M510 which contained the same melt fraction but followed a temperature-  
275 time cycle similar to the other experiments (Fig. 4; see also Fig SI 3). M488 and M501 both  
276 contained a basalt melt fraction of 0.5 vol.% and were conducted at 1.5 and 3.0 GPa  
277 respectively have identical conductivities within the error.



278

279 **Figure 4: Reciprocal temperature versus EC of basaltic melt and olivine aggregate with 0 to 10 vol.% of**  
280 **added basaltic melt at 1.5 GPa (symbols). An olivine aggregate experiment containing 0.5 vol.% of added**  
281 **basalt was also conducted at 3 GPa (empty diamonds). The range of conductivity measured at constant**  
282 **temperature in experiment M523 is shown by the empty triangles. Lines correspond to the fit of the data**  
283 **using equation (1) and fitting parameters are presented in Table 2.**

284

### 285 3.2. Textural results

286 SEM observations of the recovered experimental charges showed that the initial cylindrical  
287 shape of the sample was preserved through the experiment with only minor irregularities,  
288 mainly where the electrodes are in contact with the thermocouples (Fig. 5; Fig. SI 4). The  
289 horizontal cracks observed throughout the sample may have been caused by tensile stresses  
290 during decompression and were omitted from the calculation of the geometrical factor  
291 (corresponding to aspect ratio of the sample, *i.e.* the surface divided by the length; Table 2).  
292 The grain size ranges up to 100 microns, but shows no significant grain growth over the  
293 duration of the experiments (Fig. SI 5). The effect of grain size on EC was not investigated  
294 here. Low magnification images show a relatively homogeneous distribution of melt, which is  
295 visible as pockets ~50 microns across in the experiment where  $\leq 2$  vol.% of melt was added  
296 (Fig. 5A, C & F). The elongated melt pockets appear to follow the flow lines typically induced  
297 by compressive deformation, *i.e.* sub-normal to the electrodes at the top and bottom of the  
298 sample, rotating sub-parallel to the electrodes in the centre of the sample, suggesting a small



299 deviatoric stress was present during the experiments (Fig. 5A and Fig. SI 4C; see more in  
300 Section 4.1). At higher magnification, we note the presence of melt as films and tubes,  
301 displayed as lines and dots respectively in 2D sections (examples of the labels on Fig. 5B). The  
302 melt appears to be fully interconnected for basalt melt fractions  $\geq 2$  vol.% but not  
303 interconnected at fractions  $< 0.5\%$  (Fig. 5 D & G). A comparison in the distribution of calcium  
304 between experiments with 0.5 and 0.25 vol.% melt contents reveals the presence of small  
305 melt-associated Ca-rich pockets in both samples but Ca-rich films are not visible in the sample  
306 with 0.25 vol.% of added melt (Fig. 5 E & H).

307

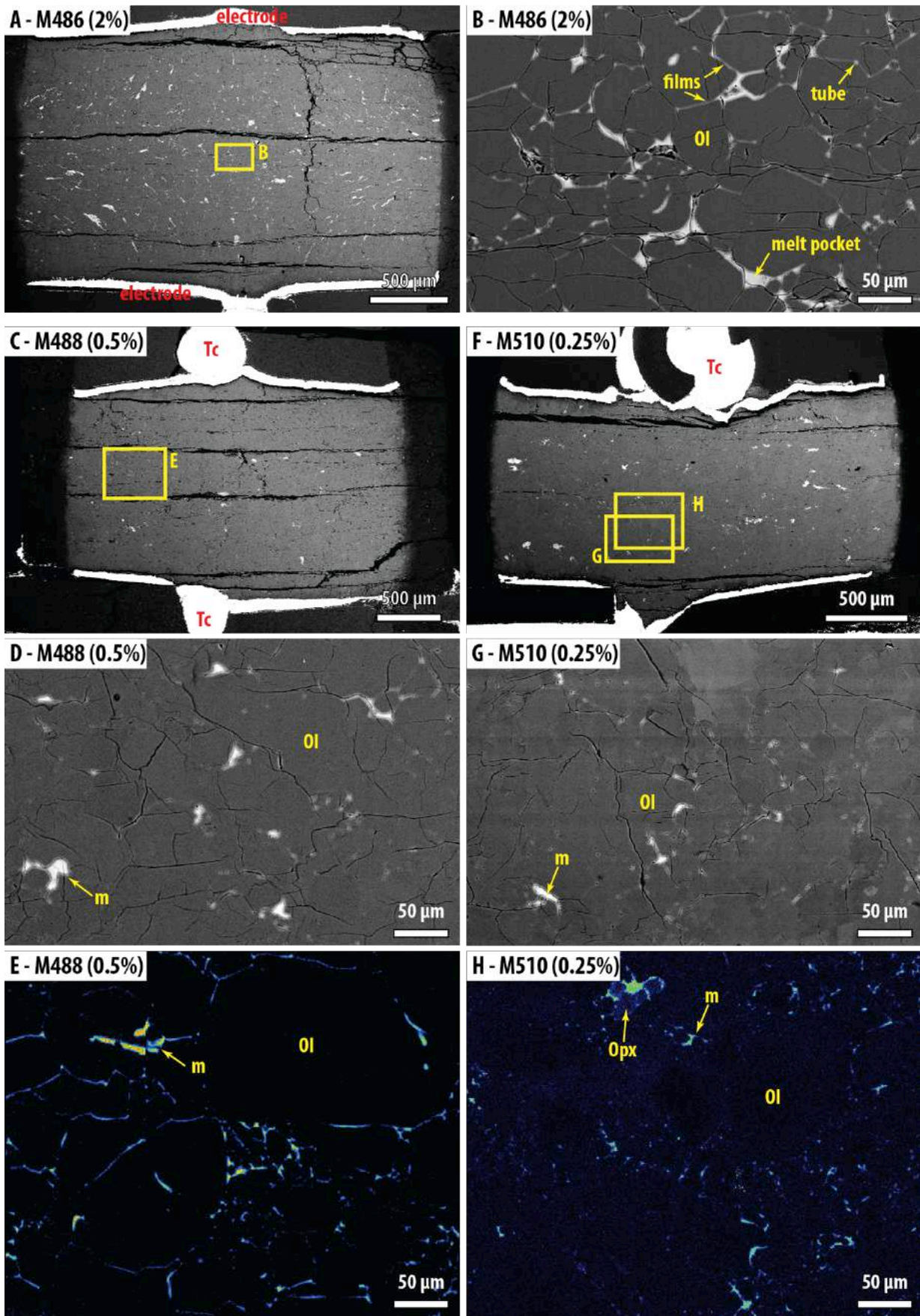
### 308 *3.3. Chemical composition and water content of experimental products*

309 The chemical composition of olivine after experiments is almost identical to the starting  
310 composition (Fig. SI 6). The slight increase of the Fo content, by up to  $\sim 0.01$  (molar  $\text{Mg}/(\text{Fe} +$   
311  $\text{Mg})$ ), is probably related to minor reaction with the MgO capsule (see section 1 of  
312 supplementary materials), slight loss of Fe to the Pt electrodes and/or a minor readjustment  
313 in mineral/melt Fe-Mg partitioning.

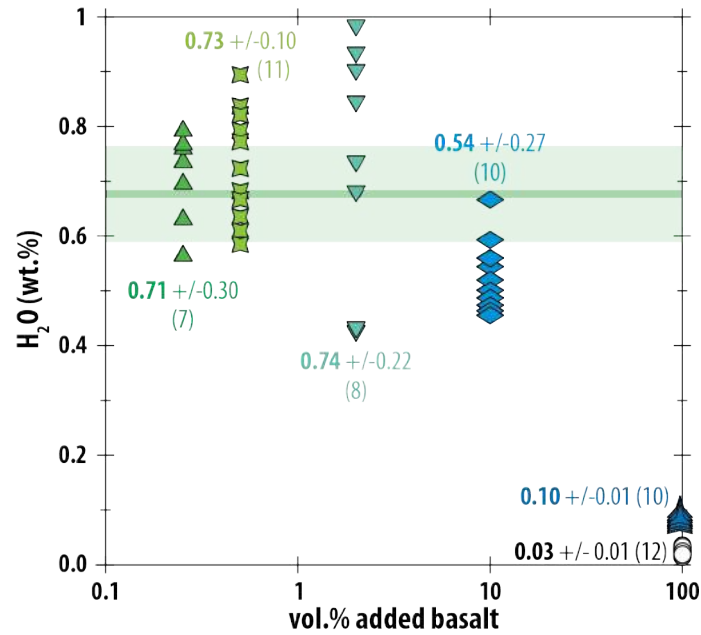
314 The chemical composition of the melt in the experimental products is similar to that of the  
315 starting basaltic melt (Table 1). There is some variation apparent in the concentrations of  
316 MgO,  $\text{Al}_2\text{O}_3$ , and FeO and a small variation in the sodium concentration (electrical charge  
317 carriers) but none of these differences exceed 10%, except for the experiments with a basalt  
318 fraction of 0.5 vol.% that show changes that are slightly larger than this. The chemical  
319 compositions and textural observations give no indication that interactions occurred between  
320 olivine crystals and melt that could have significantly affected the EC measurements.

321 The water content measured in olivine is below the detection threshold, thus implying a  
322 concentration of water lower than 10ppm in the solid material, in comparison with the dry  
323 forsterite used as a calibration standard. In contrast, the glasses contain substantial amounts  
324 of water, with the experiments containing the lower melt fractions producing the most  
325 hydrous glasses (Fig. 6). The experiment with no crystals produced a glass with little water  
326 (0.1 wt.%  $\text{H}_2\text{O}$ ), slightly more than the starting glass (0.03 wt.%). Experiments with lower  
327 melt fractions resulted in glasses containing between 0.54 wt.%  $\text{H}_2\text{O}$  (10 vol.% of added  
328 basalt) and 0.74 wt.%  $\text{H}_2\text{O}$  (2 vol.% of added basalt) (Fig. 6). The glasses from the experiments  
329 with 0.25, 0.5 and 2 vol.% added melt have similar water contents but there is no clear a  
330 correlation between the water content in the experimental glasses and the added melt  
331 fraction (Fig. 6).

332



333  
 334 Figure 5: Back-Scattered Electron (BSE) images (A to D, F and G) and relative concentration maps for  
 335 calcium (E and H) in experiments involving 2, 0.5, and 0.25 vol.% of added basalt. On SEM images, the  
 336 metal electrodes are white, the melt (m) is light grey and olivine (Ol) is dark grey. Calcium mapping  
 337 highlights melt pockets and films around olivine crystals (black and dark blue areas). Rare  
 338 orthopyroxene crystals (Opx) are present at the top of the sample in image H, coming from impurity in  
 339 the starting material.



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Figure 6: Water contents (bold font) of melts in experimental products reported with the number of analyses (number in brackets). The average water content in melts from experiments with added melt fractions between 0.25 and 0.10 is  $0.68 \pm 0.09$  wt. % (horizontal green line).

