The effect of pressure and water concentration on the electrical conductivity of dacitic melts: Implication for magnetotelluric imaging in subduction areas

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ABSTRACT

Silica-rich hydrous magmas are commonly stored in crustal reservoirs, but are also present at mantle depths in subduction contexts as a result of slab melting in the presence of considerable amounts of water and other volatile species. Magnetotelluric surveys frequently identify highly conductive zones at crustal or mantle depths possibly revealing the presence of such silica-rich melts and this can be used to trace the cycling of water in subduction zones and its relationship with arc-magmatism. The achievement of such a purpose is impeded by poor knowledge of the electrical conductivity of both dry and hydrous silica-rich melts at pressure. To fill this gap, we performed in situ electrical conductivity measurements on a dacitic melt using a 4-wire set up to 1300 °C, 3.0 GPa and H_2O content up to 12 wt.%. Melt conductivity is strongly correlated with its water content, and we reveal a complex effect of pressure being relatively small at low water contents and major at high water contents: with increasing water content, the activation volume ranges between 4 (dry) and 25 cm^3/mol ($H_2O = 12$ wt.%) and the activation energy decreases from 96 kJ (dry) to 62 kJ (12 wt.% H_2O). By comparison with diffusivity data, sodium appears to be the main charge carrier, even at high (12 wt.%) water content. A T–P–[H_2O] model predicting the conductivity of dacitic melts shows that crustal and mantle wedge conductive bodies can be interpreted by the presence of silica-rich, hydrous, partially crystallized magma.

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1. Introduction

Outcrops of deep rocks, showing sections of the upper mantle and of the crust, provide an indirect snap shot of deep processes as they have cooled slowly during emplacement, resulting in large modifications of their textures, chemical compositions and mineralogy. In particular, melting processes that can induce large scale mechanical weakening (Holtzmann et al., 2003, 2012; Katz et al., 2006; Holtzmann and Kohlstedt, 2007; Kohlstedt and Holtzmann, 2009; Hashim et al., 2013) are mostly erased during the exhumation and cooling of deep rocks. In order to map and understand melting processes occurring at depth, geophysical investigations (e.g. magnetotelluric, seismic tomography) must be deployed over the regions of interest. Magnetotelluric investigations, for example, provide evidence for anomalously high electrical conductivity in the oceanic upper mantle (Evans et al., 2005; Baba et al., 2006; Naif et al., 2013; Key et al., 2013), under the Andean arc (Booker et al., 2004; Unsworth et al., 2013) or in the crust below the South Himalayan ranges (Unsworth et al., 2005). The detection of

such highly conductive regions reveals the existence of deep phases having highly mobile charge carriers and being connected over large distance. Experimental investigations have shown that partial melts can trigger high conductivity (Roberts and Tyburczy, 1999; Gaillard and Iacono-Marziano, 2005; ten Grotenhuis et al., 2005; Gaillard et al., 2008; Yoshino et al., 2010; Hashim et al., 2013; Sifré et al., 2014). The presence of melt is in particular the most likely explanation for the large conductive region beneath the Altiplano–Puna Volcanic Complex (APVC; Booker et al., 2004; Unsworth et al., 2013). Considering the conjunction of (i) the uplift of the crust centered on Uturuncu Volcano, (ii) the geothermal springs, and the (iii) dimension of the conductive body, a major replenishment has likely occurred and this demands the thorough appraisal of the storage conditions of melt at depth in the APVC system (de Silva, 1989a, b; Pritchard and Simons, 2002; Pritchard and Simons, 2004; de Silva et al., 2006; de Silva and Gosnold, 2007; Sparks et al., 2008; Del Potro et al., 2013; Muir et al., 2014). The quantitative interpretation of such a structure revealed by magnetotelluric profiles requires robust laboratory characterization under controlled conditions. So far, several works have addressed the electrical conductivity of silicate melts (Presnall et al., 1972; Waff and Weill, 1975; Tyburczy and Waff, 1983, 1985; Robertz and Tyburczy,

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1999; Bagdassarov et al., 2004; Gaillard, 2004; Maumus et al., 2005; Poe et al., 2008; Pommier et al., 2008, 2010; Yoshino et al., 2010; Ni et al., 2011; Hashim et al., 2013; Sifré et al., 2014), but few of them have addressed hydrous melts (Gaillard, 2004; Pommier et al., 2008; Ni et al., 2011; Hashim et al., 2013; Sifré et al., 2014) and the effect of pressure on melt conductivity remains unclear.

This study presents experimental results of in situ electrical conductivity measurements acquired on a dacite from Uturuncu Volcano at various pressure, temperature and water content. A model integrating the effects of pressure, temperature and water concentration is established from the data. Then, we discuss the role of water and pressure on electrical conductivity and the applications to the interpretation of magnetotelluric surveys. We discuss the electrical anomalies underneath the Uturuncu volcanic center, but we also present quantitative interpretations of the electrical structures below other volcanic areas in arc-settings, where hydrated dacitic melts are likely (Usu, Taupo, Merapi and Saint Helens volcanoes). Finally, we conclude with the possibility of detecting super hydrous melts resulting from melting of slab (e.g. Schiano et al., 1995; Neumann and Wulff-Pedersen, 1997; Shimizu et al., 2004; Ishimaru et al., 2007; Bali et al., 2008), since such melts must trigger high electrical conductivity at ca 90 km, at the base of the mantle wedge.

