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# **“SIGMELTS”: A WEB PORTAL FOR ELECTRICAL CONDUCTIVITY CALCULATIONS IN GEOSCIENCES ★**

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★ Available at <http://www.calcul.isto.cnrs-orleans.fr/sigmelts/>

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## **Abstract**

Electrical conductivity measurements in the laboratory are critical for interpreting geoelectric and magnetotelluric profiles of the Earth's crust and mantle. In order to facilitate access to the current database on electrical conductivity of geomaterials, we have developed a freely available web application (SIGMELTS) dedicated to the calculation of electrical properties. Based on a compilation of previous studies, SIGMELTS computes the electrical conductivity of silicate melts, carbonatites, minerals, fluids, mantle materials as a function of different parameters, such as composition, temperature, pressure, water content, oxygen fugacity. Calculations on two-phase mixtures are also proposed using existing mixing models for different geometries. An illustration of the use of SIGMELTS is provided, in which calculations are applied to subduction zone related volcanic zone in the Central Andes. Along with petrological considerations, field and laboratory electrical data allow discrimination between the different hypotheses regarding the formation and rise from depth of melts and fluids and to quantify their storage conditions.

**Keywords:** electrical conductivity, database, laboratory measurements, geoelectrics, magnetotellurics.

## 1. Introduction

In the past twenty years, substantial improvements in the magnetotelluric (MT) method have allowed detection of numerous conductivity anomalies in the Earth's crust and mantle. These anomalies have been typically attributed to the presence of partial melt and fluids (e.g., Ingham, 1988; Jödicke et al., 2006; Baba et al., 2006; Wannamaker et al., 2008). Deep geoelectrical soundings are a robust tool to investigate the mechanisms of melt and fluid formation at depth (e.g., Evans et al., 2002; Brasse and Eydam, 2008). The distinction between silicate melts, carbonatites or aqueous fluids as well as the determination of their storage conditions (P, T, composition, melt or fluid fraction) requires the use of electrical measurements in laboratory (Pommier et al., 2010c). Several laboratory studies have investigated the dependence of the electrical properties of magmas and mantle materials as a function of different parameters, such as composition, temperature, pressure, water content and oxygen fugacity (e.g., Tyburczy and Waff, 1983, 1985; Satherley and Smedley, 1985; Gaillard, 2004; Huang et al., 2005; Pommier et al. 2008, 2010a,b; Wang et al., 2006; Yoshino et al., 2008). Although there are examples of where the laboratory data have been used to interpret field data (e.g., Tarits et al., 2004; Evans et al., 2005; Jödicke et al., 2006; Brasse and Eydam, 2008; Wannamaker et al., 2008; Jones et al., 2009; Pommier et al., 2010c), there are also many instances where there are disconnects between those interpreting field MT data and the laboratory results. A solution to compensate for this problem is to make these laboratory data more accessible for the geophysical community. In this contribution, we present a freely available and easy-to-use web application (SIGMELTS) allowing the calculation of the electrical conductivity of geomaterials at relevant conditions for the Earth's crust and

mantle. By compiling previous results of electrical measurements in laboratory, this software enables to discriminate between the effect of different parameters on the bulk conductivity of silicate melts, carbonatites, fluids, minerals and mantle materials, such as the temperature (T), the pressure (P), the composition, the water content, the oxygen fugacity ( $fO_2$ ) and the crystal content. Different existing geometrical models are proposed to calculate the bulk conductivity of a two-phase mixture. Based on the electrical resistivity ( $=1/\text{electrical conductivity}$ ) value of a mantle anomaly, an application has been developed in order to determine the corresponding melt fraction at defined conditions (T, P, composition). Calculations using SIGMELTS are finally applied to a subduction context, this illustration underlining the importance of coupling laboratory measurements and petrological considerations to interpret field data.