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## 4. Discussion

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### 4.1. Experimental limitations

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#### 4.1.1. Chemical contamination

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The experiments were conducted for durations as short as possible (except M523) in order to limit melt loss or chemical contamination of the sample with the surrounding host assembly. Only the experiment conducted with pure basaltic liquid (M480) shows a minor amount of melt percolating into the MgO sleeve (Fig. SI 4 A & B). Based on the presence of melt after 27 hours at 1319°C, including regions close to the MgO sleeve, we believe that there is no significant escape of liquid from the sample over the experimental duration. A stable sample volume and EC measurement is, therefore, maintained over the duration of the experiments. The contamination of the sample by the MgO sleeve is limited to a narrow peripheral layer of 100 to 150 micrometers in the longest duration experiment (excluding M523), representing less than 5% of the sample diameter. On the other hand, the platinum electrodes alloy to some degree with iron from olivine and the melt, the latter remaining homogeneous in composition (see iron distribution in the 100% melt experiment, Fig. SI 4B) except in a narrow (< 50 microns) layer at the contact with electrodes. This alloying, however, does not influence the electrical conductivity of the sample.

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#### 4.1.2. Textural equilibrium

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Once above the basalt liquidus temperature of the first heating, the EC reaches a value reproduced during later cooling and heating cycles (see the experiment with 0.25 vol.% of basalt, Fig. 3). According to this observation, we conclude that the melt should have promptly percolated through the sample and wetted the electrodes. The examination of the experiment M523 shows that melt pockets are preserved even after 27 hours without further wetting of the crystal aggregate (Fig. SI 4K & L). Coaxial strain in the experiments would have favored the percolation of the melt through the aggregate as highlighted by preferentially oriented melt pockets in samples involving 2 and 10 vol.% of added basalt. The melt distribution geometry in the samples is complex and it is not clear how small amount of coaxial strain would have contributed to enhance the EC in the samples. However, the consistent orientation of these persistent melt pockets parallel to the electrodes (perpendicular to the

375 electrical path) should have not led to an increase in the bulk conductivity of the sample  
376 (Zhang et al., 2014).

#### 377 4.1.3. Melt fraction determination

378 The determination of post-experimental melt fractions by SEM observation is challenging due  
379 to the image resolution, and the conversion from 2D to 3D. Post-experimental melt fraction  
380 estimates are usually under-estimated at low magnification due to the difficulty in observing  
381 the thin melt films and pockets, particularly for the samples with the lowest melt fractions  
382 (Fig. SI 7). On the other hand, at higher magnification, heterogeneity in melt distribution, *i.e.*  
383 the presence of scattered melt pockets of different sizes, leads to biased estimates of the melt-  
384 crystal ratio. This can lead to errors in the melt fraction determination that are larger than the  
385 initial mass ratio of the mixed components. Consequently, though the glass fraction observed  
386 on post-mortem SEM picture is similar to the one determined from the initial weight ratio of  
387 olivine and basalt in the starting material of each experiment, we rely only on the latter (Fig.  
388 5, Fig. SI 4 and Fig. SI 7). In addition, it is possible that the pure olivine aggregate does not  
389 remain melt-free at high temperatures (for instance,  $T > 1350^{\circ}\text{C}$ ), since the solidus  
390 temperature of an olivine aggregate particularly in the presence of even minor amounts of  
391  $\text{H}_2\text{O}$  could easily be over stepped (Hashim, 2016). However, according to Chantel et al. (2016),  
392 the very low amounts of melt that could be expected in the pure olivine aggregate ( $< 0.1\%$ )  
393 would not wet the grain boundaries, as reflected in the very high EC compared to samples  
394 with a low added basalt fraction (Table 2 and Fig. SI 7) even though intergranular mass  
395 transport is strongly influenced by minor amounts of hydroxyl as proven by the work of  
396 Gardés et al. (2012). It is shown that activation energy of diffusion in hydrous-saturated grain  
397 boundaries is reduced compared to dry grain boundaries.

#### 398 4.2. Implications of the melt distribution

399 For experimental durations investigated in this study ( $< 27$  hours), melt pockets are preserved  
400 regardless of the melt fraction (Fig. 5), including when the melt is not fully interconnected  
401 (melt fraction  $< 0.5$  vol.%). Complete redistribution of a small melt fraction appears to require  
402 much longer timescales than employed in the experiments. Similar persistent melt pockets  
403 were also observed by Garapic et al. (2013) after 430 hours at high temperature.  
404 Alternatively, a threshold melt fraction may be required for the complete redistribution of  
405 melt pockets, as discussed in the next section. Their stability excludes any textural evolution  
406 that would affect the electrical results.

407 Although tubes are common features in all samples, films on the grain boundaries are not  
408 recognized in the samples containing 0.25 vol.% of added basalt or less (Fig. 5). Such feature  
409 seems determinant to switch from a low degree of interconnectivity where films are not  
410 present to a high degree of interconnectivity where films are present alongside pockets and  
411 tubes. The presence of films implies dihedral angles smaller than  $10^{\circ}$  (Cmíral et al., 1998). Our  
412 observations therefore suggest that olivine does not exhibit dihedral angles less than  $10^{\circ}$   
413 in the presence of very small melt fractions. Furthermore, dihedral angles were observed to be  
414 temperature-dependent in melt-bearing olivine aggregates ranging from  $19^{\circ}$  to  $9^{\circ}$  between  
415  $1300^{\circ}\text{C}$  and  $1450^{\circ}\text{C}$  (Yoshino et al., 2009). In the olivine-basalt system, the disappearance of  
416 films with lower melt fraction seems to record the interconnectivity threshold as supported  
417 by the EC measurements (see next section). However, our experimental setup does not allow  
418 us to distinguish between the individual effects of pockets or films on the bulk conductivity of  
419 the partially molten assemblages.

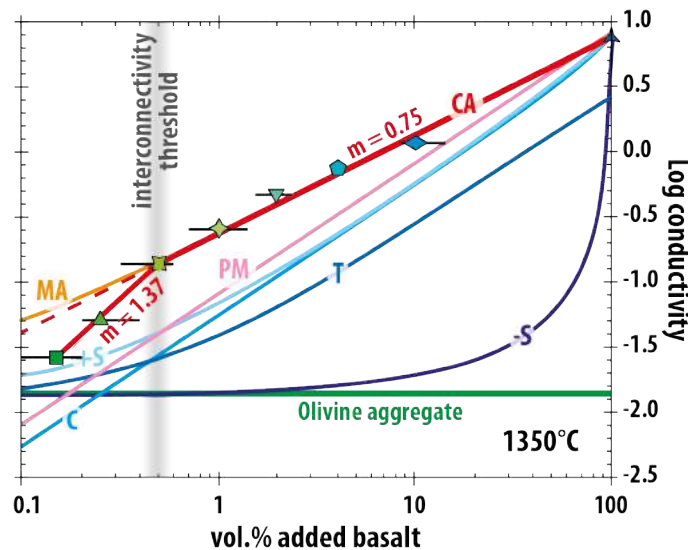
#### 420 4.3. Choice of the mixing law

421 The activation energy and pre-exponential factor were determined for each experiment based  
422 on an Arrhenius relationship of EC (Eq. 1; Table 2; Fig.4). The calculated EC values closely  
423 reproduce the experimental data (Fig. 4). For the pure olivine aggregate, only data points  
424  
425

426 obtained at temperatures higher than 1230°C were used to determine the fit, corresponding  
 427 to temperature where ionic conduction is assumed to be the dominant transport mechanism  
 428 (Fig. 3 and Section 6 of supplementary materials). The value of the EC fitted at 1350°C is  
 429 plotted against the added melt fraction in Figure 7: from 100 down to 0.5 vol.%, the EC of  
 430 partially-molten olivine aggregates defines a trend significantly higher than the models  
 431 commonly used in the literature, such as +Spheres, Tubes, and Cubes models (Grant & West,  
 432 1965; Waff, 1974) (Fig. 7), which can be modeled most closely using the Conventional Archie's  
 433 law (Eq. 2):

$$\sigma_{bulk} = \sigma_l \chi_l^m \quad (\text{Eq. 2})$$

434 where  $\sigma_{bulk}$  is the EC of the system,  $\chi_l$  the melt fraction in vol.%,  $\sigma_l$  the EC of the liquid and  $m$   
 435 is a measure of how the ratio  $\frac{\sigma_{bulk}}{\sigma_l}$  varies as a function of melt fraction and degree of  
 436 interconnection of the melt (Glover, 2010 and references therein). The value  $m$  will be  $< 2$  for  
 437 a well-interconnected liquid phase and it will tend to unity only if the liquid phase is fully  
 438 interconnected and is the only conductive phase (Glover, 2010). In our case, at 1350°C and  
 440 added basalt fraction  $> 0.5$  vol.% (high degree of interconnectivity), the power law exponent  
 441  $m = 0.75 \pm 0.02$  while the first term is the conductivity of the basaltic liquid, i.e.  $\log \sigma_l = 0.89$   
 442  $\pm 0.03$  ( $\sigma$  in S/m). This low value of  $m$  indicates that the liquid phase is highly interconnected  
 443 and that another conduction mechanism contributes to the bulk conductivity so as to provide  
 444 a value of the exponent  $m < 1$ . The existence of another conduction mechanism than the melt  
 445 is also demonstrated by the higher EC than given by the parallel model ("PM" in Fig. 7), which  
 446 is supposed to represent the maximum EC where the melt is the unique conduction  
 447 mechanism.  
 448



449 Figure 7: Electrical conductivity versus the fraction of added basalt (in volume %) (Log scale) from the  
 450 current experimental data (blue to green symbols which are identical to legend of Fig. 4) compared with  
 451 the Modified Archie's law (MA), Conventional Archie's law (CA), Parallel model (PM), +Spheres (+S),  
 452 Cubes (C), Tubes (T) and -Spheres (-S) models (curves) from the literature at 1350°C. See text for model  
 453 references. Black segments represent the error on the model fraction estimated by image analysis (see  
 454 supplementary information).  
 455

456 The maximum value of  $m$  ( $0.84 \pm 0.05$ ) is obtained when considering the experiments with 0.5  
 457 to 2 vol.% of added basalt that contain similar water contents ( $\sim 0.68 \pm 0.09$  wt.%). Based on  
 458 the experiments of Ni et al. (2011) at 1450°C, the effect of 1.1 wt.% of water would increase  
 459 the EC by 0.3 log unit only ( $\log \sigma = 1.0$ ), and the resulting  $m$  exponent would be  $0.86 \pm 0.04$ .  
 460 Therefore, the value of the exponent  $m$  cannot be the result of the small water content  
 461 difference observed in the experiments. Since the melt composition does not vary  
 462

463 significantly, in particular in the Na content, the reason why the value of  $m$  is lower than unity  
464 may reside in the solid phase, even though the EC of the latter is almost 3 log units lower than  
465 the basalt melt. Grain boundary effects and/or the existence of an electric double layer  
466 (Grahame, 1947) might enhance EC and would argue in favor of a low  $m$  exponent after the  
467 Na-coating of crystallizing olivine but these concepts cannot be demonstrated by our  
468 experiments.

469 The  $m$  value we find is comparable to that (0.89) experimentally determined by Yoshino et al.  
470 (2010a), but significantly different from that calculated by Miller et al. (2015) of  $1.3 \pm 0.3$ . Such  
471 a value is inconsistent for melt fractions lower than 0.8% since the conductivity of the melt-  
472 bearing olivine aggregate becomes lower than that of olivine-only (Log  $\sigma = -2.05$ ; Constable,  
473 2006). The exponent calculated by Yoshino et al. (2010a) on an olivine-carbonatite system ( $m$   
474 = 1.14) implies a very good interconnectedness, but the existence of one conducting phase  
475 only, probably due to the higher conductivity of carbonatite melt than basaltic one (more than  
476 one order of magnitude).

