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Transient self-potential anomalies associated with recent lava flows at Piton de la Fournaise volcano (Réunion Island, Indian Ocean)

S. Barde-Cabusson [a,*,1], G. Levieux [a,b], J.-F. Lénat [a], A. Finizola [c], A. Revil [d,e], M. Chaput [a], S. Dumont [f], Z. Duputel [f], A. Guy [f], L. Mathieu [a], S. Saumet [a], F. Sorbadère [a], M. Vieille [f]

[a] Laboratoire Magmas et Volcans Univ. Blaise Pascal-CNRS-OPGC, 5 rue Kessler, Clermont-Ferrand, France
[b] IPGP, CNRS, UMR 7154, Paris, France
[c] Laboratoire GéoSciences Réunion, Université de la Réunion, IPGP, CNRS, UMR 7154-Géologie des Systèmes Volcaniques, La Réunion, France
[d] Colorado School of Mines, Dept. of Geophysics, Golden, CO, USA
[e] CNRS-LGIT (UMR 5559), University of Savoie, Equipe Volcan, Le Bourget-du-Lac, France
[f] Ecole et Observatoire des Sciences de la Terre, Université Louis Pasteur, Strasbourg, France

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ABSTRACT

Self-potential signals are sensitive to various phenomena including ground water flow (streaming potential), thermal gradients (thermoelectric potential), and potentially rapid fluid disruption associated with vaporization of water. We describe transient self-potential anomalies observed over recent (<9 years) lava flows at Piton de la Fournaise volcano (Reunion Island, Indian Ocean). Repeated self-potential measurements are used to determine the decay of the self-potential signals with time since the emplacement of a set of lava flow. We performed a 9 km-long self-potential profile in February 2004 in the Grand Brûlé area. This profile was repeated in July–August 2006. The second repetition of this profile crossed eight lava flows emplaced between 1998 and 2005 during seven eruptions of Piton de la Fournaise volcano. The self-potential data show clear positive anomalies (up to 330 mV) and spatially correlated with the presence of recent lava flows. The amplitude of the self-potential anomalies decreases exponentially with the age of the lava flows with a relaxation time of ~44 months. We explain these anomalies by the shallow convection of meteoric water and the associated streaming potential distribution but we cannot exclude possible contributions from the thermoelectric effect and the rapid fluid disruption mechanism. This field case evidences for the first time transient self-potential signals associated with recent volcanic deposits. It can be also a shallow analogue to understand the variation of self-potential signals in active geothermal areas and transient self-potential signals associated with dike intrusion at larger depths. The empirical equation we proposed can also be used to diagnose the cooling of recent lava flow on shield volcanoes.

1. Introduction

Self-potential signals refer to quasi-static electrical potential anomalies, usually measured at the ground surface of the Earth, that are associated with the occurrence of source current densities existing at depth (Sill, 1983; Corwin, 1997). One of the inherent problems associated with the interpretation of self-potential signals lies in the variety of source mechanisms in conductive media (Revil and Linde, 2006). For instance, self-potential signals can be generated by redox potentials associated with ore bodies or the metallic casing of boreholes or contaminant plumes that are rich in organic matter (Sato and Mooney, 1960; Minsley et al., 2007; Linde and Revil, 2007; Castermant et al., 2008). A second source of self-potential anomalies is the thermoelectric effect (Nourbehecht, 1963; Sill, 1983) that is associated directly with a gradient of the temperature affecting the chemical potential gradient of charge carriers (Revil, 1999; Revil and Linde, 2006). A third source is related to gradients of the chemical potential of the ionic charge carriers at constant temperature (MacInnes, 1961; Nourbehecht, 1963; Revil, 1999). A fourth source of self-potential signals is the streaming potential contribution related to the flow of the pore water relative to the mineral grain framework in saturated (Overbeek, 1952; Nourbehecht, 1963) and unsaturated conditions (Revil and Cerepi, 2004; Linde et al., 2007). A fifth potential contribution, called the rapid fluid disruption effect, has been also proposed by Johnston et al. (2001) based on previous works by Blanchard (1964) in non-porous media. However the experiments conducted by Johnston et al. (2001) were strongly criticized by Revil (2002) and were unable to prove the existence of a true self-potential signature of vaporization of the water phase. As explained by Revil (2002), this does not rule out this mechanism as being an additional contribution to self-potential signals.