## **2. Software elaboration and computing details**

SIGMELTS is a client-side only web application written in JavaScript. As such all the computations and plotting are done within the browser. It relies on the jQuery framework for the interface (<http://jquery.com/>) and the Flotr library for the plots (<http://solutioire.com/flotr/>). The interface is articulated around several tabs for each type of computation and enforces the limitations of the models implemented (e.g. bound checking and mandatory parameters dynamically depend on the composition of the material considered). This allows an immediate, without a-priori learning, use of the software. The application is implemented as a template-instantiating engine: the complete data and logic of each tab is stored in a structure that is fed to a generic function generating the HTML tree and the Javascript functions

needed. Adding a new tab boils down to adding a new data structure to the main Javascript file. The source code is released under the MIT license.

Seven tabs presently compose SIGMELTS. Five of them are dedicated to the computing of the electrical conductivities of silicate melts, carbonatites, common minerals, crustal fluids and mantle materials at defined conditions. Two examples of these tabs are presented in Figure 1a and 1b. The user can change the values of the input parameters (e.g., T, P, composition) in a range that is in accordance with the experimental conditions of previous studies (valid range). It can happen that the proposed valid range for a parameter exceeds the range of the previous experimental studies, since some relevant conditions for the Earth materials have not been investigated in experimental studies (e.g., very high water contents in silicate melts). In this case, it is clearly specified to the user that an extrapolation is performed. When it is inevitable, the user is invited to define the input parameter among a restricted range of possibilities in a pop-up menu (e.g., Composition parameter in “Mantle” tab, Figure 1b). The computed output value corresponds to the electrical conductivity of the geomaterial at the defined input values. The visualization of results in a plot is possible. The sixth tab is dedicated to geometrical considerations and calculates the bulk electrical conductivity of a two-phase mixture using different existing models. The seventh tab, called “**Melt fraction estimation**”, is presented in Figure 1c. In this case, the output value is the melt fraction stored in depth (mantle) that corresponds to the bulk electrical value of an MT anomaly entered by the user.

We draw the attention of the user on the fact that conductivity calculations at disequilibrium can be done and that it is on the responsibility of each user to properly define the parameters values, by referring to thermodynamic models based on phase equilibria for igneous systems (e.g. MELTS, Ghiorso and Sack, 1995).

### 3. The electrical conductivity of geomaterials

#### 3.1. Silicate melts

The presence of magma chambers, deep magma sources and zones of partial melt in the Earth's crust and mantle makes molten silicates the most obvious candidates to explain high conductivity anomalies at depth. In SIGMELTS, the electrical conductivity of silicate melts is calculated after the model of Pommier et al. (2008). Input parameters are T, P, Na<sub>2</sub>O and water contents (Figure 1a). Oxygen fugacity is not considered since its effect on the conductivity of silicate melts can be neglected to a first approximation (Waff and Weill, 1975; Pommier et al., 2010a). An example of calculations is shown in Figure 2. The semi-empirical model of Pommier et al. (2008) is based on the Arrhenian dependence of the electrical conductivity of silicate melts to the temperature:

$$\sigma = 1/\rho = \sigma_0 \cdot \exp(-(E_a + P \cdot \Delta V)/R \cdot T) \quad (1)$$

with  $\sigma$  the electrical conductivity (ohm.m)<sup>-1</sup>,  $\rho$  the electrical resistivity (ohm.m),  $\sigma_0$  the pre-exponential factor (ohm.m)<sup>-1</sup>,  $E_a$  the activation energy (J/mol),  $P$  the pressure (MPa),  $\Delta V$  the activation volume (cm<sup>3</sup>/mol),  $R$  the universal gas constant (8.3143 mol<sup>-1</sup>.K<sup>-1</sup>) and  $T$  the temperature (K). The activation energy is obtained using the Anderson-Stuart model (Anderson and Stuart, 1954; Nascimento and Watanabe, 2007) modified to include the effect of the Na<sub>2</sub>O and water contents (up to 6wt%H<sub>2</sub>O) of the melt (Pommier et al., 2008). The pre-exponential term is determined using the following general compensation law:

$$\ln \sigma_0 = (E_a/17853) + 3,65 \quad (2)$$

This model works well for water contents <6wt%, this being the maximum experimentally investigated value but is mathematically, but is not adapted for much higher water contents. For water contents >6wt%, the following equation is used to determine the activation energy (Gaillard, 2004):

$$E_a = -2925 \cdot \ln(H_2O) + 64132 \quad (3)$$

Where  $H_2O$  is the water content in wt%. Even if this simple equation does not include a compositional parameter, it reproduces the  $E_a$  of the two datasets on compositionally different hydrous melts (hydrous rhyolite (data up to 3wt%  $H_2O$ , Gaillard, 2004), and hydrous phonolite (data up to 6wt%  $H_2O$ , Pommier et al., 2008)).

Results from the model were compared to results from previous studies (Waff and Weill, 1975; Rai and Manghnani, 1977; Tyburczy and Waff, 1983, 1985; Gaillard, 2004; Pommier et al., 2008, 2010b). The experimental data from previous studies are reproduced with a difference less than 0.5log-unit (except for (1) some samples from Rai and Manghnani, 1977: the conductivity of C50, C90 and C214 samples on the whole T range, of C8 and C222 melts above 1200C and of C42 melt below 1200C is reproduced with a difference that ranges between 0.8 and 1.7 log-units and (2) samples 70-15 and PG16 from Waff and Weill, 1975). The largest discrepancies between experimental and modeled data regard studies that did not use impedance spectroscopy (Waff and Weill, 1975; Rai and Manghnani 1977) and for which an important effect of electrodes probably affected the electrical measurements (Pommier et al. 2010b). These discrepancies are not attributed to a problem of composition effect inherent to our model. For example, both Rai and Manghnani, 1977 and Tyburczy and Waff, 1983 measured the conductivity of the basaltic melts and the data of Tyburczy and Waff are well reproduced with our conductivity model (difference less than 0.3log-unit) (cf Figure 2a).



The compositional parameter considered in the calculations is the Na<sub>2</sub>O content, in agreement with the fact that the electrical conductivity of natural silicate melts (silicic to basaltic) is essentially controlled by sodium mobility (Waff and Weill, 1975; Gaillard, 2004; Pommier et al., 2008). Actually, as demonstrated in Pommier et al. (2008), there is good agreement between the activation energy  $E_a$  derived from Na diffusion and the one derived from electrical conductivity measurements. Being more voluminous than sodium, potassium is expected to diffuse with a slower rate in the melt (usually,  $D_{Na} \sim 10 \cdot D_K$  is taken, Chakraborty, 1995) and the determination of the contribution of each potential charge carriers showed that the contribution of K to the bulk conductivity can be neglected in the modeling of the electrical response of the sample (Pommier et al., 2008). The maximum sodium content in the existing dataset of conductivity measurements is less than ~8wt%. In SIGMELTS, calculations with a sodium content up to 10wt% are authorized. The Na<sub>2</sub>O range allows the estimation of the conductivity of alkali-rich melts. At 1200°C, the conductivity of a dry melt containing 2.29 wt%Na<sub>2</sub>O is ~3times lower than the conductivity of a dry melt containing 6.11wt%Na<sub>2</sub>O (Figure 2). As shown in Figure 2, the increase in the electrical conductivity of silicate melts with water becomes significant for melts containing more than 4wt%H<sub>2</sub>O. Because it has been demonstrated that silicate melts can store very high amounts of water at depth (up to 30wt%H<sub>2</sub>O, Gaetani and Grove (2003)), the valid range of values for the H<sub>2</sub>O content parameter has been extended to 30wt%. However, the user should be aware that for water contents exceeding about 6wt%, the absence of experimental data does not allow us to implement a correction to the conductivity model.

