Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G37015.1

Hydrothermal fluid flow disruptions evidenced by sub-surface changes in heat transfer modality: the La Fossa cone of Vulcano case study

Tullio Ricci[1], Anthony Finizola[2], Stéphanie Barde-Cabusson[3], Eric Delcher[2], Salvatore Alparone[4], Salvatore Gambino[4], and Vincenzo Milluzzo[5]

[1]Istituto Nazionale di Geofisica e Vulcanologia, via di Vigna Murata 605, 00143 Roma, Italy

[2]Laboratoire GéoSciences Réunion, Université de la Réunion, Institut de Physique du Globe de Paris, Sorbonne Paris-Cité, CNRS UMR 7154, 15 Avenue René Cassin, CS 92003, 97744, Saint-Denis, La Réunion, Indian Ocean, France

[3]Institute of Earth Sciences Jaume Almera, ICTJA-CSIC, C/Lluís Solé i Sabarís s/n, 08028 Barcelona, Spain

[4] Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo, Piazza Roma 2, 95125 Catania, Italy

[5] Eni Angola, Avenida Lenine 58, Luanda, Angola

ABSTRACT

Detecting volcanic unrest is of first importance for eruption forecasting, especially on volcanoes characterized by highly dangerous – and often seemingly unpredictable – phreatic or phreatomagmatic eruptions. We present a simple and innovative analysis of shallow vertical temperature profiles up to 70 cm depth. These data were recorded at La Fossa cone of Vulcano, during an episode of increased hydrothermal and seismic activities that occurred between September and December 2009. This work involves the use of the coefficient of determination (R^2) on vertical temperature profiles in order to identify changes in conductive vs. convective heat transfer modality. The increase in convective heat transfer can be related to the disruption of the hydrothermal system due to its pressurization and/or variation of ground permeability between the hydrothermal system and the surface. While raw temperature data do not evidence any significant variation during the period investigated and the classic temperature gradient is highly influenced by seasonal variations, the fluctuation of R^2 displayed striking spikes coinciding with seismic swarm occurring inside the volcanic edifice. Such a low cost device associated with easy, real time data processing could constitute a very promising – yet deceptively simple – technique to monitor hydrothermal systems, assessing the hazard posed by high energy eruptions for populations living close to active volcanoes.

INTRODUCTION

Hydrothermal systems are characterized by important mass and energy transfer, through the circulation of hot fluids underground that can be evidenced by geological, geophysical, or geochemical observations. One consequences of hydrothermal circulation is the alteration and the weakening of the permeable ground inside volcanic edifices. Hydrothermal alteration highly decreases the permeability of the medium and disrupts fluid circulation through self-sealing processes. Such modifications may increase pore pressure, whose changes in hydrothermal system give an indication about the general state of volcanic unrest, sometimes promoting highly hazardous explosive phreatic or phreatomagmatic eruptions (Heiken et al., 1980; Barberi et al., 1992; Germanovich and Lowell, 1995; Ui et al., 2002; Starostin et al., 2005; Fournier and Chardot, 2012).

Studying variations in hydrothermal systems activity is crucial to exploring their role in and potential to forecast highly explosive explosions. Therefore, identifying the key parameters which indirectly highlight the state of pressurization of the system is necessary to develop early warning of highly explosive eruptions. Temperature is perhaps the easiest and most obvious observable, which can be measured with soil temperature sensors, infrared cameras, or by satellite based multispectral infrared images (Gaudin et al., 2013).

Unfortunately, changes in temperature of hydrothermal system fluids, are not an easy parameter to be used to identify precursors of volcanic unrest. In fact, temperatures are affected by many external parameters such as daily and seasonal variations, rainfall, and wind speed and direction (Dawson and Fisher, 1964; Keszthelyi et al., 2003; Chiodini et al., 2005; Hochstein and Bromley, 2005; Peltier et al., 2012).

The aim of this paper is to propose an innovative method to process soil temperature time series that could be used in volcano observatories for real time monitoring. This new technique can identify disruptions of hydrothermal fluid flow potentially leading to volcanic unrest.