* Corresponding author. Dipartimento di Scienze della Terra, Università di Firenze, Via La Pira 4, 50121, Firenze, Italy. Tel.: +39 055 2757479; fax: +39 055 2756242.
E-mail address: s.barde.cabusson@gmail.com (S. Barde-Cabusson).
[1] Present address: Dipartimento di Scienze della Terra, Università Degli Studi di Firenze, Italy.

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Because of the diversity of these sources, the self-potential method has been considered as a qualitative geophysical method for a long time since its discovery by Fox (1830). However, in the two last decades, quantitative interpretations of self-potential signals have been performed for various applications in hydrogeophysics (e.g., Trique et al., 2002; Rizzo et al., 2004) and volcanology (e.g., Ishido and Pritchett, 1999; Revil et al., 2003).

In the present work, we report two self-potential surveys carried out before and after the emplacement of lava flows at the Piton de la Fournaise volcano. These surveys show that positive self-potential anomalies are created above recent lava flows, which corresponds to very shallow thermal anomalies i.e. not related to deep hydrothermal roots. We show how these self-potential anomalies vanish over time as the lava flows cool down. On active volcanoes, when mapping perennial structures, fault zones or hydrothermal activity, this type of shallow transient self-potential anomalies can represent a spurious signal. On the other hand, lava flows thus provide natural, small-scale analogue models of the building and vanishing of thermal areas on volcanoes.

2. Self-potential and thermal anomalies

We start this paper by a quick review of the observations made in the literature regarding the correlations observed between self-potential and thermal anomalies. Over the past few decades, self-potential measurements have been extensively used to delineate shallow thermal anomalies over active volcanoes and geothermal fields. Examples of strong (>100 mV) positive self-potential anomalies unambiguously related to shallow thermal anomalies have been observed by Zohdy et al. (1973), Zablocki (1976), Anderson and Johnson (1979), Aubert et al. (1984), Lénat (1987), Nishida and Tomiya (1987), Matsushima et al. (1990), Malengreau et al. (1994), Lewicki et al. (2003), and Finizola et al. (2003, 2006) just to cite few of them. The case of positive self-potential anomalies associated with recent lava flows has been already reported on basaltic shield volcanoes by (Lénat 1987; Jackson and Kauahikaua, 1987). Usually these positive self-potential anomalies are interpreted as the surface signature of preferential pathways for the upflow of hydrothermal fluids of deep origin (Zablocki, 1976; Ishido et al., 1989; Lénat et al., 1998; Finizola et al., 2004). In some other cases, these anomalies can be associated with thermohydromechanical disturbances associated to magmatic intrusion emplacement at depth (Hashimoto and Tanaka, 1995; Revil et al., 2003) or shear and hydrofracturing (Moore and Glaser, 2007). A comprehensive modelling of the relationship between transient self-potential anomalies and hydromechanical disturbances has been provided recently by Crespy et al. (2008) in the laboratory and Legaz et al. (2009a) in the field.

However, hydrothermal fields are not always associated with large self-potential anomalies. Small anomalies (<100 mV) were observed on the summit crater of Me-akan volcano (Hokkaido, Japan) in an area of intense fumarolic activity (temperature >500 °C) (Matsushima et al., 1990). Another example concerns the very small self-potential anomalies (few tens of mV) observed on the summit crater floor of Esan volcano (Hokkaido) despite the presence of intense fumarolic activity (Nishida et al., 1996). Recent developments of the electrokinetic theory describing the occurrence of self-potential signals associated with the movement of the water phase predict that the streaming potential coupling coefficient decreases with the water saturation and is null at the irreducible water saturation (Revil et al., 2007). This explains also why dry steam does not produce self-potential signals. In addition, the pH of the pore water plays a critical role in the occurrence of self-potential signals as illustrated by the observations made by Legaz et al. (2009b) at Inferno lake, Waimangu, New Zealand.

