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Electromagnetic and geochemical methods applied to investigations of hydrothermal/volcanic unrests: Examples of Taal (Philippines) and Miyake-jima (Japan) volcanoes

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ABSTRACT

Magnetic, -electric and -electromagnetic phenomena (EM) are almost always observed on volcanoes before and during volcanic eruptions, if EM methods are well-designed and applied on the field. But unfortunately these methods are, most often, still used independently. They also do not benefit of dense inter-correlated networks which should allow more accurate results and fine modelling of the volcanic activity. On volcanoes which display hydrothermal/magmatic unrests, EM methods can be combined with geochemical (GC) methods. The integration of these methods allows us to image in detail hydrothermal systems, to find out possible scenarios of volcanic unrest, and to monitor the on-going activity with some knowledge on the sources of heat, gas and fluid transfers. The objectives of this paper is (1) to outline the appearance and the characteristics of EM signals before an eruptive event when multi-EM methods are applied on the field, (2) to sketch out the complementary between EM and GC methods when these methods are jointly applied on volcanic/hydrothermal systems. Two case studies are given in the paper. On Miyake-jima volcano in Japan integrated EM methods started in 1995. Although the seismicity only appeared 13 days before the July 8, 2000 collapse of the summit, changes in the magnetic field, electrical resistivity and electric potential have progressively appeared after 1996. Based on geophysical observations and on continuous magnetotelluric soundings, a synthesis of the EM observations allows proposing a coherent model of the volcano unrest. The second case study is Taal volcano in Philippines on which sporadic, but sometimes intense, seismic crises are observed since 1992. A strong and large scale hydrothermal system stands on the volcano and is periodically re-activated. Commonly applied since 2005, combined EM and GC methods give an accurate description of the hydrothermal activity and heat discharge. EM methods, as magnetic and self-potential, map the hydrothermal system and locate the source of thermal and fluid transfers at depth, while soil degassing and thermal imageries clearly point out the location of the most active areas where thermal discharges take place. GC methods also specify the origin of the gas and fluids escaping from faults, fumaroles, and geothermal areas. Between 2005 and 2007, no large change in the hydrothermal activity took place, in spite of sporadic seismic swarms and surface activities which could lead to sudden phreatic explosions. The heat discharge of the volcano is estimated and monitored with time, based on repeated surveys. Such combined EM and GC methods are now integrated in the monitoring of the slow unrest of the volcano.

1. Introduction

Since many years, a large range of geophysical and geochemical (GC) signals related to volcanic activity have been recorded, including seismicity, ground deformation, changes of flux and composition of gas and water, thermal anomalies, gravity, electricity and magnetism. Among these techniques, the study of

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volcano-magnetic, -electric and -electromagnetic phenomena (EM) is relatively young. The so-called EM methods are more and more promising following pioneer works (i.e. Nagata, 1941; Johnston and Stacey, 1969; Johnston, 1989; Anderson and Johnson, 1976) that evidenced the great potentiality of these methods to characterize fluids and heat exchanges from deep volcanic sources to the ground surface. In this paper, we show that EM methods sometimes coupled with soil gas geochemistry and thermography, supply more consistent information on the dynamics of steady-state hydrovolcanic systems and might be a reliable response to track volcanic unrest and eruptive activity.

Many active volcanoes display extensive interactions between a deep magmatic supply and superficial aquifers. They often result in more or less developed hydrothermal systems. Therefore, imaging and monitoring structural and hydrothermal features are required to characterize the eruptive dynamism. It is the preliminary step to adequately select and set monitoring systems.

On the other hand, the final practical goal of monitoring active volcanoes is to forecast eruptive events with the highest level of confidence. It means that (1) the time of the surface activity has to be determined precisely, (2) the type of activity should be evaluated depending on historical eruptions and on precursory phenomena, (3) the location of the deep and sub-surface activities is needed, together with their potential interactions, and (4) the strength of the future eruption has to be estimated. To achieve these objectives, processing data from real time networks and repeated surveys, should be a reliable response. At present, nearly all eruptions might be forecast if enough high sensibility sensors are continuously operating, and if data processing and analysing are performed daily. However, the four points related to a complete forecast achievement are not yet reached.

In the following, we focus on two complementary approaches. In the first part, we discuss combined EM and GC methods for understanding the structure and the magma–fluid interactions at Taal explosive volcano in Philippines (14 N, 121 E). Possible eruptive scenarios are identified. The present day observations contribute to answer the points (2) and (3) for forecasting the next eruption. In the second part, we detail EM observations made during 6 years prior to the July 8, 2000 Miayke-jima phreato-magmatic eruption (Japan, 34°05'N, 139°30'E) which has led to the formation of a caldera of about 1.4 km wide and 400 m depth. No large scale GC methods were applied before the eruption due to weak soil degassing and inexistent hot springs. Based on the different EM observations (Nishida et al., 1996; Sasai et al., 1997, 2001, 2002; Zlotnicki et al., 2003) and on continuous magnetotelluric (MT) soundings, the characteristics of the signals (amplitude, spatial distribution, time scale) which have progressively appeared before the caldera formation are investigated. A coherent model of the volcanic unrest is proposed. Results show that points (3) and (1), developed before, are practically achieved although neither the type of activity nor the strength of the eruption are not yet correctly estimated.