2. Background on electrical conductivity

As with diffusivity and viscosity, the electrical conductivity σ (S·m^{-1}) of silicate melts is pressure and temperature dependant, and can be described by an Arrhenius law:

$$\sigma = \sigma_0 \ \ \exp\left(\frac{-Ea-P\Delta V}{\Re T}\right) \tag{1}$$

where σ_0 is the preexponential factor (S/m), Ea is the activation energy (J), ΔV (cm^3/mol) is the activation volume, T is the temperature (K), P is pressure (Pa) and $\Re$ is the universal gas constant. The electrical conductivity is the sum of the individual transport mechanisms; however, the electrical conductivity is generally dominated by one or two mechanisms (Gaillard, 2004). In amorphous (melts and glasses) silicate compositions, the mobility of ionic species dominates. Ionic conductivity is connected to diffusive transport of charge carriers within the melt, and follows the Nernst–Einstein equation:

$$\sigma_i = \frac{D_i.q_i^2.N_i}{k.T.Hr} \tag{2}$$

with the tracer diffusion coefficient D_i (m^2·s^{-1}) of an ion i, its charge q_i (C), the concentration of i (m^{-3}), the Boltzmann constant k (1.38 · 10^{-23} J·K^{-1}), the temperature T (K) and the Haven ratio Hr. The Haven ratio Hr of silicate melt or glass is related to the mechanisms of migration of the charge carriers within the melt, and generally ranges between 0.2 and 1 (Heinemann and Frischat, 1993). Gaillard (2004) used $Hr = 1$ for rhyolitic melts.

3. Experimental methods

3.1. Starting materials

3.1.1. Sample syntheses

Electrical measurements were performed on a dacitic rock from Uturuncu Volcano, located in the Southwest Bolivia (Altiplano–Puna Volcanic Complex). It has been exhaustively studied under the reference UTU41B (Muir et al., 2014). It consists in phenocrysts of plagioclases embedded in a matrix of orthopyroxene, biotite, ilmenite and Ti-magnetite groundmass. Its bulk chemical composition is given in Table 1.

Table 1
Chemical composition normalized to 100% of the volatile-free starting dacite after melting at 1450 °C and 1 atm.

SiO$_2$	TiO$_2$	Al$_2$O$_3$	FeO	MnO	MgO	CaO	Na$_2$O	K$_2$O
67.93	0.91	15.30	4.24	0.07	1.45	3.31	2.09	4.69
1.33	0.21	0.65	0.60	0.08	0.20	0.33	0.10	0.21

The dacite was first crushed in an agate mortar into a powder (grain size < 45 μm). The powder was placed in a platinum crucible and heated to 1000 °C in air at 1 atmosphere in order to remove volatile species. Then, the crushed dacite was molten at 1450 °C for 3 h, resulting in a glass with less than 0.05 wt.% of water and no detectable amount of CO$_2$. The glass obtained was (1) drilled to provide dry samples for conductivity measurements or (2) crushed for the synthesis of 3 hydrated samples.

Hydrated samples were prepared by adding the desired amount (mass) of water to the glassy powder in a welded shut capsule. Syntheses of hydrated glasses were done in internally heated pressure vessel for 3 days ended by a rapid quench at 300 MPa, 1200 °C and 350 MPa, 1020 °C for the glass containing 3.3 and 7.1 wt.% of water respectively (see also next section). The glass with 12.2 wt.% H$_2$O was synthesized in piston cylinder at 1.5 GPa, 1000 °C for 13 h using a 3/4 inch assembly. Dry and hydrous starting materials are crystal- and bubble-free at the micrometer scale, except the [H$_2$O] = 12.2 wt.% sample that contained few amphiboles (less than 5% in volume) resulting most likely from crystallization during quench. The 3.3 wt.% H$_2$O glass was synthesized in a 15 mm diameter capsule so as to drill cylindrical samples. The two other syntheses were performed in 5 mm diameter capsule, and samples were prepared after crushing and cold pressed reconstitution of pellets with the desired dimension (see In situ electrical measurements section).

3.1.2. Determination of the water concentration

Double polished chips of the four synthetic glasses were analyzed by Fourier Transform Infrared spectroscopy (FTIR) to check their water concentration (Microscope IR Continuum coupled with a Nicolet 6700 spectrometer and a MCT detector). An IR source, a KBr beam splitter and a CaF$_2$ window were used to acquire absorption spectra with 200 scans and a resolution of 4 cm^{-1} in the range 6000–1500 cm^{-1}. Each sample was analyzed through a profile (1.3 to 2.0 mm in length) of 20 spots minimum to check its homogeneity. A linear baseline correction was used to determine the peak height absorbance, and we calculated the water concentration by the Beer–Lambert law, using extinction coefficients reported by Wysoczanski and Tani (2006) and density calculated after Ohlhorst et al. (2001). The thickness of the sample was measured by the calibrated stage of the microscope, and checked by a Mitutoyo digital micrometer. The propagated uncertainty takes into account the accuracy of (1) the thickness (± 3 μm), (2) the absorbance peak height, (3) glass density and (4) extinction coefficient, resulting in a maximal error in [H$_2$O] content of 10% relative. To minimize the uncertainty, samples were kept as thick as possible but transparent for IR rays (thickness < 200 μm). When possible, the fundamental H$_2$O-stretching vibration was used (3530 cm^{-1}). Otherwise, when the signal of the fundamental stretching H$_2$O vibration was oversaturated, the water concentration was determined by adding the molecular water (5200 cm^{-1}) and OH– (4500 cm^{-1}) stretching vibrations (Fig. 1A to C). The hydrated synthetic glasses contain 3.3 (± 0.3), 7.1 (± 0.7) and 12.2 (± 0.5) wt.% of homogeneously dissolved water (Fig. 1D).

3.2. In situ electrical measurements

3.2.1. Internally heated pressure vessel (IHPV)

Low-pressure experiments (P < 300 MPa) were conducted in a gas medium IHPV following the same protocol as that of Gaillard (2004)