The positiveness of the self-potential anomalies associated with thermal anomalies is well-explained by the electrokinetic theory. The zeta potential, a key parameter describing electrokinetic effects, is negative. Basically, this means that the surface of the rock minerals is negatively charged. This charge is counterbalanced by positive mobile charges in a more external layer of the mineral. A fluid flow in the pore space (e.g. hydrothermal convecting water) carries these mobile charges downstream, thus making it positively charged (e.g., Overbeek, 1952; MacInnes, 1961; Revil, 2002). However, several cases of positive zeta potential have been reported in hydrothermal systems. Electrical surface potential of calcite, a secondary mineral often present in hydrothermal systems, can range from positive to negative values depending on CO_2 partial pressure, pH, and $[Ca^{2+}]$ (Revil, 1995; Pokrovsky et al. 1999). Guichet et al. (2006) demonstrated the effect of calcite precipitation on the electrokinetic behaviour of sand samples. They found zeta potential ranging from −17 to +8 mV for pH ranging from 8.6 to 11.7 depending on the amount of precipitated calcite. A few cases of positive zeta potential in active hydrothermal fields are presented by Hase et al. (2003) and Aizawa et al. (2008). This means that in some few cases, negative self-potential signals can be observed in the flow direction.

The magnitude of self-potential signals is also controlled by the distribution of the electrical resistivity of the ground (e.g., Ishido, 2004), which can be strongly influenced by the temperature itself (Revil et al., 2002). Resistivity is also very dependent on the water content of the rock, which can change over time in a geothermal system because of liquid–vapour phase changes (for a field example see Legaz et al., 2009b). In their experiments on advancing boiling front in a porous medium, Moore and Glaser (2004) have shown that the streaming potential can increase by a factor of 2 to 50 by comparison with single phase flow. This enhancement could be due to the increase in the bulk resistivity of the material.

3. Field survey

The Piton de la Fournaise is located on the west side of Réunion Island in the Indian Ocean (Fig. 1). It is one of the most active volcanoes in the world. Since 1998, the activity of this shield volcano has been characterized by an average of three eruptions per year producing mostly lava flows. During the last decade or so, several lava flows have reached the coastal area in the depression called Grand Brûlé (Bachèlery, 1999; Peltier, 2007) (Fig. 1). These recent lava flows are well-individualized bodies and can therefore be easily identified over a basement formed by older cold lava flows. Older lava flows are also more or less invaded by tropical vegetation. In this area, the lava flows crossed a south north running road and sometimes reach the sea (Fig. 1). Because this road is the only connection in this part of the island, it was rebuilt after each event (Fig. 2).

We performed self-potential measurements along a 9 km-long profile (Fig. 1). This profile is part of a larger dataset forming closed loops in this part of Réunion Island. We applied a closure correction along these loops to limit cumulative errors on such long profiles. A first dataset of self-potential measurements was acquired in February 2004 and repeated in July/August 2006, therefore with a time lapse of ~31 months. All the measurements were performed using non-polarizing $Cu/CuSO_4$ electrodes and a calibrated high impedance voltmeter (10 Mohm) with a sensitivity of 0.1 mV. During the measurements, the reference and moving electrodes were switched every few hundred meters in order to avoid the systematic error due to electrodes offset. We controlled the contact between the electrodes through the ground by checking the electric resistance before each measure point. As a rule of thumb, the electrical resistance between the two non-polarizing electrodes should be always ten times smaller than the internal impedance of the voltmeter (Corwin, 1997). The measured ground resistances were almost always smaller than 200 kΩ. During the 2006 survey, ~90% of the data were below 100 kΩ and only ~4% of the resistances reached values above 500 kΩ. No correlation appeared between self-potential