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Electrical conductivity of a phonotephrite from Mt. Vesuvius: The importance of chemical composition on the electrical conductivity of silicate melts

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ABSTRACT

The bulk electrical conductivity of the phonotephritic lava from the 1944 eruption of Mt Vesuvius was measured using complex impedance spectroscopy in a multianvil apparatus at 1 GPa and temperatures up to 700 °C. Melting experiments prior to the electrical measurements were also performed on this sample in a piston cylinder apparatus in order to gauge how bulk conductivity varies as a function of its melt fraction. Unlike the behaviour found in basaltic rocks in which conductivity increases with increasing melt fraction, we observe a conductivity decrease of the order of a factor of ten for samples at 700 °C ranging in melt fraction from 32 vol.% to completely molten. We attribute this anomalous behaviour to the progressive loss of highly conductive leucite upon melting. The addition of potassium to the melt phase, however, does not result in an increase of the total alkali concentration due to the melting of other mineral components. We also present an empirical model to predict the electrical conductivity of fully molten silicate liquids as a function of temperature and chemical composition, based on conductivity data for natural silicate liquids found in the literature. The inclusion of compositional terms reduces the error by more than a factor of four with respect to a composition independent, temperature-only parameterization.

1. Introduction

The electrical conductivity of both solid and molten silicate materials is highly sensitive to temperature and chemical composition and can thus serve as an important indicator to the conditions of the Earth's interior. For example, Xu et al. (2000a) constructed the first laboratory-based conductivity profile of the mantle by combining a series of two-phase assemblages of mineral conductivity data obtained at high P and T. Their profile is in excellent agreement with several geophysical models of mantle conductivity derived from magnetotelluric studies. Anomalously high conductivity zones revealed by field-based electromagnetic methods are likely to be host to partially molten material (Partzsch et al., 2000; Schilling and Partzsch, 2001) but the extent of melting or the chemical composition of the molten material can only be correlated to the bulk electrical conductivity through laboratory studies. Because both melt fraction and its chemical composition are strongly dependent on bulk composition and temperature, the resulting electrical properties of any partially molten material are still far from being well understood.

Bulk electrical conductivity is expected to increase when a liquid phase appears as ionic conduction mechanisms will become much more important due to the much higher diffusivities of ionic species compared to their solid state mobilities. Even at relatively low charge carrier concentrations (i.e. low melt fractions), if the melt phase is interconnected and the mobility of a charge carrier is several orders of magnitude faster compared to its mobility in the solid state, bulk conductivity will increase. Presnall et al. (1972) demonstrated this behaviour for a synthetic basalt for which bulk conductivity increased by approximately two orders of magnitude over the narrow temperature range between solidus and liquidus. Sato and Ida (1984) also observed a dramatic increase in the bulk conductivity of a gabbro upon melting. Roberts and Tyburczy (1999) demonstrated that chemical composition of the melt phase plays an important role in determining the bulk conductivity by examining a variety of different partially molten systems. In their experimental study, melt fractions varied from 0–6 vol.%, yet parallel conduction between both solid and melt phases was observed even as low as ca. 2 vol.%, highlighting the importance of faster conduction mechanisms even at such low carrier concentrations. Scarlato et al. (2004) investigated a wider range of melting of a basaltic lava flow sample from Mt. Etna and concluded that melt chemistry plays a minor role compared to the more important effect of melt fraction. Gaillard and Marziano (2005) measured the electrical conductivity of a basaltic magma at various stages of crystallization to determine the

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Table 1
Bulk composition (wt.%) determined by X-ray fluorescence spectroscopy of phonotephritic rock used in this study

	Phonotephrite	Basalt
	(This study)	(Scarlato et al.)
SiO_2	48.60	47.08
TiO_2	0.87	
Al_2O_3	19.17	16.41
Fe_2O_3	8.07	2.07
FeO		8.50
MnO	0.15	0.18
MgO	3.94	6.10
CaO	7.73	10.94
Na_2O	2.65	3.50
K_2O	7.71	2.03
P_2O_5	0.85	0.56
LOI	0.16	0.47

Bulk composition of basaltic rock used in the Scarlato et al. (2004) study is also shown.

main chemical components in the residual liquid responsible for controlling bulk conductivity. They concluded that as the magma continued to evolve, an evolving form of the Arrhenius equation could be used to describe its conductivity, such that both the pre-exponential (σ_o) and activation energy (Ea) terms varied linearly as a function of temperature.