#### 477 478 **4.4. Interconnectivity threshold of the melt fraction (0.5 vol.%)**

479 For experiments with added basalt fractions of 0.25 and 0.15 vol.%, the EC is lower than the  
480 trend previously described (dashed line, Fig. 7) but still higher than the olivine-only aggregate  
481 defining a higher exponent of  $m = 1.37$ . We deduce that the basaltic melt is no longer fully  
482 interconnected but remains still well-interconnected overall, and still contributes to an  
483 increase in the bulk EC. Therefore, under our experimental conditions, an interconnectivity  
484 threshold exists at a added basalt fraction of 0.5 vol.% in the olivine aggregates. No  
485 mathematical law reproduces such a change in connectedness with the melt fraction. Such a  
486 threshold is likely linked to the appearance/disappearance of films, switching to a low/high  
487 degree of interconnectivity and resulting in different electrical transport properties. The low  
488 degree of interconnectivity is explained by the persistence of tubes in the solid aggregate. The  
489 threshold evidenced here occurs at very low melt fraction, and could be easily masked by the  
490 high jump in EC observed upon melting observed in other study (e.g. Maumus et al., 2005).  
491 The threshold depends on the melt distribution (tubes / films...), thus on the wetting  
492 properties of the melt with the solid phase (Yoshino et al. 2009; Zhu et al. 2011).

#### 493 494 **4.5. Model of the EC of partially-molten olivine aggregate**

495 Since the difference between the conventional and the modified Archie's laws is negligible  
496 above the interconnectivity threshold (added basalt fraction  $\sim 0.5$  vol.%), we use the  
497 conventional law to fit all data from this study with a high degree of interconnectivity: we  
498 now incorporate the temperature dependence on the EC to the previous fit by regressing the  
499 evolution of the Archie's law parameters with temperature. The correlation of the two  
500 parameters with temperature provides the following simplified equation:

$$501 \log \sigma = (aT + b) * \log \chi_m + (cT + d) \quad \text{(Eq. 3)}$$

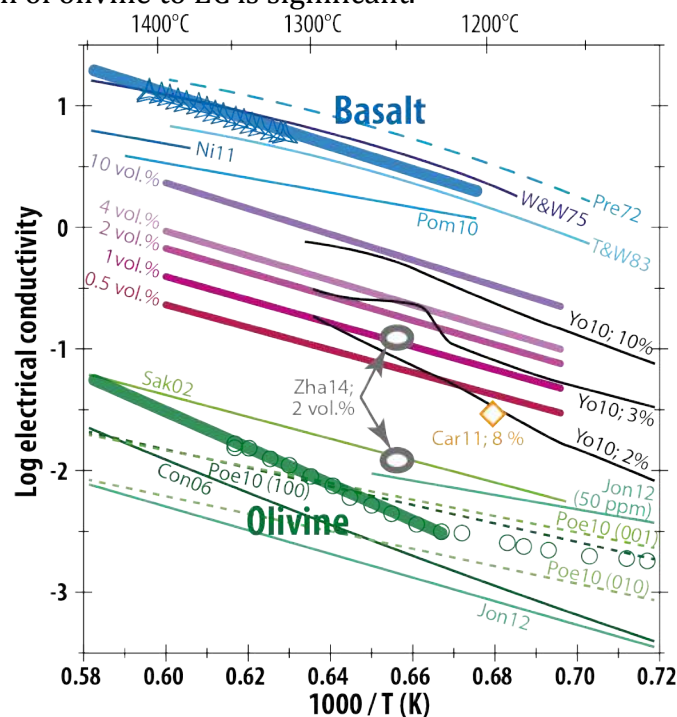
502 where  $\sigma$ ,  $T$ ,  $\chi_m$  are the electrical conductivity (in S/m), the temperature (in Kelvin) and the  
503 melt fraction respectively, and  $a$  to  $d$  are fitting parameters determined from the experiments  
504 ( $a = 3.66E-04 \pm 8E-6$ ;  $b = 0.151 \pm 0.013$ ;  $c = 4.52E-03 \pm 1E-4$ ;  $d = -6.448 \pm 0.16$ ). The mixing model  
505 integrating both temperature and melt fraction is valid for temperatures higher than 1230°C  
506 and melt fractions  $\chi_m$  higher than 0.5 vol.%.

507 The same Equation 3 can be applied to fit calculate the EC of partially molten olivine  
508 aggregate with melt fraction ranging between 0.5 down to 0.15 vol.% and temperature higher  
509 than 1230°C. In that case, the fitting parameters are  $a' = 1.57E-04 \pm 4E-6$ ;  $b' = 1.113 \pm 0.006$ ;  $c' =$   
510  $3.92E-03 \pm 9E-5$ ;  $d' = -4.082 \pm 0.14$ . In this range of melt fraction with a lower degree of  
511 connectivity, if  $m = 1.37$ , then the preexponential factor  $A = 2.9$  log units, being a value too  
512 high for the conductivity of basaltic melt. Hence, there must be other phase more conductive

513 than olivine to get  $m = 1.37$ , such as, for instance, grain boundary effects that become more  
514 and more significant at lower melt fractions (Marquardt et al., 2015).  
515

516 Both models reproduce very closely the experimental results (see Fig. SI 8) and is compared  
517 with data from the literature (Fig. 8) except the solid end-member for which the Arrhenius fit  
518 is used (Eq. 1; Table 2).

519 Conductivities for both solid and liquid end-members fall in the range of their respective  
520 values defined by previous studies, though most of the melt measurements were performed  
521 on basaltic liquids that do not appear to respect an Arrhenius law (Fig. 8) (Presnall, 1972;  
522 Waff & Weill, 1975; Tyburczy & Waff, 1983; Pommier et al., 2010; Ni et al., 2011). The EC  
523 measurements on the pure olivine aggregate reproduce closely those reported for olivine by  
524 Poe et al. (2010) along the (100) and (001) axis orientations at lower temperatures ( $T <$   
525  $1250^{\circ}\text{C}$ ) but the data diverge quite significantly at higher temperatures. A comparison  
526 between our measurements and those reported for dry olivine and olivine containing 50 ppm  
527 of  $\text{H}_2\text{O}$  (Jones et al., 2012) is consistent with SIMS analyses indicating  $< 10$  ppm  $\text{H}_2\text{O}$  in our  
528 olivine aggregates. Caution should be taken, however, when comparing transport mechanisms  
529 determined for single crystals, with those of polycrystalline aggregates since models for this  
530 conversion have not be thoroughly tested. Finally, the extrapolation of olivine EC measured at  
531 low temperature (typically  $< 1200^{\circ}\text{C}$ ) to natural upper mantle conditions by assuming a  
532 constant  $E_a$  may be misleading, in particular at low melt fractions and high temperatures  
533 where the contribution of olivine to EC is significant.



534  
535 **Figure 8: Electrical conductivity plotted against the reciprocal temperature for basalt, olivine aggregate**  
536 **and partially molten olivine aggregates with various fractions of basalt. Thick curves are model end-**  
537 **member conductivities (basalt and olivine aggregate), plotted with the experimental data (3 point stars**  
538 **and circles respectively). Modeled mixtures from this study (purple to pink) are also shown. Previous**  
539 **studies on basalt with comparable compositions are shown as thin blue curves (Presnall, 1972; Waff &**  
540 **Weill, 1975; Tyburczy & Waff, 1983; Pommier et al., 2010; Ni et al., 2011), whereas previous olivine**  
541 **measurements are shown by thin green curves (Sakamoto et al., 2002; Constable, 2006; Poe et al., 2010;**  
542 **Jones et al., 2012) and partially molten olivine aggregate measurements (Yoshino et al., 2010; Caricchi et**  
543 **al., 2011; Zhang et al., 2014). The two values from Zhang et al (2014) correspond to measurement in the**  
544 **direction normal (lower value) and parallel (higher value of conductivity) to the shear direction. Melt**  
545 **proportions from Yoshino et al. (2010a) and Caricchi et al. (2011) are expressed in weight %.**

546

547 The comparison of the EC of partially molten olivine aggregate with the study of [Yoshino et al.](#)  
548 [\(2010a\)](#) (10, 3 and 2 wt.% of basalt added to olivine aggregate), corresponding to volume  
549 proportions of 8, 2.4 and 1.6 vol.% when assuming densities of 3.3 for olivine and 2.7 for the  
550 basalt), show similar values at  $T < 1300^{\circ}\text{C}$ , but the higher  $E_a$  they found and the presumed  
551 absence of water in their experimental products results in lower EC at higher temperatures  
552 [\(Fig. 8\)](#). One significant difference between the two studies is the starting grain size (up to 100  
553 micrometers here against a few micrometers in [Yoshino et al., 2010a](#)). Our model also gives a  
554 higher conductivity than deformed partially-molten olivine aggregates ([Caricchi et al., 2011](#);  
555 [Zhang et al., 2014](#)). In the study of [Zhang et al. \(2014\)](#), the electrical anisotropy of a peridotite  
556 with 2 vol.% of basaltic melt is investigated during deformation. The EC in the direction  
557 parallel to the shear direction is one order higher than in the one normal to the shear plane.  
558 Such a difference comes from the good melt interconnection and agrees with our results [\(Fig.](#)  
559 [8\)](#). In addition, the EC value of the experiment with 2 vol.% of added melt lowered by one  
560 order of magnitude would provide a melt fraction close to 0.25 vol.%, therefore in the field of  
561 low degree of interconnectivity, such as suggested by [Zhang et al. \(2014\)](#).

