Electrical conductivity and pore-space topology of Merapi lavas: implications for the degassing of porphyritic andesite magmas

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Abstract. Pore-space topology is studied in recent compact angular blocks and scoria fragments from block-and-ash flow deposits of Merapi volcano, Indonesia. Connected porosity and electrical conductivity of cored clay-free samples are measured in the laboratory at varying fluid salinity. The electrical formation factor, tortuosity and cementation index are derived and the pore-space topology is found to be porosity-dependent. The electrical flow pattern is controlled by crack-like paths in compact angular block, and by vesicles geometry in more porous scoria fragments. Because Merapi lavas are highly viscous and crystal-rich, we infer that the development of pore connectedness and vesicle coalescence is promoted by shear strain. Along with ascept rate considerations we conclude that degassing of Merapi magma occurs mostly in the conduit during ascent.

1. Introduction

The dynamics of volcanic eruptions is largely controlled by the degassing history of magmas during their ascent toward the surface. The modality of fluid transfer in magma evolves as cooling and crystallization proceed during ascent. Experimental investigation on the transfer of fluids in hot vesiculating magmas is a difficult task. For this reason, various indirect approaches have been developed to characterize pore-space connectedness and to discuss the processes of fluid transfer in magmas. This includes nitrogen absorption technique and mercury porosimetry [see e.g., Whitham and Sparks, 1986], image analyses of thin sections of pyroclastic material, or permeability measurement on rocks samples [e.g., Klig and Catches, 1996, and references therein]. We develop here a new approach based on electrical conductivity and porosity measurements of pyroclastic rock samples that are derived and the pore-space topology is found to be porosity-dependent. The electrical flow pattern is controlled by crack-like paths in compact angular block, and by vesicles geometry in more porous scoria fragments. Because Merapi lavas are highly viscous and crystal-rich, we infer that the development of pore connectedness and vesicle coalescence is promoted by shear strain. Along with ascent rate considerations we conclude that degassing of Merapi magma occurs mostly in the conduit during ascent.

2. Field Sampling

Petrophysical measurements were obtained from 11 blocks sampled at Merapi in block-and-ash flow deposits of the June 1984 event (in Kali Putih at Jurangjero), of the Nov. 22, 1994 event (in Kali Boyong, near Kaliuran), and of the July 1998 event also in Kali Putih. Voight et al. [2000] describe the chronology of events and Camus et al. [2000] summarize place names and petrology. The 1984 and 1994 deposits were studied by Boudon et al. [1993] and Abdurachman et al. [2000], respectively. The 1998 event also produced a deposit of similar characteristics. Unaltered clay-free blocks were selected to cover a large porosity range and were classified into five categories according to their lithology (compact angular blocks or scoriaceous fragments) and year of emplacement (1984, 1994 or 1998).

3. Experimental Procedure and Results

Measurements were obtained from 26 cylindrical samples, 2.5 cm in diameter, directly cored in the blocks in the laboratory. The path of the electrical flow is controlled by the water-filled fractional connected porosity, \( \phi \), which has been measured using the triple weighing technique. In our sample collection \( \phi \) varies between 0.04 and 0.39 (Table 1).

The electrical resistivity measurements were performed on cores previously wrapped with Teflon ribbon in order to avoid desaturation and surface conduction. Two different equipments were used for the measurements. The 22 cores of the 1984 and 1994 events were analyzed with a CDM230 conductimeter which fits the current frequency automatically to minimize the capacitive component. The 5 cores of the 1998 event were analyzed with a Wayne-Kerr bridge which allows adjustment of the current frequency (20 Hz to 300 kHz). Comparative tests performed with the two equipments leaded to choose a frequency of 1kHz when working with the Wayne Kerr bridge as very similar resistivity measurements were obtained at that frequency for the full salinity range of the study (0.02 to 30 g/l). In all cases, measurements were carried out with cores saturated with NaCl brines (once equilibration with the saturating solution was reached) on a two-electrodes assemblage. Six to seven measurements were made with saturating solution of increasing NaCl concentration. Further details on the electrical resistivity measurement procedure are given e.g. in Joumaux et al. [2000].

The measured resistivities of the cores and of the saturating NaCl solutions allowed calculation of the electrical surface conductivity, \( C_s \), using the model of Revil and Glover [1998]. These authors give a comprehensive theoretical background of this parameter. In our samples \( C_s \) varies on one order of magnitude from 0.07 to 0.59 mS/m (Table 1).

