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Dynamics of volcanic eruptions: Understanding electric signatures for activity monitoring

Jacques Zlotnicki

CNRS-UMR62524, Observatoire de physique du Globe de Clermont-Ferrand, 24, avenue des Landais, 63171 Aubière cedex, France

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ABSTRACT

Aside common methods as seismology, ground deformation, and geochemistry, electromagnetic and especially electric ones can efficiently be applied for imaging and monitoring active volcanoes and hydrothermal systems that most often control the initial eruptive phase. Surveys and mappings image ground fluids flow, faults systems, and structural interfaces with anomalies up to several hundred of mV. Reiteration of surveys highlights time and spatial evolution. Continuous networks must extend surveys when the activity becomes stronger. Resolution in the data can reach a few microvolts as compared to the tens of millivolts for surveys. Observations made on several volcanoes definitively show that electric signals, up to some tens of millivolts, may appear some hours to a few weeks before ground deformation and seismicity, and are related to some extent to the location of the future activity. These transient signals may have a relationship with those recorded aboard satellites. Both of them appear during the transition period between the "fatigue" and the "dynamical" stages, which announces accelerating and irreversible processes.

1. Introduction

Up to now, seismology, ground deformations and geochemistry are much more prevalent in studying and monitoring volcanoes compared to electric and magnetic methods, although these latter methods may bring much information on the possible scenarios of future activity, among which a smooth a-seismic renewal of activity a long time prior to an eruptive event. In the following, attention will be primarily focused on electrical methods with the objective:

(1) to describe the potentiality of electrical methods for imaging volcanic structures of depths of up to several hundred meters in which hydrothermal systems take place;
(2) to illustrate changes in the electrical pattern of the static electric field [self-potential (SP) anomalies] linked to volcanic activity;
(3) to analyze signals of durations of less than a few hours that appear prior to volcanic activity, from land and satellite observations.

2. Mapping the electrical signature of volcanoes

The recognition of a deep magma body, generally located at depths between 6 and 12 km, is a difficult task that cannot yet be completely solved by any method. Most volcanic eruptions are initiated by disequilibria at this depth whatever the mechanism involved: injection from a deeper juvenile magma, crystallization, thermal input, or increase of stress. Generally, these phenomena begin a long time (up to some years) before an eruption, and it is difficult to monitor the weak, slow, and deep changes (Sasai et al., 2002) that may give rise to a patchwork of

Email address: jacques.zlotnicki@wanadoo.fr.

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small signals at the ground surface in the absence of seismicity. On the opposite, signals may be enhanced when deep phenomena begin to involve sources at a shallower depth, as in hydrothermal systems. These secondary sources induce thermal, gas emission, groundwater flow, change in the effective stress field, and opening micro-fissures inside aquifers. Thereby hydrothermal systems play the role of a relay and amplifier of phenomena having their origins at more out-of-reach depths. Transmission of the induced signals to the ground surface is effective through faults, craters/calderas rims, fumaroles, mud ponds and geothermal fields. Therefore, the difficulty in understanding, monitoring and predicting volcanic activities might be lessened by the fact that the dynamism of most eruptions is controlled by the upper volcanic structures.

One technique is based on the straightforward measurement of the electrical potential difference between two non-polarized electrodes well positioned in the ground. Using a reference electrode considered as a relative zero potential, the measurement of the potential every 10 to 50 m along an unrolled cable gives information on the groundwater circulation and the structural heterogeneities crossed by the survey, which can be as long as 10 km. Mixing different surveys with common sub-references allows us to totally map the SP anomalies at the ground surface. These anomalies define the "electrokinetic effect" and correspond to groundwater flows carrying electrical charges (Aubert and Dana, 1994; Ishido and Mitzutani, 1981). This method is effective, inexpensive, non-intrusive, and can easily be reiterated. However, data inversion requires the knowledge of many physical parameters that are often poorly known. Let us now consider examples of SP mappings on several volcanoes.