#### 562 563 *4.6. Estimation of the melt fraction in the upper mantle*

##### 564 *4.6.1. Oceanic asthenosphere*

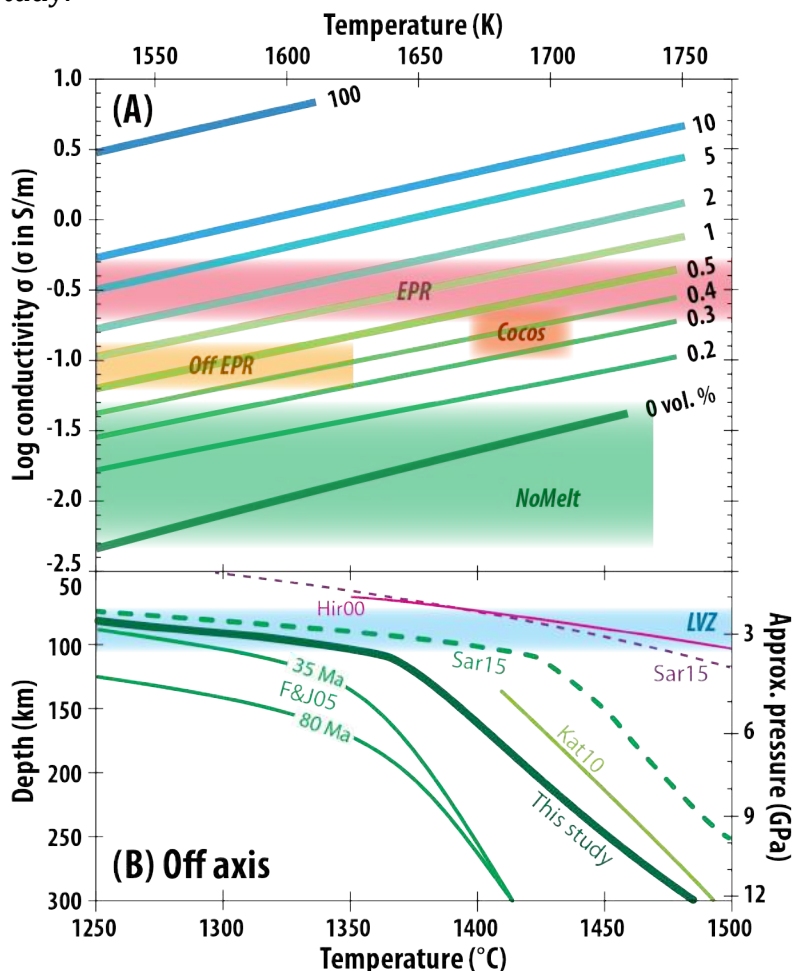
565 Our model for the EC of melt-bearing olivine aggregates can be adapted for the interpretation  
566 of melt-induced electrical anomalies located in the upper mantle, in situations where (i) the  
567 melt is likely basaltic in composition and exceeds 0.15 vol.%, (ii) assuming the EC of  
568 peridotite is similar to that of an olivine aggregate, (iii) the grain size has negligible effect on  
569 the EC and (iv) regions are deformed by long-range tectonic stresses. The absence of a  
570 measureable pressure effect on the EC between 1.5 and 3.0 GPa implies that the mixing model  
571 developed in this study can be applied to understand the conductivity structures of the LAB  
572 and LVZ. Our model implies an interpreted maximum melt fraction of 0.4 - 1 vol.% to explain  
573 the conductive, off-axis region of the East Pacific Rise (off EPR), assuming a temperature of  
574  $1350^{\circ}\text{C}$  ([Evans et al., 2005](#); [Baba et al., 2006](#); [Sarafian et al., 2015](#)) [\(Fig. 9A\)](#). The lower EC of  
575 the Cocos plate LAB ( $\log \sigma = -0.6$  to  $-0.9$  S/m) and higher assumed temperature ( $1420^{\circ}\text{C}$ ; [Naif](#)  
576 [et al., 2013](#)) leads to a melt fraction range of 0.3 to 0.5 vol.%, implying that the melt would not  
577 be fully interconnected [\(Fig. 9A\)](#). These melt proportions estimated for the top of the  
578 asthenosphere in these two regions are lower than previous estimates (e.g. [Evans et al., 1999](#),  
579 [2005](#); [Baba et al., 2006](#); [Hirschmann, 2010](#); [Yoshino et al., 2010a](#); [Ni et al., 2011](#); [Naif et al.,](#)  
580 [2013](#)) as a result of the mathematical models previously employed underestimating bulk EC  
581 at low melt fractions. On the other hand, the melt fractions remotely estimated using our  
582 model agree with estimates of  $<1\%$  based on melt migration and incremental melting models,  
583 in which there is a maximum melt fraction that can be retained by the solid matrix ([Kelemen](#)  
584 [et al., 1997](#)). They also agree to the value of 0.5 vol.% estimated by [Chantel et al \(2016\)](#) based  
585 on ultrasound velocity measurements.

##### 586 587 *4.6.2. East-Pacific Rise and Mid-Ocean Ridge regions*

588 The melt fraction estimated beneath the EPR crest will depend strongly on the solidus of the  
589 peridotite and, therefore, on the adiabatic gradient. We use a melting depth interval of  
590 between 60 and 100 km ([Langmuir et al., 1993](#); [Baba et al., 2006](#); [Key et al., 2013](#)) and employ  
591 the volatile-poor peridotite solidus determined by [Hirschmann \(2000\)](#) [\(Fig. 9B\)](#) to constrain  
592 the pressure (2 to 3 GPa) and temperature ( $1330$  to  $1400^{\circ}\text{C}$ ) of the melting zone beneath the  
593 EPR. Under such conditions, based on the conductivity value of [Baba et al. \(2006\)](#) and our  
594 [results](#), we estimate melt proportions of between 0.8 and 4 vol.%, which is consistent with the  
595 value of [Kelemen et al. \(1997\)](#), and references therein), although less than half the value of  
596 10% proposed by [Key et al. \(2013\)](#).



597 Contrary to the suggestion of Miller et al. (2015), high concentrations of volatiles in the melt  
 598 (> 0.7 wt%) and olivine aggregate are not required to explain conductive anomalies in the  
 599 oceanic upper mantle, under ridge or at the top of the asthenosphere. However, higher  
 600 concentrations of volatiles dissolved in the melt would significantly increase the bulk  
 601 conductivity (Gaillard 2004; Ni et al., 2011; Sifré et al., 2014; Laumonier et al., 2015) and the  
 602 temperature, melt fraction and volatile concentration would be highly correlated. It therefore  
 603 becomes impossible to resolve between the effects of temperature or volatile concentration  
 604 using EC alone and some additional constraint needs to be found, a problem that is beyond  
 605 the scope of this study.



606 Figure 9: (A) Reported values of electrical conductivity of various upper mantle anomalies: East Pacific  
 607 Ridge (EPR, Baba et al., 2006), Off axis EPR (Off EPR, Evans et al., 2005; Baba et al., 2006), Cocos plate  
 608 (Naif et al., 2013) and the NoMelt experiment (Sarafian et al., 2015) compared with the EC of partially  
 609 molten olivine aggregates (lines, this study) for various plausible basalt fractions (numbers on the right  
 610 of the lines). The temperature ranges of the Off EPR and NoMelt experiments displayed in the graph are  
 611 plotted according to a geotherm calculated from the NoMelt depth-conductivity and the olivine-only EC  
 612 from this study (see section 4.7). (B) Other geotherms from the literature and the approximated depth of  
 613 the LVZ are plotted for comparison (F&J05: Faul and Jackson, 2005; Kat10: Katsura et al., 2010; Sar15:  
 614 Sarafian et al., 2015), along with the position of the dry peridotite solidus (Hir00: Hirschmann, 2000;  
 615 Sar15: Sarafian et al., 2015).  
 616

617  
 618 **4.7. Temperature estimation of the “NoMelt” upper mantle**

619 Sarafian et al. (2015) reported the EC structure beneath the 70 Ma Pacific plate, located  
 620 between the Clarion and Clipperton fracture zones where no melt should be present  
 621 (“NoMelt” experiment). We estimate the temperature distribution of this site using our  
 622 olivine-only sample conductivity and assuming the absence of melt and significant  
 623 proportions of volatiles in constituting mantle minerals (Fig. 9A & B). The resulting

624 temperature increases almost linearly from 70 (1265°C) to 110 km (1362°C) and from 110 to  
625 300 km (1486°C) with gradients of  $\sim 5^\circ/\text{km}$  and  $0.65^\circ\text{C}/\text{km}$  respectively. The temperature  
626 profile is about  $50^\circ\text{C}$  lower than the geotherm estimated by Sarafian et al. (2015) that was  
627 based on the EC of olivine after Constable (2006); it is similar to that of Katsura et al. (2010)  
628 and significantly higher than that proposed by Faul & Jackson (2005) from fitting the shear  
629 modulus and attenuation data obtained experimentally on olivine Fo90. The geotherm we  
630 calculate implies a temperature difference by about  $100^\circ\text{C}$  from the solidus of dry peridotite  
631 (e.g. Hirschmann, 2000; Sarafian et al., 2015). Such a temperature difference excludes the  
632 presence of dry, silicate melt in those regions.

633

#### 634 4.8. Melt interconnectivity and mobility

635 The 0.5 to 1% of melt estimated using our model to explain the magnitude of the electrical  
636 anomaly at the top of the asthenosphere would have a high degree of interconnectivity but  
637 unable to segregate upwards only based on the absence of intense volcanism at the surface.  
638 On the contrary, the melt produced beneath a Mid-Ocean Ridge (MOR) rises upwards due to a  
639 buoyancy effect, which implies the existence of a minimum permeability threshold for melt  
640 ascent in the production of MOR-Basalt, consistent with the efficient draining of the mantle at  
641 melt fraction higher than 1% (Zhu et al., 2011). The permeability significantly increases  
642 between 0.5-1 vol.% (LVZ) and 0.8-4 vol.% (beneath MOR) without taking into account the  
643 anisotropic distribution of the melt. This melt fraction interval corresponds to a permeability  
644  $k$  ( $\text{m}^2$ ) bounded between  $\text{Log } k = -16.7$  (at 0.5 vol.% of melt) and  $k = -14.3$  (melt fraction of 4  
645 vol.%) based on Miller et al. (2014). The permeability calculated for a 4 vol.% melt fraction  
646 corresponds to a compaction length of the order of 70 km for a MORB-like melt at  $1350^\circ\text{C}$   
647 (McKenzie, 1985), which matches the thickness of the layer the melt has to percolate beneath  
648 EPR axis.

649

650 The critical melt fraction (melt fraction above which melt is drained through the network,  
651 Holtzman, 2016) may thus range between the melt fraction of the LVZ (sustainable melt in the  
652 mantle) and the one of intense melt production beneath the MOR. According to our results,  
653 such a critical melt fraction in the high conductivity regions ranges between 0.5 and 1 vol.% in  
654 volume, significantly higher than 0.1% estimated by Hirschmann (2010). As suggested by  
655 Miller et al. (2015), electrical and fluid flow pathways may act differently. The critical melt  
656 fraction may also depend on the local and regional stress field. We also still lack knowledge  
657 concerning the melt distribution (pervasive or scattered) in natural settings either beneath  
658 the MOR or at the LAB. Furthermore, anisotropic distribution of silicate melts may also  
659 significantly increase EC (Pommier et al., 2015a). The presence of “petit spot” volcanoes  
660 within the oceanic crust might result from localized melt concentrations higher than the  
661 critical melt fraction (about 1%) after eventual accumulation, that are thus synonymous with  
662 non-pervasive melt distribution in the LVZ, which does not require a formation mechanism  
663 that directly involves oceanic plate flexure (Hirano et al., 2006; Yamamoto et al., 2014).

664

## 665 5. Conclusions

666 The results of our *in situ* electrical conductivity measurements allow us to build a model for  
667 the electrical conductivity of partially molten olivine aggregates as a function of temperature  
668 ( $T > 1230^\circ\text{C}$ ) and melt fraction (0.15 to 100 vol.%) based on the conventional Archie’s Law.  
669 The low value of the exponent  $m$  (0.75 at  $1350^\circ\text{C}$  and melt fraction higher than 0.5 vol.%)  
670 suggests that the conductivity of partially-molten olivine aggregate operates through several  
671 mechanisms, the main one being achieved by the presence of melt. High volatiles  
672 concentrations anisotropic distribution of the melt are not necessarily required in order to  
673 explain high conductivities observed in upper mantle setting: we interpret the upper  
674 asthenosphere electrical anomaly to result from the presence of 0.5 to 1 vol.% of melt, which

675 is consistent with the persistence of melt at depths. On the other hand, the conductivity of  
676 regions beneath MOR results from the presence of higher amounts of melt (< 4 vol.%) that  
677 ascend towards the crust, thus defining a percolation threshold. Since relatively high  
678 concentrations of H<sub>2</sub>O and/or CO<sub>2</sub> have been suggested to be present in the upper mantle  
679 (leading to carbonatite melt for the case of CO<sub>2</sub>), our model and conclusions should also be  
680 tested on hydrous peridotite and/or carbonatitic melts (Dasgupta et al., 2013; Sifre et al.,  
681 2014), as well as the effect of grain size and thus grain boundary effect on the electrical  
682 conductivity, which might be tested using the approach of Marquardt et al. (2015).  
683

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691

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

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## Supplementary Information

### 1. Mg contamination from the MgO sleeve

To avoid electrical short cut, the sample cannot be surrounded by a metallic capsule. A MgO sleeve was chosen to replace any common capsule with limited chemical contamination. The longest experiments with temperature variation (M488) lasted more than 6 hours including 5 hours at temperature between 1000 and 1373. The contact between the MgO sleeve and the sample is still sharp, despite a halo of ~200 micrometers (Fig. SI 1). The contamination consists in the enrichment in magnesium in the sample periphery and in iron in its container. The boundaries of olivine crystal in the contaminated zone looks darker (aka MgO-enriched) areas. Other experiments conducted for shorter times at similar temperatures display thinner contaminated sample.