4. Parameters Describing Pore-space Topology

The model of Revil and Glover [1998] also allows derivation of the electrical formation factor, \( F \), which describes the overall macrostructure at the scale of the sample. \( F \) varies from
5. Discussion

A log-log plot of $F$ vs. $\phi$ (Fig. 1) reveals a relationship between water-filled pore-space volume and topology. The data are not strongly correlated by the original Archie's formula $F = \phi^{1.8}$, where $-1.8$ represents the average of all $m$ values of our sample collection. On the other hand, an equation of the form $F = 2.35 \times \phi^{1.2}$ fits them very well ($R^2 = 0.98$). Below we discuss the $m$ values obtained for discrete samples using the original Archie's law, and not the meaningless $m$ values obtained above for the whole sample collection. A plot of $m$ over bulk connected porosity (Fig. 2a) reveals a regular trend which confirms the relationship between pore-space geometry and porosity. In the low porosity range (angular blocks with $0.03 < \phi < 0.14$) low $m$ values (1.4–1.6) argue for a pore-space topology dominated by crack-like geometry. In the very low porosity range ($\phi < 0.07$) these cracks might partly result from thermal cracking after emplacement, perhaps completed in the range $0.07 < \phi < 0.14$ by small open micro-shear zones and/or small vesicles. At higher porosity $m$ values raise to $2.3$, denoting the progressive decoupling between electrical flow paths and bulk porosity. This is consistent with a pore-space topology gradually dominated by vesicle geometry. Thus, relatively high $m$ values in the high porosity range of our samples ($\phi > 0.2$) suggest that pore topology is dominated by narrow apertures connecting bubbles (or groups of adjacent bubbles) of larger cross-sectional area. These conclusions corroborate those obtained by mercury porosimetry on a variety of pumice fragments by Whitham and Sparks [1986].

A crack-like network can account for the high tortuosity values (Fig. 2b) of the compact angular block samples ($3.5 < \phi < 6$). The low $t$ values ($< 4$) in the scoria fragments at $\phi < 0.15$ indicates a progressive simplification of the electrical flow pattern in the high porosity range, the electrical currents follow a thin paths system regardless of the overall pore geometry. The contrast between compact angular blocks and open scoria fragments (Fig. 2b) is also shown (see text). Filled symbols are compact angular blocks and open symbols are scoria fragments.

Table 1. Results of the petrophysical measurements. Compact angular blocks are indicated in bold text for distinction with scoriaceous fragments.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>$\phi$</th>
<th>$\phi^3$</th>
<th>$F^2$</th>
<th>Sample #</th>
<th>$\phi$</th>
<th>$\phi^3$</th>
<th>$F^2$</th>
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<td>Me84-1a</td>
<td>0.19</td>
<td>0.263</td>
<td>16</td>
<td>Me94-1e</td>
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<td>0.588</td>
<td>16</td>
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<tr>
<td>Me84-1b</td>
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<td>17</td>
<td>Me94-2a</td>
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<td>0.261</td>
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<tr>
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<td>10</td>
</tr>
<tr>
<td>Me84-2ai</td>
<td>0.26</td>
<td>0.101</td>
<td>10</td>
<td>Me94-2hi</td>
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<td>0.128</td>
<td>11</td>
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<tr>
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<td>0.119</td>
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<td>0.073</td>
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<td>0.219</td>
<td>19</td>
<td>Me94-3ai</td>
<td>0.04</td>
<td>0.164</td>
<td>128</td>
</tr>
<tr>
<td>Me84-1fa</td>
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<td>0.274</td>
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<td>0.462</td>
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<td>0.514</td>
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<td>0.126</td>
<td>27</td>
<td>Me98-1A</td>
<td>0.39</td>
<td>0.222</td>
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<tr>
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<td>Me98-3B</td>
<td>0.31</td>
<td>0.235</td>
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</table>

1Fractional connected porosity.
2Surface conductivity in mSm and 3Electrical Formation Factor are calculated from the model of Revil and Glover [1998].
moderately intruded and show evidence of tearing and shear-induced deformation while more frothy pumice fragments from P1 eruptions at Mt Pelee display sub-spherical bubble shapes of highly variable size [Villemant and Boudon, 1998], e.g. comparable to those obtained in analogue material with $m=3.8$ by Revil and Cathles [1999]. Whitham and Sparks [1986] inferred that pumice fragments degas very quickly because of the high degree of pore connectedness and high internal surface area. Our results also indicate a high pore connectedness so we assume that the conclusions of these authors also apply to our Merapi samples, in spite of their lower porosity. In thin sections of the 1984 and 1994 products, this degassing is evidenced by the regularly lobate shape of bubbles which seem flattened or collapsed. This morphology is usually interpreted as resulting from "open-system" degassing [Sparks, 1997; Villemant and Boudon, 1998].