2. EM methods

Heterogeneous lithologic or structural units, hydrologic groundwater channelling, thermal transfers, gas emission, and magma feeding system characterise any volcanic edifice. These characteristics generate a specific EM signature which can be detected at the ground surface. Country rocks enclose magnetic minerals which generate a magnetic field; a hydrothermal system and the related ground fluid circulation carry electric charges and give rise to an electric (and magnetic) field; magma supply, fluids and thermal transfers induce electrical resistivity contrasts. Regional setting and tectonic structures (faults, craters rim, etc.) introduce drastic irregularities superimposed to the large scale EM signature.

Self-potential (SP) methods are appropriate for mapping ground water and fluids flow, as well as to delineate geothermal areas and hydrothermal systems (i.e. Anderson and Johnson, 1976; Corwin and Hoover, 1979; Hashimoto and Tanaka, 1995; Ishido et al., 1997; Michel and Zlotnicki, 1998; Zlotnicki et al., 1998, 2006). VLF-MT and DC electrical resistivity soundings are proper methods to scan volcanic structures from one metre or so to very few hundreds metres depth (Zohdy et al., 1973; Lénat et al., 2004; Commer et al., 2006; Zlotnicki et al., 2006; Nicollin et al., 2006). For deeper investigations, the preceding techniques become less powerful and are successfully replaced by MT soundings (generally 1000 s to 10 kHz) (Matsushima et al., 2001; Aizawa et al., 2005). In addition to these methods based on the electric field, pure magnetic surveys inform on the thermal state up to a few kilometres depth and on the structural discontinuities (i.e. Araña et al., 2000).

At a given time, EM signature defines the quasi static image of a volcanic structure and of the state of activity.

On the other hand, energy and thermal transfers partly control the eruptive dynamism depending of volcanic/hydrothermal systems. When groundwater circulation, hot gas emission, thermal convection, and hydrothermal activity are prevailing in the first hundreds metres depth, EM signatures are magnified (Adler et al., 1998; Ishido and Pritchett, 1999; Johnston et al., 2001). Consequently, EM methods become also powerful for detecting a superficial thermodynamic disequilibrium associated with a deep activity (Sasai et al., 2001, 2002). Mostly, several methods can be applied jointly.

Large scale changes in the volcanic activity can be monitored by repeated surveys and soundings. SP anomalies, up to several hundreds of mV, have been reported above geothermal areas and hydrothermal systems prior to eruptive events (Massenet and Pham, 1985; Hashimoto and Tanaka, 1995; Zlotnicki et al., 2001, 2003). Magnetic anomalies of amplitude less than tens of nT have been evidenced on many volcanoes and were primarily associated with thermal changes and piezomagnetic effects (i.e. Pozzi et al., 1979; Tanaka, 1993; Johnston, 1989; Sasai et al., 2001, 2002; Del Negro and Currenti, 2003). The time lag between two surveys – between a few days and several months – depends on the ongoing pre-eruptive activity, on the scale of anomalies and on the uncertainty due by manual measurements. Furthermore, such surveys cannot be achieved during the final stage of an eruptive event.

Continuous networks are more suitable to detect weak EM build-up anomalies. The first method was based on the total magnetic field recording (i.e. Johnston and Stacey, 1969). Scalar magnetometers were used because they are not drifting with time. Magnetic signal of about 1 nT can be identified by total magnetic field recording (i.e. Del Negro and Currenti, 2003). A second method uses buried electric lines associated with non-polarizing electrodes and SP signals of 1 or 2 mV/km in amplitude can be monitored (see review Zlotnicki and Nishida, 2003). Examples of anomalies of the electrical resistivity using artificial methods were also observed before 1986 Oshima and 2000 Miyake-jima eruptions (Yukutake et al., 1990; Zlotnicki et al., 2003). Another method, based on simultaneous records of the orthogonal electric and magnetic fields, is described in this paper. Continuous resistivity changes are computed by MT processing prior to Miyake-jima eruption.

3. Geochemical methods

Quiescent hydrothermal/volcanic active sites are worldwide distributed and result from interactions of rising magmatic fluids to the ground surface and ground waters. Typical hydrovolcanic processes produce large steaming ground areas, fumaroles, thermal waters and mud pools. They imply extensive fluids and heat transfer from boiling aquifers located over magma chambers to