### 3.2. Carbonatites

The presence of molten carbonates (carbonatites) and their probable critical role as part of upper mantle melting process have been suggested in several studies (e.g. Dasgupta and Hirschmann, 2006; Dasgupta et al., 2007; Frost and McCammon, 2008; Gaillard et al., 2008). The very high electrical conductivity of carbonatites, presented in Figure 3, imply that many deep conductive magnetotelluric anomalies can possibly be explained by only a small amount of molten carbonates (Gaillard et al., 2008). In SIGMELTS, calculations of the electrical conductivity of carbonatites consist in the Arrhenius equations determined at 1bar by Gaillard et al. (2008). Calculations predict a decrease in the electrical conductivity of carbonatites of about one order of magnitude between 1 and 10GPa (Supporting online material in Gaillard et al., 2008). The parameters considered in SIGMELTS are the carbonatite composition and the temperature. Because of the absence of a general trend relating the conductivity of a carbonatite to its chemical composition, the input value for the composition parameter consists in choosing a defined carbonatite composition among six possibilities (pop-up menu). As shown in Figure 3, the very high conductivity of carbonatites is clearly observed on the whole investigated T range: from 800 to 1400°C, the conductivity of a carbonatite melt is at least ten times higher than the conductivity of a basaltic melt containing 10wt% H<sub>2</sub>O.

### *3.3. Crustal and mantle fluids*

Fluid resistivities are sensitive to composition (salinity), pressure and temperature (Nesbitt, 1993). The knowledge of the electrical behavior of fluids as a function of these parameters is critical to understand geodynamical processes. For instance, it could predict the conditions of fluid release and rise following subduction-related metamorphism. Owing to their extremely high conductivity, mineralized

water (brines) circulating in pores and fractures are probably the main fluid conductors. COH fluid components other than water are not supposed to contribute much to the bulk conductivity (e.g., Jödicke et al., 2006). However, experimental data are needed to confirm this statement.

While electrical data on fluids are critical to characterize high conductive MT anomalies, only a few studies of the electrical conductivity of fluids (gas and liquids) have been conducted at different T and P relevant for the Earth's interior (Quist and Marshall, 1968; Holzapfel, 1969; Nesbitt, 1993; Xu et al., 1997). The effect of a gas phase (e.g. CO<sub>2</sub>) on the conductivity of a silicate magma has not been quantified, to our knowledge. The presence of a water vapour phase in a silicate melt was found to decrease the measured electrical conductivity (Pommier, unpublished data). Two main reasons explain the experimental difficulty for measuring the electrical conductivity of a fluid phase at different T and under P: 1) the difficulty for holding the fluid in the conductivity cell during the experiment (flow out from the cell due to its low-viscosity) and 2) the changes of state affecting the sample under defined (P, T) conditions, such as the complete miscibility of two phases to form one supercritical phase. Based on the existing database of the electrical response of fluids at (T, P), we propose to calculate the conductivity of the following liquids: NaCl aqueous solution between 1473 and 1673K and at 0.1MPa (Quist and Marshall, 1968), KCl aqueous solution between 373 and 737K and at 100 or 300MPa (Nesbitt, 1993) and water between 473 and 1073K and in the P range [100; 400MPa] (Holzapfel, 1969). Because of the absence of a general model relating the electrical conductivity of each type of fluid to temperature, pressure and to the concentration of the aqueous solution (for NaCl and KCl solutions), the P and concentration parameters are proposed in a

restricted range of values in pop-up menus. For each P and composition, the dependence of the conductivity to the temperature is calculated using empirical polynomial regressions ( $r^2 > 0.90$ ).