2.1. Application to different levels of activity

For our purpose, we may gather active volcanoes in three groups:

(I) volcanoes that do not currently own an active hydrothermal system in their upper part;
(II) those that exhibit large hydrothermal activity expressed by clay-rich rocks, soil degassing, warm outcrops, fumaroles, and a large related geothermal field at the ground surface;
(III) volcanoes that have well-developed hydrothermal systems located at some hundred meters below their central part, and are surrounded by non-strongly mineralized bedrocks.

Group I can be illustrated by Mount Pelée in Martinique (Zlotnicki et al., 1998) or La Garrotxa monogenetic volcanic field (NE Iberian Peninsula; Bolos et al., 2014). Group II concerns volcanoes submitted during several tens to hundreds of years to large interactions between meteoric or seawater recharges and hydrothermal fluxes coming from depth. In such conditions, SP anomalies generally do not reach hundreds of millivolts, and are not well-contrasted along geothermal fields and mineralized fissures. Soufrière of Guadeloupe (Brothelande et al., 2014; Zlotnicki et al., 2006), White Island in New Zealand (Hashimoto et al., 2004; Mizuhashi et al., 2004), Taal volcano (Fikos et al., 2012; Zlotnicki et al., 2009a) and probably Vulcano in Italy (Revil et al., 2008) belong to this Group II. Group III corresponds to a great number of volcanoes with an active hydrothermal system that has not yet involved the mineralization of the surrounding bedrocks. Let us recall some of them: La Fournaise in Réunion Island (Lénat, 1987; Michel and Zlotnicki, 1998), Miyake-jima (Sasai et al., 1997), Aso (Hase et al., 2005) and Fujiyama in Japan (Aizawa et al., 2005), Stromboli in Italy (Finizola et al., 2002), Masaya in Nicaragua (Mauri et al., 2012), and Tenerife volcanic complex in Canary Islands (Villasante-Marcos et al., 2014).

The above statements mean that SP mappings on volcanoes allow one to detect both the state of a hydrothermal system, if any, and the current activity. Mount Pelée and Miyake-jima can be used as case studies for illustrating two opposite states of hydrothermal activity.

2.1.1. Mount Pelée in Martinique Island

Mount Pelée (Martinique Island) is an andesitic composite volcano culminating at 1397 m a.s.l. and belonging to the Lesser Antilles inner arc (14°47′N, 61°10′W) (Fig. 1a). Since the settlement of European communities in 1635, four eruptions have occurred. The 1792 and 1851 eruptions were moderate, with phreatic phases, while the last two eruptions (1902–1904 and 1929–1932) were magmatic, with the formation of domes (Vincent et al., 1989). The 1902 eruption killed 28,000 inhabitants. At present, neither geothermal field nor surface activity takes place on the volcano, except in a small area to the southwest corresponding to the remaining trace of vents of the 1792 and 1851 eruptions. Rare volcanic seismic events are recorded per year, and hydrothermal exchanges are limited to the infiltration of meteoric water (5 m/year).

In 1991, SP measurements were performed with Pb–$PbCl_2$ electrodes (Petiau and Dupis, 1980) every 50 m in average, along 70 km of profiles (Fig. 1b) (Zlotnicki et al., 1998). Potential reference was fixed on the shoreline. SP values decrease as the altitude increases and the minimum, −1500 mV, was reached at the top of the volcano, in agreement with the absence of a hydrothermal system. Negative linear relationships between potential difference values and altitude, called "topographic effect", are observed along most of the radial profiles and express the simple gravitational infiltration of water through the edifice. The west–east cross-section evidences the addition of short wavelength SP anomalies related to structural boundaries characterizing calderas of Étang Sec and Macouba (Fig. 1b–d). In 1991, only a weak positive anomaly ($<$ 200 mV) to the southwest was observed which coincided with the residual trace of vents of the 1792 and 1851 eruptions. Resulting information are that:

(1) no active hydrothermal system was present;
(2) no deep thermal fluxes were coming from depth;
(3) as the whole, in 1991 the volcano was in a very quiet hydrothermally steady state.