In this study, we examine the electrical properties of a phonotephritic lava flow sample from Mt Vesuvius over a similar range of partial melting as that investigated for the basaltic rock investigated by Scarlato et al. (2004). As a disproportionately high number of experimental data can be found for the electrical conductivities of basaltic rocks (Presnall et al., 1972; Rai and Manghnani, 1977; Tyburczy and Waff, 1983; Scarlato et al., 2004), we take the opportunity to examine a rock substantially richer in sodium and potassium in order to gauge how bulk chemistry and melting influences the electrical properties of silicate systems in general. Moreover, Mt Vesuvius, located in Southern Italy immediately east of the city of Naples, is an active volcano with several highly destructive eruptions in its history, with a very high hazard potential in the event of its reactivation. Therefore, knowledge of the structure and behaviour of the magmatic system is crucial for the interpretation of its dynamics and for the hazard assessment within and around the Naples area. In particular, controversy remains regarding the deep structure of the volcano and the size and location at depth of the magma reservoir(s) feeding the volcano on the basis of petrographic, geochemical, isotopical and seismic data (Barberi and Leoni, 1980; Barberi et al., 1981; Belkin and De Vivo, 1993; Zollo et al., 1996; De Natale et al., 1998; Di Maio et al., 1998; Marianelli et al., 1999; Auger et al., 2001; Civetta et al., 2004). Comparison of our laboratory estimates of the electrical conductivity of the Vesuvian samples with seismic tomography and magnetotelluric investigations (Zollo et al., 1996; Di Maio et al., 1998; Auger et al., 2001) in the volcanic area of Mount Somma–Vesuvius can help shed some light in the definition of the deep structure of the volcano. We investigate how bulk chemical composition and melting behaviour influences its bulk electrical conductivity for comparison with other rock types. We show that for our alkali-rich bulk composition, changing the melt chemistry with increased melting is indeed important, as bulk conductivity can even decrease. We also have compiled a number of electrical conductivity data for natural silicate melts found in the literature with the aim of finding an empirical approximation for determining electrical conductivity as a function of the melts temperature and concentration of major oxide components. At present, the approximation is applied only to completely molten systems, but along with the experimental results of this study, we discuss how it might be influenced by the presence of mineral phases.

2. Experimental methods

2.1. Samples and sample preparation

Experiments were carried out in the HP–HT Laboratory of Experimental Volcanology and Geophysics, INGV-Rome. We measured the electrical conductivity of a highly undersaturated ultrapotassic phonotephritic to tephri-phonolitic lava originating from the effusive phase of the eruption of Mt. Vesuvius (Italy) in 1944. The sample is a highly porphyritic lava containing abundant leucite phenocrysts. Plagioclase phenocrysts and microphenocrysts are the next most abundant phases, followed by clinopyroxene and rare olivine microphenocrysts. Its holocrystalline groundmass is composed of the same minerals and includes rare sanidine and opaque minerals. Its bulk chemical composition (see Table 1) is relatively rich in potassium (7.71 wt.%) owing to the presence of leucite. Four mm diameter cored samples were cut into disks of approximately 1 mm thickness for complex impedance measurements. In order to investigate the electrical properties of the bulk material as a function of melt fraction, some experiments in which the samples were partially melted were carried out in a piston cylinder apparatus (see Table 2 for experimental temperatures) prior to the electrical measurements. All electrical measurements were kept at temperatures low enough (maximum 700 °C) to maintain a constant amount of melt. Thus, the melt phase could be considered either a supercooled liquid or glass during the impedance measurements. SEM analyses of samples both before and after the impedance measurements indicated neither a reduction in the amount of melt due to crystallization nor an increase due to additional melting. The piston cylinder run products were recovered and prepared in the same manner as the starting materials described above.

2.2. In-situ electrical measurements at high P and T

An 840 tonne uniaxial press containing a Walker-type multianvil apparatus with cubic 32 mm tungsten carbide anvils (17 mm edge length truncations) was used to generate sample pressures up to 0.9 GPa. Although the multianvil apparatus is typically used for generating much higher pressures, typically on the order of 25 GPa, in this case it was chosen because of the greater access to the sample for the electrical measurements with respect to the piston cylinder apparatus. Numerous studies (Xu et al., 1998; Katsura et al., 1998; Poe and Xu, 1999; Xu et al., 2000a) have demonstrated that it is possible to perform complex impedance spectroscopy in the multianvil at pressures and temperatures corresponding to mantle depths down

Table 2
Melt and mineral phase characteristics of the partially molten samples investigated

Expt	M33	M32	M35	M34	M31
T (°C)	1060	1100	1140	1200	1350
vol.% glass	70	32	84	93	100
SiO_2	53.29	55.16	52.23	52.78	52.55
Al_2O_3	11.93	12.60	11.29	11.91	11.98
FeO	9.61	10.03	9.09	9.38	8.74
MgO	4.89	3.19	6.42	5.51	5.98
CaO	8.97	6.37	10.71	9.41	9.54
Na_2O	2.50	3.20	2.00	2.26	1.91
K_2O	6.22	6.77	6.10	6.73	7.10
Leuc ($K_{0.96}Na_{0.04}$)	15.1	14.4	10.1	6.3	
Plag ($Na_{0.15}Ca_{0.83}K_{0.02}$)	10.1	8.6	4.4	3.3	
Oliv (Fo_{71})	4.2	0,2			
Cpx ($En_{35}Fs_{17}Wo_{48}$)	3.9	12.1	1.9		

Volume fractions were estimated by SEM image analysis. Major element concentrations (wt.%) of vitreous phase and mineral phases present (not shown) were determined by electron microprobe analyses. Mineral concentrations (shown in wt.%) were determined by mass balance calculation using melt fraction and melt and mineral chemical compositions.