### *3.4. Mantle materials*

The electrical conductivity of the Earth's mantle has been widely investigated and numerous electrical measurements have been conducted on olivine and other mantle materials (see the reviews of Tyburczy, 2007 and Yoshino, 2010). Depending on the mantle material composition, different models have been proposed (Table1) and are based on the Arrhenian dependence of the conductivity to the temperature:

- the models by Constable (2006) (SEO3 model) and Wanamaker and Duba (1993) for dry olivine conductivity. **Note that the SEO3 model does not take into account the effect of anisotropy in hydrous olivine and that measurements of Wanamaker and Duba (1993) were performed in the [100] crystallographic direction only,**

- the models of Wang et al. (2006), Yoshino et al. (2006) **and Poe et al. (2010)** for the wet olivine conductivity,

- the models of Hinze et al. (1981) and Dai and Karato (2009a) for the conductivity of pyroxenes,

- the model of Wang et al. (2008) for the conductivity of dry and hydrous dunite, pyroxenite and lherzolite,

- the models of Huang et al. (2005) and Yoshino et al. (2008) for both the ringwoodite and wadsleyite conductivities and Romano et al. (2009) for hydrous wadsleyite conductivity,

- the model of Katsura et al. (1998) for the perovskite.

An additional model that calculates the conductivity of metamorphic mantle is presented and is based on the experimental measurements of Xie et al. (2002) on a serpentinite (Table 1). In agreement with the experimental conditions in the previous studies, the input parameters for the calculations of the conductivity of mantle materials in SIGMELTS are the composition, the temperature, the oxygen fugacity and the water content.

As shown in Figure 4, the difference in conductivity values for the same mantle composition using two different models can reach more than 1log-unit. Anisotropic signatures of the principal crystallographic directions in olivine (e.g. DuFrane et al., 2005) can explain differences in olivine conductivity models. Regarding the other mantle materials, a probable explanation for inconsistencies between some laboratories lies in the difficulty to conduct careful electrical measurements at high pressure. Pressure effect on the conductivity of a mantle material was found to be weak and negligible (Xu et al., 2000). Thus, pressure is not explicitly part of the input parameters. However, because each mantle material has a defined stability field (in the order of peridotite (olivine)>wadsleyite>ringwoodite>perovskite with increasing depth, e.g. Yoshino, 2010), choosing a mantle composition in the input parameters implies consideration of a particular range of pressures (Table 1).

### *3.5. Minerals and partial melt*

The effect of the electrical conductivity of minerals can be significant in the case of partially to very crystallized magmas. In SIGMELTS, the electrical conductivity of common minerals found in lavas is calculated in an individual tab. Input parameters are the mineral type (choices within a pop-up menu) and the temperature. Calculations are based on previous studies of Tyburczy and Fisler

(1995) and references therein, Nell et al. (1989), Romano et al. (2006) and Dai and Karato (2009b). Several measurements on partially crystallized melts have been conducted (Scarlato et al., 2004; Poe et al., 2008). However, since the crystal content is not monitored (and thus precisely quantified) during these experiments, such studies have not led to models linking the bulk electrical conductivity to the crystal fraction. As a result, geometrical models of two-phase materials (see section 3.6.) are usually used to estimate the bulk conductivity of a partially crystallized silicate melt (Gaillard and Iacono-Marziano, 2005; Pommier et al., 2008). Even if these models consider that melt and crystals are two independent phases, they can be used as a first approximation. Actually, the possible effect on the electrical conductivity of chemical interactions between crystals and liquid phases is probably negligible compared to the charge carrier contribution.

### *3.6. Geometrical considerations*

The association of two materials of different conductivities is very common in geological contexts, underlining the need to develop models that can calculate the bulk conductivity value of a two-phase mixing material. A partially molten mantle, and regions containing either a brine (e.g. a saline aqueous solution interconnected in porous sediments) or magma (liquid, crystals (and gas)) are examples of multi-phase materials.

Because the fluids we are considering are typically orders of magnitude more conductive than their host rock, the effect of the geometrical arrangement of the fluid on the bulk electrical conductivity of two materials is critical (Figure 5). Based on geometrical considerations, several two-phase mixing models have been proposed (e.g., Glover et al., 2000; Ten Grotenhuis et al., 2005) and SIGMELTS proposes to use

the most common formalisms, which are the Hashin-Shtrikman (HS) bounds (Hashin and Shtrikman, 1962), the modified Archie's law (Glover et al., 2000), the cube model (Waff, 1974) and the tube model (Schmeling, 1986). Another model accounts for completely wetted grain boundaries (valid for melt or liquid fraction <15% and  $\sigma_{\text{melt or fluid}} \gg \sigma_{\text{solid matrix}}$ ) (Waff, 1974; Schmeling, 1986).