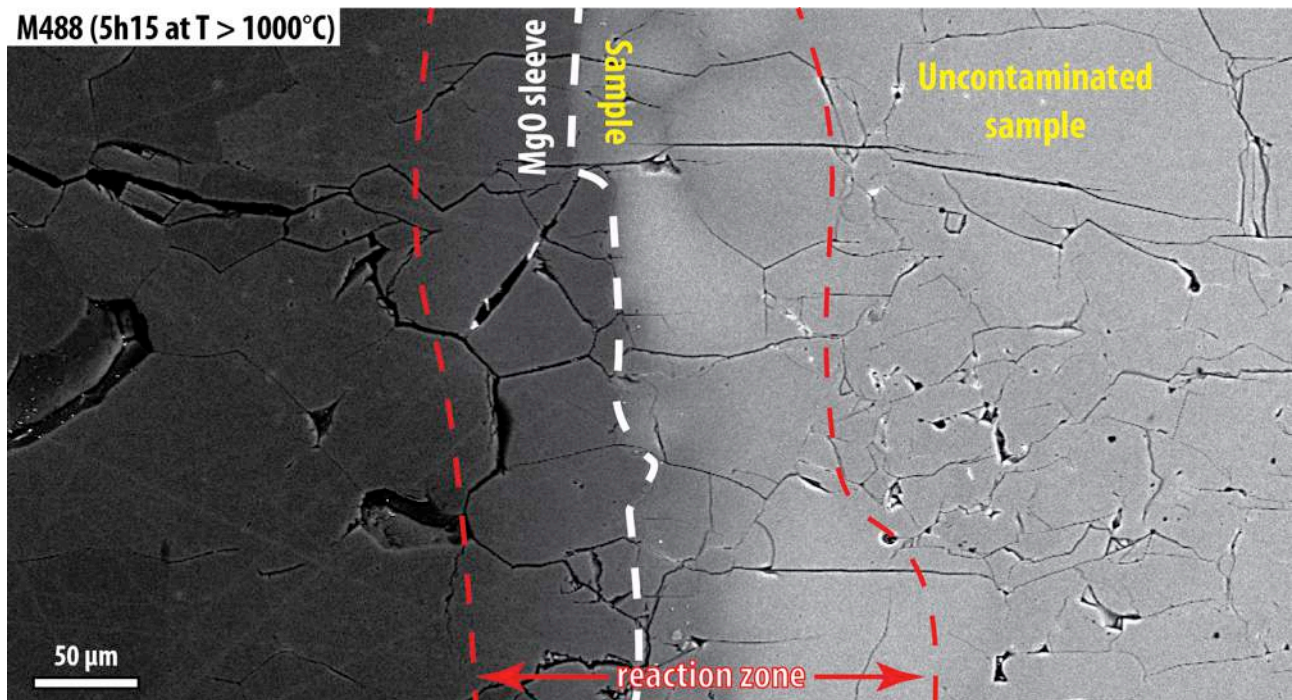
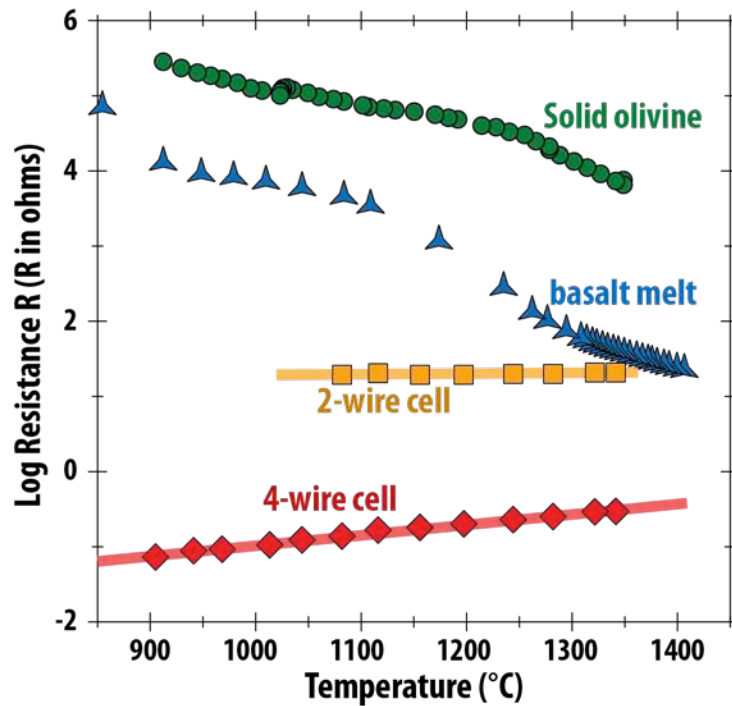


Fig. SI 1: SEM image of the sample periphery in contact with the MgO sleeve. Contamination (MgO from the sleeve to the sample, mostly iron from the sample to the sleeve) operated over a ~200-micrometer thick reaction zone.

24 **2. 2-/4-wire set up**

25 We examine in the following way whether the circuit resistance is low enough to measure our  
26 sample, keeping in mind that basaltic liquid should have a high conductivity. During a test run,  
27 a short circuit happened preventing us to measure the sample resistance. Nonetheless, we  
28 examined the resistance of the electric cell alternating the 2- and 4-wire methods at the same  
29 experimental conditions ( $P=1.5$  GPa,  $T$   $900 < T < 1340^{\circ}\text{C}$ ) than successful experiments, i.e.  
30 experiments providing sample conductivity measurements (Fig. SI 2). The results are  
31 compared with those of runs M496 and M480 (solid and liquid end-members respectively). At  
32  $T > 1350$ , the resistance of the basalt melt becomes comparable with that of the short circuit  
33 obtained by the 2-wire set up, is 1 order of magnitude higher than the resistance obtained  
34 using the 4-wire method. From these observations, we conclude that the 4-wire technique is  
35 necessary.

36



37

38 Fig. SI 2: Temperature vs. electrical resistance (log scale) of the short cut electrical cell using a 2- or 4-wire set up.  
39 The minimum resistance measurable with each setup is plotted alongside the resistance of the melt-free olivine  
40 aggregate (M496) and the one of the basaltic melt (M480).

41

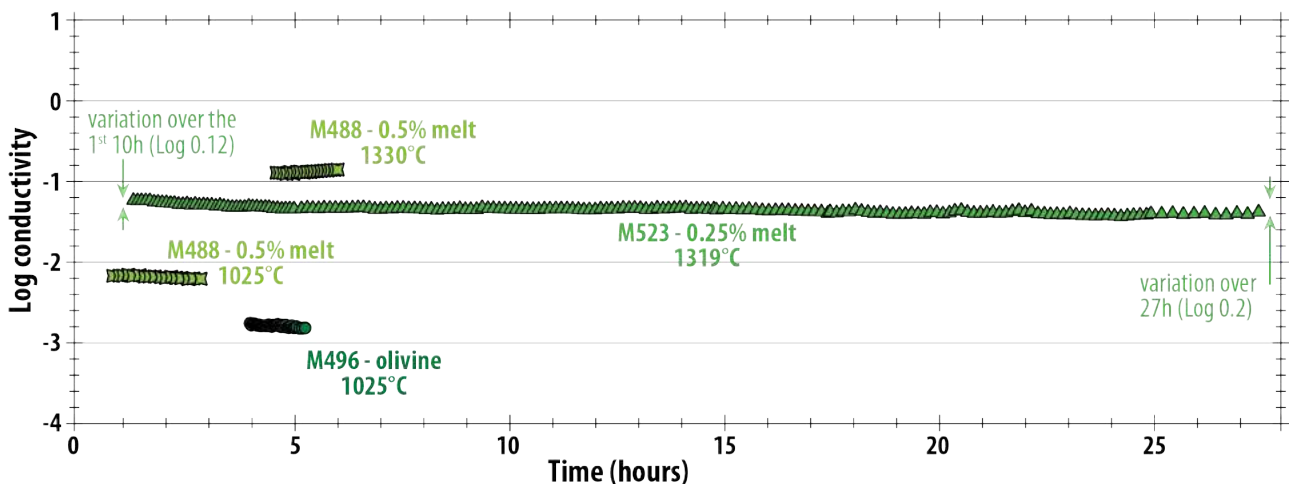
42 **3. EC variation over time (at T = constant)**

43 The reproducibility of the electrical conductivity measurements depends on several factors,  
44 the main ones being listed hereafter:

- 45 - The stability of the temperature
- 46 - The persistence of the sample dimensions
- 47 - The small deformation of the assembly, depending on the pressure steadiness
- 48 - The absence of melt migration
- 49 - The limitation of any chemical reaction of the sample with its surrounding materials

50 In order to (i) examine the stability of the measured conductivity, and (ii) explore a longer  
51 duration to track the melt distribution, one experiment (M523) with the first melt fraction  
52 below the interconnectivity threshold (0.25-0.50%) was performed over 27 hours. The  
53 electrical conductivity decreases by 0.12 log unit over the first 10 hours (Fig. SI 3). The  
54 variation over 27 hours is within to 0.2 log unit. The electrical conductivity is mostly affected  
55 by small variations of the temperature (1319°C +/- 6) over short periods (tens of seconds)  
56 but also by the decrease of the temperature over hours: the average temperature difference  
57 between the first and the last hour is about 6°C. Such a difference may result in the slow  
58 oxidation of the thermocouples, which discredits very long experiment using that setup.  
59 However, the very good reproducibility of the measurements over heating-cooling paths  
60 demonstrates the quality of the data presented in this study and the maximal duration of ~6  
61 hours limits strong variation of the factors listed above.

62



63

64 Fig. SI 3: Time vs. electrical conductivity (log scale) of M523 containing 0.25% of added basalt. The data is plotted  
65 with conductivity at constant temperature measured in some other experiments. The variation is shown in between  
66 the two pairs of vertical arrows during the first 10 hours and during the all experiment (t = 1319°C +/- 6).