The apparent degassed character of Merapi lavas may appear unexpected because bubble motion and coalescence is strongly inhibited by the very high magma viscosity: crystal content exceeds 70% (modal analysis from this study yielded ~60% phenocrysts and ~15% microlites, in agreement with other modal data compiled in Camus et al. [2000]) and residual liquids are rhyolite [Camus et al., 2000, Hammer et al., 2000]. A mixture of this type would thus develop a high macroscopic yield strength and strain in the upper levels of the magmatic system should be accommodated along narrow shear-zones of possible Newtonian rheology, as sometimes evidenced at Merapi by slab-like extrusions similar in size and shape to those described by Sparks et al. [2000] at Soufrière Hills volcano, Montserrat.

The degassed nature of Merapi lavas may be related to the very low ascent rate of the magma. Siswowidjoyo et al. [1995] have calculated an average output rate at Merapi of ~0.04 m$^3/s$ during the period 1890-1992. For the period considered in the present work this rate temporarily increased to a maximum of 0.32 m$^3/s$ according to Hammer et al. [2000], during a dome growth episode following the November 22, 1994 eruption. Siswowidjoyo et al. [1995] estimated a conduit radius of ~25 m, in agreement with our field observations and summit maps examination (the active part of the dome is significantly smaller than the entire dome). If plug flow and no magma compressibility are assumed, simple calculations indicate that the Merapi magma moves upward at a speed of ~2-14 m/day, or ~0.6-5 km/year, during periods of normal (0.04 m$^3/s$) and high-level (0.32 m$^3/s$) activity, respectively. This is

![Figure 2](image-url)  
**Figure 2.** Plots of (a) electrical cementation index $m$ and (b) electrical tortuosity $\tau$ vs. fractional connected porosity $\phi$ for all samples. Symbols as in Fig. 1.

![Figure 3](image-url)  
**Figure 3.** Plot of electrical formation factor $F$ vs. cementation index $m$ showing contrasted properties of compact angular blocks (filled symbols) and scoria fragments (open symbols).
significantly less than the 20-30 m/day extrusion velocities measured in 1997 at Soufrière Hills volcano, Montserrat [Sparks et al., 2000]. The depth of the shallowest magma chamber at Merapi is poorly constrained. Siruwodijoyo et al. [1995] tentatively estimated the length of the upper Merapi magmatic conduit to a few km (and less than 10 km) and Radatomopurbo and Poupinet [2000] located the top of a magma chamber at 1.5 km below the summit, according to seismicological studies. Hence, the Merapi magma probably spends several years in the conduit. This estimate is consistent with the high crystal content and relatively large crystal sizes. The time-scale of magma ascent at Merapi is thus similar to the time-scale of magma residence time in the shallow magma reservoir, which was estimated on the base of 210Pb-226Ra radioactive disequilibria at about 2 yr by Gauthier and Condomines [1999]. However this estimate is several orders of magnitude lower than the time-scale of magma ascent during Plinian-type eruptions. Owing to the small volume of magma involved in the activity at Merapi (Gauthier and Condomines [1999] have estimated the shallow magma reservoir capacity at 1.6 x 10^7 m^3), we infer that the magma transferred most of its volatile content to the periphery of the active magmatic conduit. At Merapi, the gases escaping at Gendol and Woro fumarolic fields, located at some hundreds of meters from the active extrusion, illustrate this process. Their magmatic origin is ascertained by their high temperature and isotopic composition. Degassing-induced microlite crystallization also plays an important role in the upper parts of the magmatic system. Our "open system" degassing model agrees with the "closed system" model of Gauthier and Condomines [1999], for the 1984-1992 dome growth episode, which requires that radon fully degasses between the shallow reservoir and the dome.

We conclude that vesicle connectedness in our samples mainly results from bubble expansion, in the magma chamber and/or in the conduit, accompanied or followed by shear-induced deformation, principally in the conduit and the dome. Shear-induced bubble deformation likely acts during ascent and extrusion as a major mechanism promoting connection of both expanding and deflecting vesicles. As shear stresses operate first within the conduit, we believe that crystal-rich andesites erupted at low extrusion rates are particularly well suited for "open system" degassing behavior during shallow ascent. These findings obtained at Merapi should apply to other long-lived porphyritic andesite eruptions in the world.

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