The two-phase mixing model used to calculate the melt fraction in the MT anomaly interpretation tab is the HS upper bound. Note that a phase mixing model that would consider isolated pockets of melt in a more resistive matrix (e.g., HS lower bound) is not adapted in that context. Indeed, unconnected melt would not noticeably increase the bulk conductivity (Sato and Ida, 1984; Roberts and Tyburczy, 1999; ten Grotenhuis et al., 2005) and thus would be undetectable by MT measurements (Simpson and Bahr, 2005).

#### **4. Application to a subduction-related volcanism context**

MT techniques represent a reliable means of investigating mantle melting processes associated with subduction (see Evans et al., 2002 for a discussion). In this section, we consider the data recorded by Brasse and Eydam (2008) in the subduction-related volcanism zone in Central Andes. This model is taken at face value and potential issues of resolution of sensitivity of the data to particular features are not considered here. As shown in Figure 6a, several structures have been resolved in their study through inversion. The resulting resistivity model contains a main conductive body located between 70 and >140km depth with arm-shaped extensions reaching into the lower crust below the central Altiplano (also cf Figure 8 in Brasse

and Eydam (2008)). This conductive anomaly is likely to correspond to a partially molten asthenospheric wedge associated with rising melt and fluids, in accordance with the low densities detected at a similar location in the gravimetric study of Tassara et al. (2006). A possible interpretation of the conductivity model of Brasse and Eydam (2008) in Central Andes using SIGMELTS calculations and petrological constraints is presented in Figures 6b and 6c.

In this attempt to combine petro-chemistry and electrical conductivity, the main parameter to define is unquestionably the temperature, since one of the first order controls on Earth's conductivity with increasing depth is its thermal structure. Calculations presented below are performed at temperatures that are in agreement with the thermal models of subduction zone (e.g. Schmidt and Poli, 1998). Once temperature is constrained, other parameters, especially composition, can be considered.

The subducted slab presents an increase in the conductivity with depth, from  $\sim 10^{-3}$  to  $1(\text{ohm.m})^{-1}$  (Brasse and Eydam, 2008; captions ① and ② in Figures 6a and 6b). The highest conductivities at the top of the slab are probably caused by fluid circulation. The bottom part of the extremity of the slab, close to the mantle wedge, displays lower conductivities ( $<0.01(\text{ohm.m})^{-1}$ , caption ② in Figures 6a and b). Thermal models display a temperature range for the upper part of the slab of  $\sim 400$ - $800^\circ\text{C}$ . Experimental studies show that, at these T, conductivities  $<0.01(\text{ohm.m})^{-1}$  are in agreement with a metamorphic mantle (serpentinite at 2.5 and 3.5 GPa and T  $<\sim 650^\circ\text{C}$  (Xie et al., 2002) and serpentinized rocks at 50-250MPa (Stesky and Brace, 1973))(Figure 6a). For comparison, peridotite (olivine) is more resistive and would



require  $T > 1200^{\circ}\text{C}$  to match with a conductivity value of  $0.01(\text{ohm.m})^{-1}$  (Constable, 2006; Wanamaker and Duba, 1993).