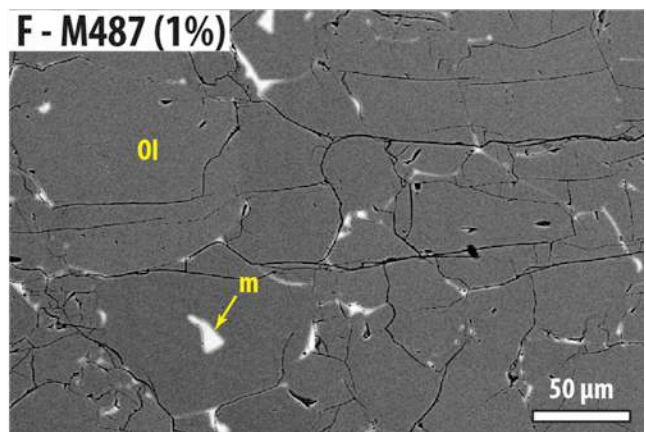
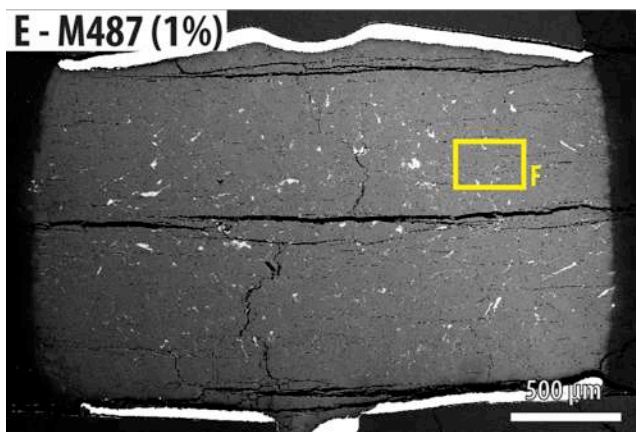
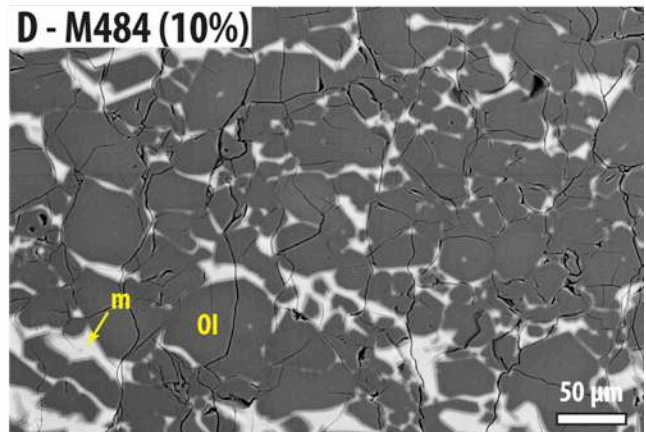
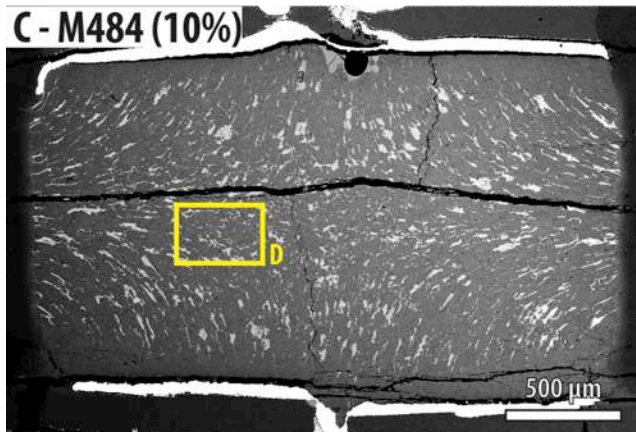
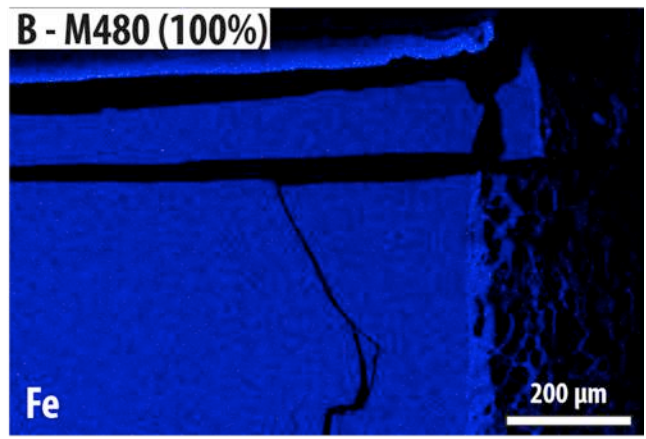
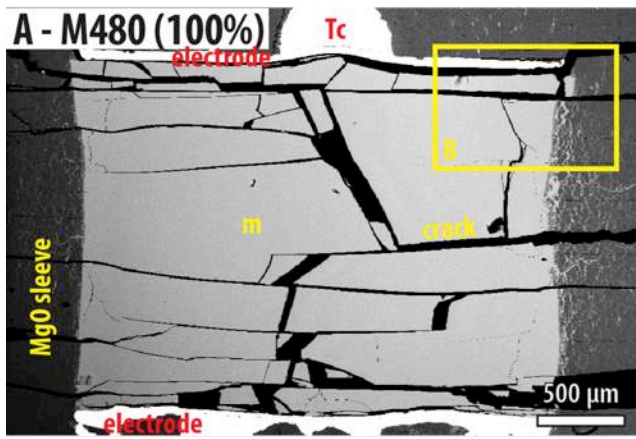
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68 **4. Extension of textural features**

69 **4.1. SEM and chemical mapping illustrations**

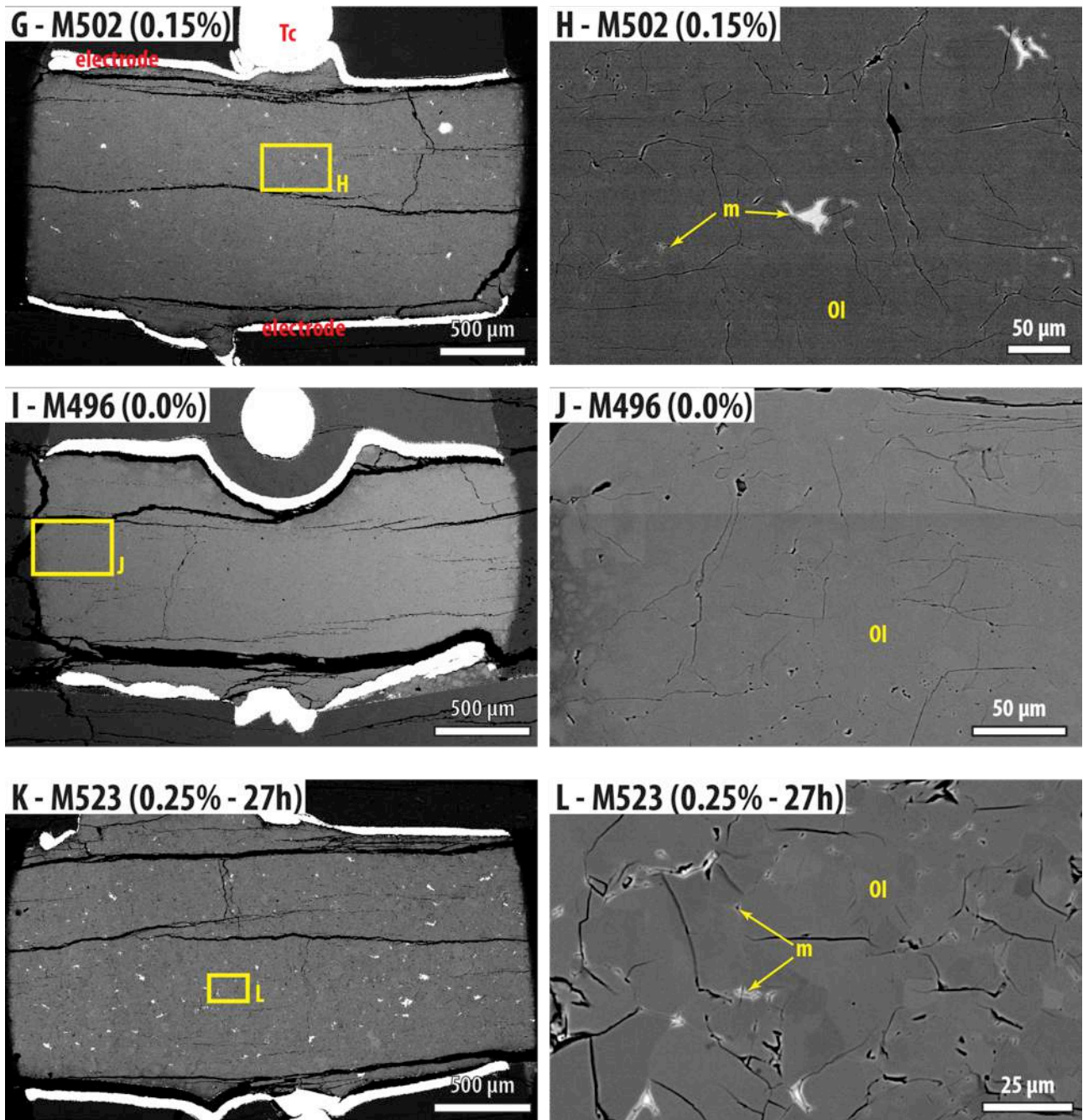
70 Fig. SI 4 shows supplementary SEM pictures illustrating the experiments not presented in the  
71 main text. The sample composed of basaltic melt only preserved its cylindrical shape and  
72 glassy texture, though little amount of melt infiltrated the MgO surrounding sleeve, (Fig. SI  
73 4A). The electrode locally enriched in iron, but the glass still has a homogeneous composition  
74 (Fig. SI 4A). Other pictures shows general view and enlargements of various melt fraction  
75 experiments (Fig. SI 4C to L). Alongside the 2% added basalt experiment, the experiment  
76 involving 10% of basalt also produced a peculiar melt pocket preferred orientation. As  
77 explained in the main text, the orientation parallel to the electrodes should not enhance the  
78 bulk conductivity; on the contrary, such an orientation refers to the parallel model tilted by  
79 90°, providing depleted melt regions and thus, lowering the bulk conductivity normal to the  
80 concentrated-melt planes.



81

82

Fig. SI 4 (to be continued)



83

84 Fig. SI 4: SEM pictures of experiments and chemical mapping of iron in the basaltic glass (B). Tc, ol and m are  
 85 thermocouple, olivine and melt respectively.

86

87

#### 4.2. Electron Backscatter Diffraction (EBSD)

88 The EBSD patterns of sample M502 (0.15%), M488 (0.5%) and M484 (10% of added basalt)  
 89 were acquired on a ZEISS SEM, Leo Gemini 1530 with a Schottky field emission gun employing  
 90 an accelerating voltage of 20 keV and a beam current of about 2.0 -2.5 nA using a 60 mm  
 91 aperture and the high current option. The specimens were placed at 14 to 17 mm working  
 92 distance and we used a step size of 2.6 μm for mapping. The microscope is equipped with a  
 93 NordlysS camera, Oxford, with a CCD resolution of 1344\*1024\*12bit. Acquisition was set to  
 94 0.152 seconds per pattern and good pattern quality was obtained, while having a carbon

95 coating of 3-6 nm thickness. Patterns were captured with 4\*4 binning on the camera, with 8  
96 counts per window averaging, no background removal, minimum camera gain, and no image  
97 processing. Automated indexing routine and analyses was obtained using the software  
98 package CHANNEL 5 by HKL Technology. Automated SEM-EBSD measurements critically  
99 rely on the accuracy of the indexing procedure (Prior et al., 1999). We indexed olivine with  
100 the lattice parameters  $a = 4.756$ ;  $b = 10.207$ ;  $c = 5.98$  and  $\alpha, \beta, \gamma = 90^\circ$ . The reference file  
101 used the 6 strongest reflections of olivine, and no reference for the melt phase. 60-70% of the  
102 points were indexed; which is very good considering melt, cracks and pores are not indexed  
103 using conventional EBSD indexing routines. The reflections were calculated from the  
104 scattering factors of the atoms using the kinematical diffraction theory, even though it is not  
105 strictly fulfilled in this specific diffraction geometry, nevertheless the intensities of the  
106 reflections are approximately correct. In more than 51% of the data points a good solution  
107 was found, the remaining map point were not indexed, partially this is a result of melt and  
108 cracks in the sample. The criteria for rejection a solution and thus not indexing were (1) if less  
109 than 5 reflection bands could be identified, were three non-coaxial bands are considered  
110 sufficient to yield a unique solution; (2) if the mean angular deviation of the calculated  
111 reflection bands in Hough space was larger than  $1.5^\circ$ . The main source of problems arising  
112 from the indexing algorithm is lower indexing success in pseudo symmetric related crystals  
113 across twin boundaries, usually lower indexing rates in on or the other twin-part, and  
114 indexing problems related to overlapping diffraction patterns from two crystals at grain  
115 boundaries, resulting in low confidence and thus no solution. To obtain maps with 100%  
116 indexed data points we would have to assign grain boundary data points to orientations that  
117 are identical to the orientations of the majority of its eight neighbors and thus one or the  
118 other grain. However, due to the presence of a melt phase on some interfaces this is not a  
119 reliable method in the absence of a possibility to “index” the melt phase.