The main conductor, located between 70 and  $>140\text{km}$  depth (captions ③ and ④ in Figures 6a and 6b), presents a heterogeneous conductivity, the core being more conductive than the outline. Here, we make the hypothesis that this heterogeneity regards the electrical properties of the material rather than a resolution issue of the field data. The conductivity of the core of this anomaly ranges between 0.1 and  $1(\text{ohm.m})^{-1}$  (so-called Structure D in Brasse and Eydam, 2008). Phase equilibrium relationships of magmas and peridotite as well as thermal models showed that melting in the mantle wedge was found to occur at a minimum  $T$  of  $1300^{\circ}\text{C}$  (Schmidt and Poli, 1998 and references therein). At  $1300^{\circ}\text{C}$ , the electrical conductivity of a dry alkali basalt (MORB-type) at 1atm is  $\sim 2.2(\text{ohm.m})^{-1}$  (Rai and Manghnani, 1977; Pommier et al., 2010). If the dependence of the conductivity to the pressure is taken into account and extrapolated to 3GPa (activation volume of  $20\text{cm}^3/\text{mol}$ , Pommier et al, 2008), the conductivity decreases to  $0.62(\text{ohm.m})^{-1}$  at 3GPa. This value is in agreement with the conductivity range of the detected anomaly. However, these calculations consider pure melt fraction (i.e. all molten). If we consider partial melting (i.e. the presence of melt interconnected in a more resistive mantle-matrix), the conductivity significantly decreases. Actually, the solid matrix is more resistive and its conductivity is assumed to range from 0.01 to  $0.005(\text{ohm.m})^{-1}$ , according to Brasse and Eydam (2008)). For a melt fraction of 10vol.%, the bulk conductivity (melt + solid matrix) is only  $0.045(\text{ohm.m})^{-1}$  (Figure 6b).

Temperature and/or the presence of dissolved water can considerably increase the conductivity of the melt and, thus, the bulk conductivity (Gaillard, 2004;

Pommier et al., 2008). At 3GPa, heating a dry MORB-type basalt from 1300 to 1350°C would increase its conductivity of more than 60% (from 0.62 to 1.0(ohm.m)<sup>-1</sup>). The presence of hydrous basalt is particularly likely in subduction zones. The amount of water dissolved in the melt may reach values as high as 30wt% at similar pressures before the melt dissolves silicates to come into equilibrium with the surrounding material (Gaetani and Grove, 2003). As shown in Figure 6b, at 1300°C, only 0.02vol% of a basalt containing 30wt% H<sub>2</sub>O provides a bulk conductivity of 1(ohm.m)<sup>-1</sup>, while a melt fraction of 30vol.% is required with a basalt containing 10wt% H<sub>2</sub>O.

The combined effect of water and carbon dioxide can alter the bulk composition in the mantle wedge and trigger partial melting reactions (Peacock, 1990; Dasgupta et al., 2006, 2007). CO<sub>2</sub> can be released by metamorphic reactions in the subducting crust (Peacock, 1990) or by the melting of carbonated peridotite at greater depths (Dasgupta et al., 2006). This melting occurs at depths up to 330km, producing and releasing between 0.03 to 0.3vol% of carbonatitic liquids and CO<sub>2</sub>-rich fluids (Dasgupta et al., 2006). Unfortunately, if the subducting crust is well resolved throughout inversions in Brasse and Eydam (2008), it is not the case for the zone deeper than 140km. This can be explained by a screen effect due to the presence of the main conductor at shallower depth, as pointed out by Brasse and Eydam (2008) (Simpson and Bahr, 2005; Pommier et al., submitted). The water contained in and extracted from the subducted slab (Poli and Schmidt, 1995) is likely to combine with these C-species materials, resulting in the enhancement of silicate melting (Dasgupta et al., 2007). This melting process could explain the detected anomaly at the mantle wedge. It has been demonstrated that, at these P, T conditions, there is a complete miscibility between silicate melts and hydrous fluids, the resulting material being a

supercritical fluid (e.g., Bureau and Keppler, 1999; Newton and Manning, 2008). Unfortunately, the electrical conductivity of such supercritical fluids is unknown and here we assume that mixing models can be used to provide a first approximation of the electrical conductivity of the supercritical one-phase material. At 3GPa and 1300°C, the conductivity of a mixing of hydrous basalt (10wt%H<sub>2</sub>O) and mantle carbonatite in the proportions 0.9-0.1, respectively, is  $\sim 25(\text{ohm.m})^{-1}$ . If we consider a solid matrix conductivity of  $0.002(\text{ohm.m})^{-1}$ , only 6vol% of the basalt-carbonatite conductive phase are needed to match with the bulk conductivity value of  $1(\text{ohm.m})^{-1}$  (Figure 6b and c). The mechanism of silicate melting induced by the combination of water and carbon dioxide rather than by flux melting of nominally anhydrous mantle peridotite constitutes a plausible explanation for the observed anomaly in Central Andes.