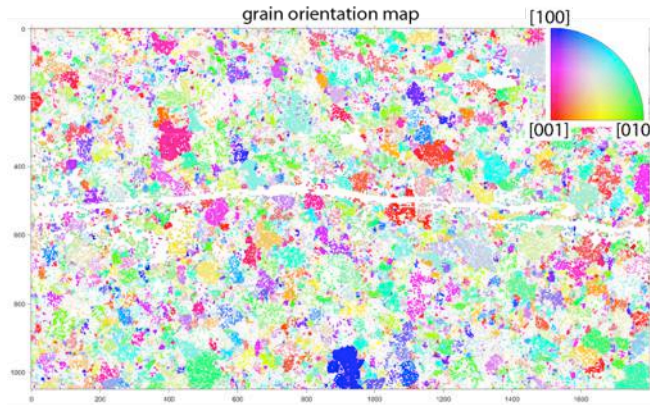
120 Further analyses were done using the MTEX software package written by Ralf Hielscher and  
121 Florian Bachmann (e.g. Hielscher & Schaeben, 2008; Bachmann et al., 2010, 2011). We  
122 corrected for the pseudo symmetry relation of  $60^\circ$  rotation about the [100] axis in olivine and  
123 dilated the grains that had more than 5 connected pixels index that were distributed over  
124 several rows. The raw data and the results are displayed in figure SI 5 using the inverse pole  
125 figure color scheme of the TSL software. Crystal size distributions were calculated using both  
126 software package CHANNEL 5 by HKL Technology and the OIM TSL. The results are very  
127 similar and only the Channelf 5 results are displayed.

128

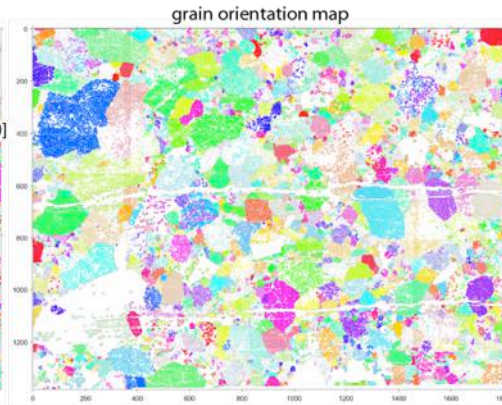
129 **Fig. SI 5 (next page):** EBSD measurement results from samples M502 (column A), M488 (column B), M484 (column  
130 C). In the first row the orientation maps are displayed with respect to the compression direction (see legends),  
131 second row shows the number-weighted grain size distribution as  $\ln(\text{grain size})$ , and the third row highlights the  
132 lattice preferred orientation (LPO) characteristics in pole figures, e.g. stereological projections of the three main  
133 crystallographic axis of olivine in the sample reference frame, where north-south is the compression direction, east-  
134 west is the lineation in the foliation plane. We used a half-width of 10 in the orientation distribution function (ODF)  
135 estimation and the pole figures are projected in equal area, lower hemispheres. The contouring is fixed to a  
136 maximum of multiples of uniform distribution (MUD) of 4, to compare the LPO amongst the samples.

137

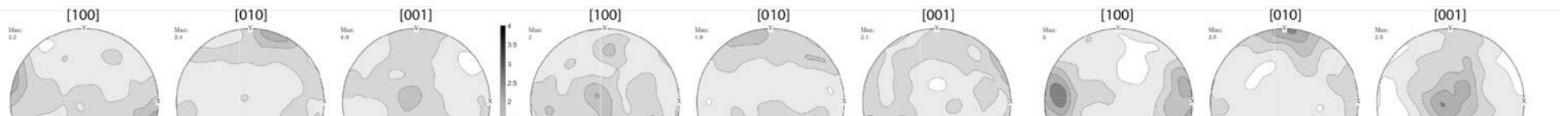
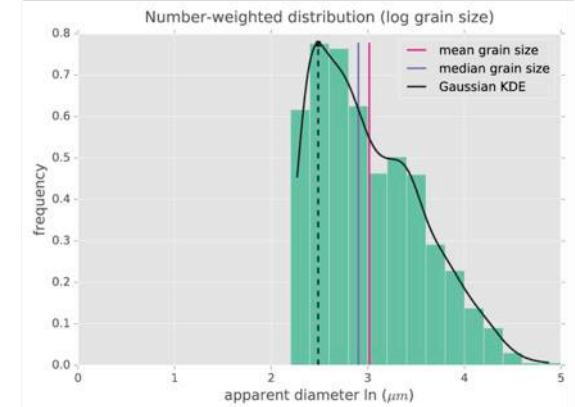
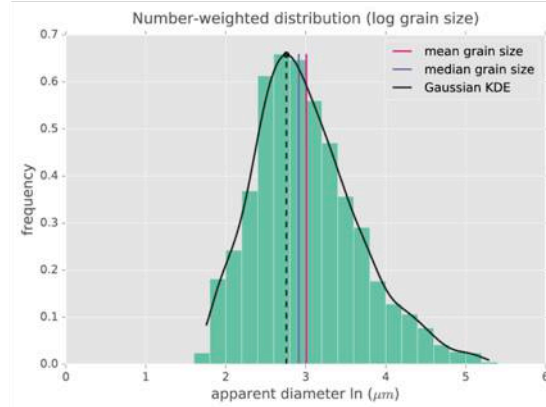
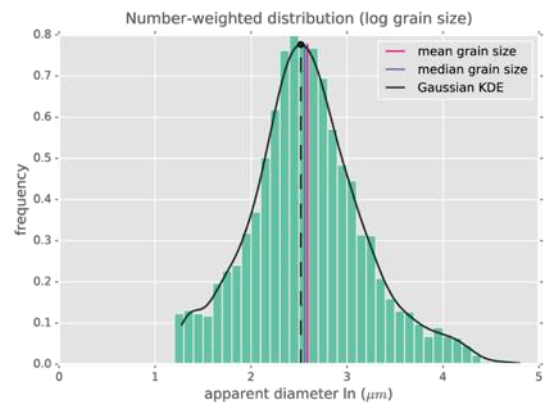
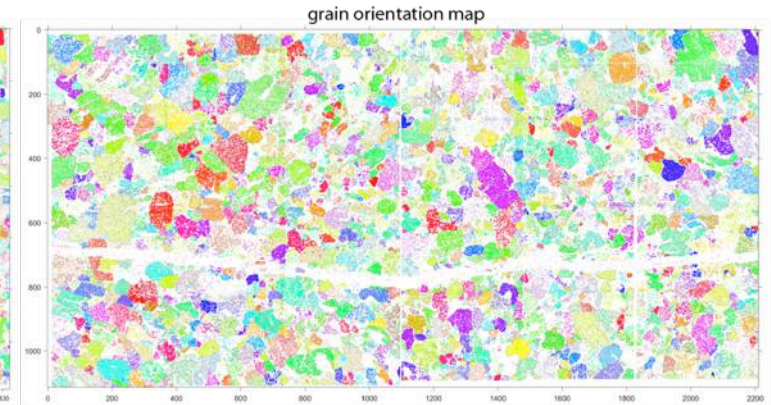
**A) M502 (0.15% melt)**



**B) M488 (0.5% melt)**



**C) M484 (10% melt)**

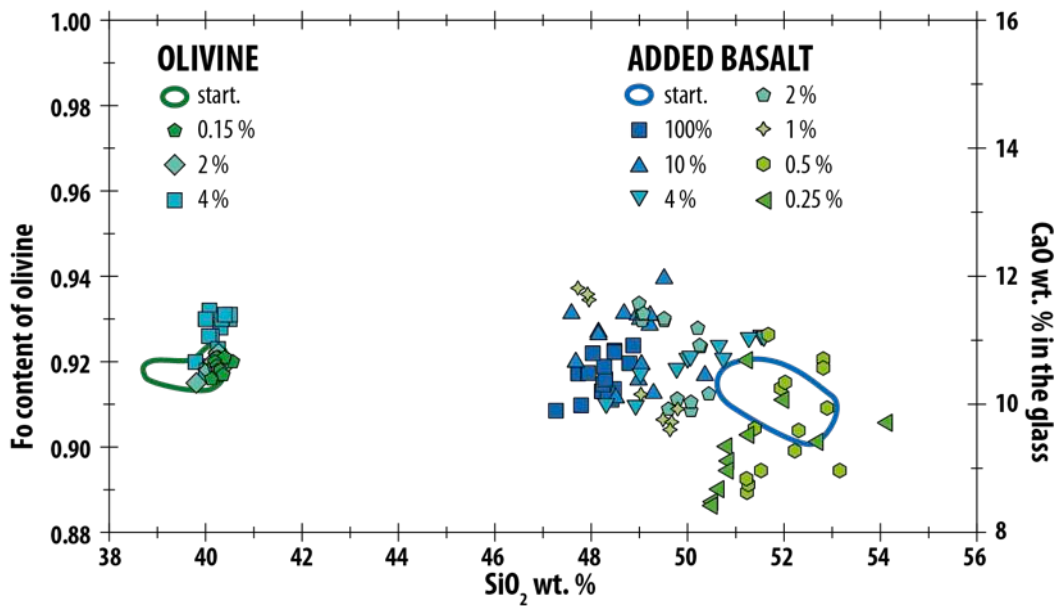


139 **5. Chemical composition of olivine and the glass**

140 Major elements

141 The variation of the chemical composition is more important for the melt than for olivine (Fig.  
142 SI 6; Table 1). The CaO concentration decreases with the SiO<sub>2</sub>, and tends to increase with the  
143 melt fraction. However, there is no clear evidence for a relationship between the melt fraction  
144 and the CaO (nor other element) in the melt. Such a trend supports the idea of limited melting  
145 of olivine since the lowest melt fractions would diverge the most from the starting basalt by  
146 dilution of olivine elements.

147



148

149 Fig. SI 6: Fo content (molar Mg - Fe ratio) of olivine and CaO concentration in the glass of various experiments.

150

151

152 Extension on Secondary Ions Mass Spectrometer measurements

153 The water content was measured using the Cameca IMS 1280HR of the SwissSIMS laboratory  
154 of the University of Lausanne (Switzerland). To minimize the water background in the  
155 machine, samples were mounted in indium, altogether with a reference material.