If the higher resistivity of the outline of the main conductor ( $\sigma < 0.2(\text{ohm.m})^{-1}$ ) is not a resolution issue of MT data but corresponds to the material resistivity, then it can be interpreted as the consequence of a change in the nature and/or the storage conditions (T, P) of the conductive material. It is also probable that this decrease in conductivity is caused by the fact that a smaller amount the conductive phase is involved in the rising to shallow depths. Only 4vol.% of a 10wt% H<sub>2</sub>O basalt at 1300°C is needed to obtain a bulk conductivity of  $0.2(\text{ohm.m})^{-1}$  at 2GPa. It is likely that very conductive fluids (aqueous fluids) are released from the slab and rise to shallower depths all along with the melt (Poli and Schmidt, 1995). The bulk conductivity of a mixing of 10vol% of a KCl solution (0.5m) and a hydrous basalt at 1300°C (10wt%H<sub>2</sub>O) is  $\sim 8.5(\text{ohm.m})^{-1}$  at 2GPa. If interconnected in a solid matrix

( $0.002(\text{ohm.m})^{-1}$ ), this conductive phase reproduces the bulk value of  $0.2(\text{ohm.m})^{-1}$  with an amount of only 3.5vol% (Figure 6b).

A poorly resolved structure has been detected at  $\sim 20\text{km}$  depth ( $P \sim 0.7\text{GPa}$ ) below the western Cordillera volcanoes (caption ⑤ in Figures 6a and 6b) and could indicate a deep crustal magma chamber (so-called Structure E in Brasse and Eydam, 2008). Should the presence of this structure be confirmed, it can be interpreted in terms of hydrous magma (Figure 6c). Temperature estimates are in the range  $\sim 850\text{--}980^\circ\text{C}$  (Sparks et al., 2008). Considering that dacitic-andesitic lavas emitted by the Cordillera volcanoes have a sodium content of about 3.5wt% (Sparks et al. 2008; Figueroa et al., 2009), the conductivity of the anomaly matches with a magma containing 3wt%  $\text{H}_2\text{O}$  at  $900^\circ\text{C}$ . This water content is in agreement with constraints from petrological studies (1.4-5.3wt%  $\text{H}_2\text{O}$ , Sparks et al., 2008). A dry magma at the surface would have a conductivity of  $0.5\text{--}2(\text{ohm.m})^{-1}$  (caption ⑥ in Figures 6a and 6b).

## 5. Concluding remarks

A new software (SIGMELTS) allowing to compute the electrical conductivity of geomaterials at relevant conditions for the Earth's crust and mantle has been presented. This web application aims at improving the accessibility to laboratory data in order to precise the interpretation of MT profiles. SIGMELTS also underlines that new electrical measurements in laboratory are needed to enlarge the present electrical database, particularly at high pressure conditions. Two main directions for future electrical measurements at high (T, P) would deserve being followed: 1) new

electrical measurements on crustal and mantle fluids such as C-species and on carbonatites are requested to understand deep geodynamical processes based on mantle melting, 2) electrical measurements on different hydrated minerals that constitute the metamorphism facies of the subducting crust would allow to well constrain the electrical evolution of the slab before mantle wedge and detect early fluids release. A substantial database would allow to predict the conductivity variations with depth in a defined region and to compare directly these conductivity maps obtained from experimental data to MT profiles. An application of conductivity calculations using SIGMELTS in the Cordillera subduction zone underlined that high-quality MT data and laboratory measurements, when combined with petrological considerations, allow to place qualitative and quantitative constraints on the different steps of the subduction process.

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