156 A 10kV Cs<sup>+</sup> primary beam was used with a ~1.5 nA current. This resulted in a typical spot size  
157 of ~10 μm by few microns deep. The electron flood gun was used to compensate surface  
158 charge. <sup>16</sup>OH and <sup>16</sup>O secondary ions were accelerated by 10kV and analysed at a mass  
159 resolution of 5000 on a faraday cup sets with 10<sup>11</sup> Ω resistor and an electron multiplier, in  
160 multi-collection mode (slit 2 of multicollection and entrance slits closed at 61μm). This  
161 resolution allows to resolve <sup>17</sup>O from <sup>16</sup>OH. The detectors were calibrated in the beginning of  
162 the session. Before each measurement, the surface was cleaned using a 25μ rastered pre-

163 sputtering beam, during 240 seconds. Each analysis took about 9 minutes, including the pre-  
164 sputtering and automated centring of secondary ions in field and contrast apertures.  
165 Mass calibration was performed at the beginning using basaltic glassy reference material with  
166 a composition similar to the one used for EC experiments, and with different water  
167 concentration (All107-D20, NS-1 and ALV519-4-1; [Helo et al., 2011](#)). A synthetic forsterite  
168 containing less than 100 ppm of water was used to monitor the instrument background for  
169 water. Those 3 glassy reference materials have major element compositions similar to the  
170 glasses from this study. The reference materials are all included in an indium mount, distinct  
171 from the indium mount containing the unknowns. Reproducibility of the reference material  
172 varies from 1 to 4 relative % (2SD).  
173 To be able to compare the unknown data with the reference material, a BHVO glass reference  
174 material (USGS Standard) has been included with the reference material and the unknown.  
175 BHVO, although not characterized for water, is also a basaltic glass and in quantity large  
176 enough to be included in both mount. Reproducibility on repeated 4 measurements on BHVO  
177 is ~2% (2SD). The  $^{16}\text{OH}/^{16}\text{O}$  ratio of BHVO has been compared between mounts.  
178 A block of 4 analyses of BHVO was measured every 7 to 12 analyses to monitor the  
179 instrument stability. A linear drift has been observed and corrected for.  
180

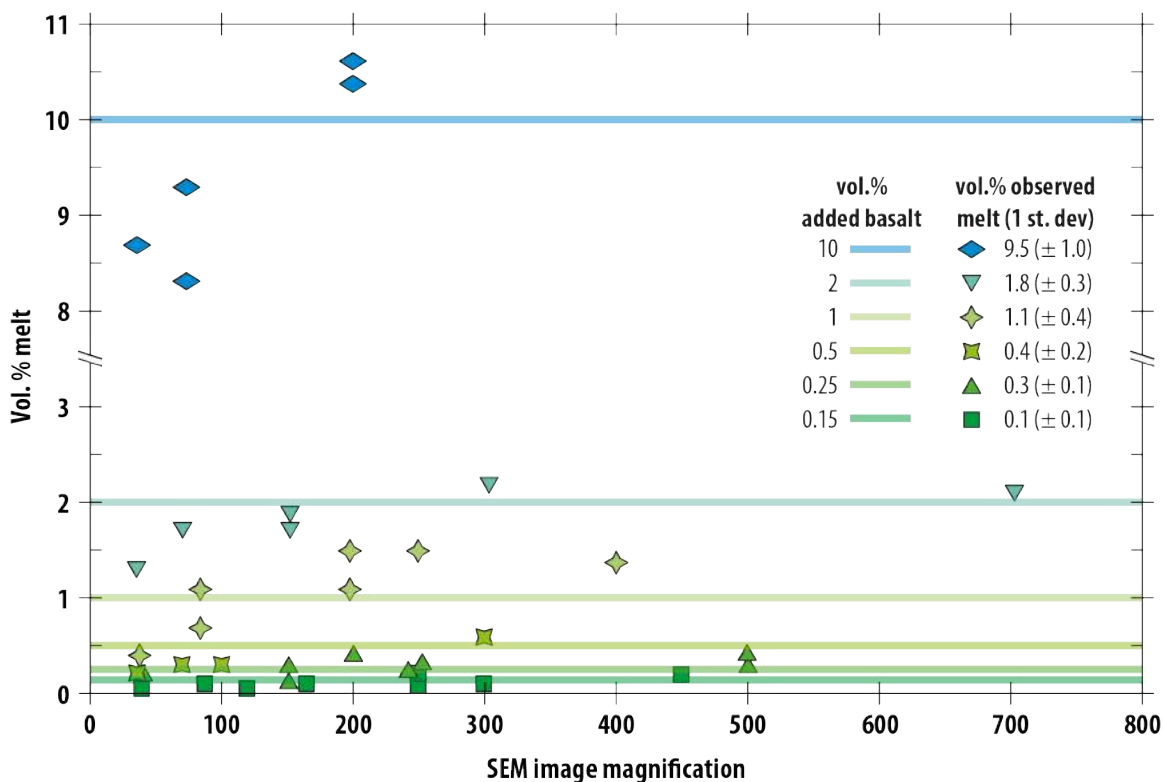


181 **6. Determination of the melt fraction**

182 Post-mortem glass fractions were measured from SEM pictures with various magnifications  
183 (Fig. SI 7). A black and white threshold was applied on the pictures and the respective 2-D  
184 fractions of solid and glass were calculated using the software SPO2003 (Launeau, 2004). No  
185 correction from 2-D to 3-D was used.

186 The averaged fraction of glass is very similar to the initial fraction of basalt, though it depends  
187 on the magnification of the pictures. At low magnification (< 150x), the melt fraction is  
188 underestimated, probably due to the difficulty to detect the small glass features (tubes,  
189 pockets). At higher magnification (> 150x), the fraction of glass is sometimes higher than the  
190 initial fraction because of the presence of pockets that locally increase the glass fraction. Due  
191 to the difficulty to precisely assess the post mortem fraction of glass, in particular at the  
192 lowest fractions, the initial proportion of added basalt is preferred in the following of the  
193 discussion.

194



195

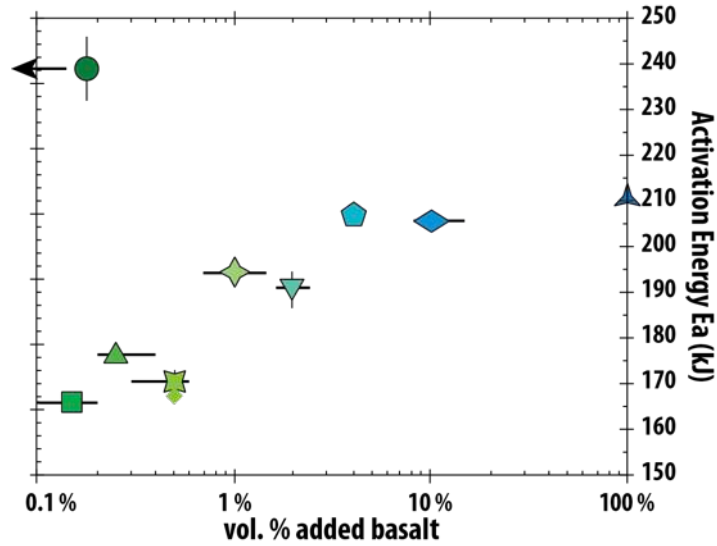
196 Fig. SI 7: proportion of melt (in volume %) determined texturally after experiments on pictures with various  
197 magnification (symbols) and initial proportions of melt (lines) determined by mass of basalt added to olivine during  
198 sample preparation (described in section 2.1 of the main text).

199

200 **7. Activation Energy and influence of the melt in the olivine-only aggregate**

201 The activation energy  $E_a$  is plotted against the fraction of the added basalt (Fig. SI 8). The  $E_a$  of  
202 samples containing basalt decreases with the fraction of the added basalt, whereas the  $E_a$  of

203 the olivine-only sample is significantly higher. These observations suggest that although the  
204 melt looks disconnected in the low (0.15 and 0.25%) melt fraction sample, the bulk  
205 conductivity is governed by the melt. Also, the high  $E_a$  of the olivine with no added melt  
206 compared to the ones of melt-bearing aggregate supports the absence or the presence in low  
207 ( $\ll 0.15\%$ ) proportions of melt in the run with no added melt (M496).

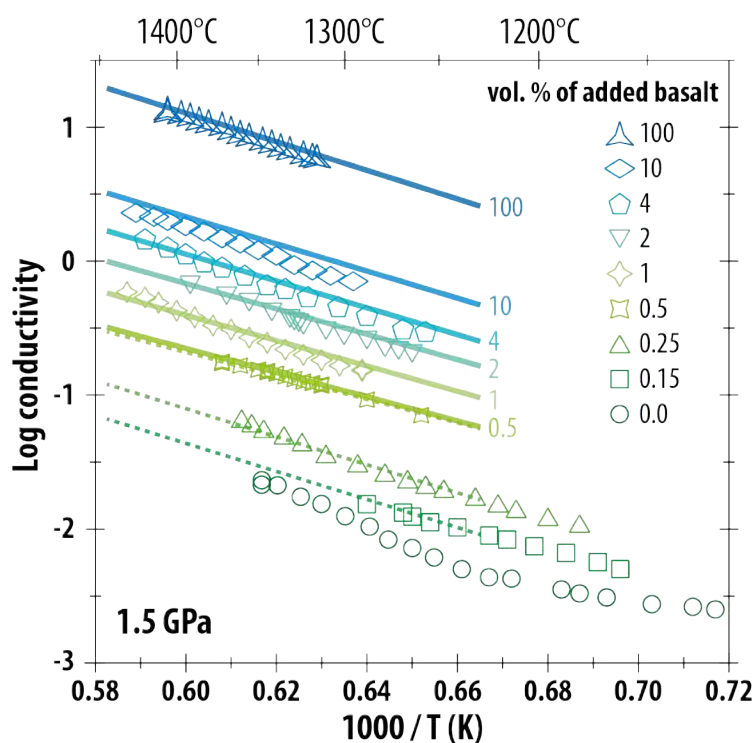


208  
209 Fig. SI 8: fraction of added basalt vs. Activation Energy. The error on the melt fraction determined texturally is  
210 represented by black bars.  
211

212

## 213 8. Fit of the global model of melt-bearing olivine aggregate

214 The model of melt-bearing olivine aggregate is plotted against the reciprocal temperature for  
215 melt fraction corresponding to experiments according to Equation 3 and using the fitting  
216 parameters  $a$  to  $d$  from 100% to 0.5 vol.% of added melt (lines on Fig. SI 9) and using the  
217 fitting parameters  $a'$  to  $d'$  from 0.5 to 0.15 vol.% of added melt (dotted lines on Fig. SI 9). It  
218 reproduces the experimental data very closely except for the 10 % melt fraction experiment  
219 that lies slightly below the model (Fig. SI 9). Such a difference could result in the anisotropic  
220 melt distribution perpendicular to the shortest electrical path between the electrodes (Fig. SI  
221 4C). When applying this model, one must pay attention to the temperature-melt fraction pair,  
222 in particular at low melt fraction and high temperature.



223

224 Fig. SI 9: Arrhenius plot of the general model of the partially-molten olivine aggregate (lines and dotted lines)  
225 compared with experimental data (symbols) obtained at 1.5 GPa.

226

227

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230

231

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