APPLICATION SITE AND INSTRUMENTATION

The test site where our temperature instrumentation was installed is La Fossa cone on Vulcano Island, because of its persistent fumarolic activity, the presence of sub-fumarolic areas evidenced by previous studies (Revil et al., 2008; Barde-Cabusson et al., 2009), and the recurrence of fumarolic crises during the last few decades (Chiodini et al., 1992; Granieri et al., 2006).

La Fossa cone, formed in the last 6 ka on the island of Vulcano, provides the historic basis for the term "vulcanian" type phreatomagmatic explosive eruptions characterized by water-magma interaction (Frazzetta et al., 1983; Büttner et al., 1999; Dellino et al., 2011). The structure of the present day edifice results from six main phases of activity (De Astis et al., 2006), chronologically associated with crater boundaries: (1) Punte Nere, (2) Palizzi, (3) Forgia Vecchia, (4) Pietre Cotte and (5) Gran Cratere (Fig.1a). Each one of these structural boundaries is associated with relevant temperature anomalies identified through measurements at 30 cm depth (Revil et al., 2008; Barde-Cabusson et al., 2009), highlighting the major role of these crater ring faults in channeling hydrothermal fluids toward the surface.

Two sites of anomalous temperature were chosen for the installation of our instrumentation and correspond to two structural boundaries located outside the main fumarolic field of La Fossa crater (see Fig.1a): (1) Gran Cratere (GC in Fig.1a) and (2) Punte Nere (PN in Fig.1a), located at 250 m and 600 m from the last eruptive crater respectively.

We used data logger EBRO, EBI-2T type 313 instrumentation to monitor the temperature in the soil. The device temperature range is -40/+150°C, with four channels and four PT1000 sensors. The resolution is 0.1°C and the measuring accuracy is 0.2°C. The temperature sensors were placed at the precise depths of 10, 30, 50 and 70 cm in areas where the soil temperature at 70 cm depth ranged between 70 and 80°C. Indeed, it is essential to avoid areas where temperature signal is saturated by the buffering effect of steam present at boiling temperature.

Since its last magmatic eruption (1888-1890), La Fossa crater has been affected by two main episodes of increased fumarolic activity and temperature. The first occurred during the period 1913-1923 (Sicardi, 1941), and the second began in 1978 after a M=5.5 earthquake (Chiodini et al., 1992). Relevant changes in the fumarolic composition occurred in 1979-81, 1985, 1988, 1996, and on December 2004 and 2005 (Granieri et al., 2006; Carapezza et al., 2011).

At Vulcano, seismicity is associated with volcano-tectonic sources or is related to fluid dynamics within the hydrothermal system (Aubert et al., 2008; Cannata et al., 2012; Madonia et al., 2013). The first case is generally related to the NNW-SSE Tindari-Letojanni regional fault system dynamics (Gambino et al., 2102) and results in a few events/year while the second comprises seismo-volcanic events occurring in the hydrothermal system underlying La Fossa cone, from several hundred to thousands/year (Alparone et al., 2010; Milluzzo et al., 2010) .

We compared seismic data with our results, since seismic swarms suggest the disruption of the hydrothermal system, an increase of the permeability inside the edifice and, consequently, an increase of hot fluids flow towards the surface (Cannata et al., 2012; Milluzzo et al., 2010).

During our experiment, seismicity detected by the Istituto Nazionale di Geofisica e Vulcanologia seismic network (Fig. 1b) was characterized by a seismic swarm which occurred at shallow depth below La Fossa cone between September 29th and December 16th 2009 (Fig.2e). During this seismic swarm a total of 3471 seismic events were detected in 79 days (an average of 43.9 events/day vs. 11.2 events/day characterizing the period before the swarm). Due to the very low energy released, the identification of hypocenters was possible only for the 72 (2.1 %) most energetic seismic events, mainly located between 600 and 1200 m b.s.l.. In terms of number of events per day, this seismic swarm was the most important of the last two decades (Harris et al., 2012). At the same time, several geochemical parameters increased by one order of magnitude, such as soil CO2 flux and SO2 in the plume, indicating disruptions in the underlying magmatic system (Inguaggiato et al., 2012).

RESULTS

Raw data for soil temperature recorded at Gran Cratere (GC) and Punte Nere (PN) in the period May 12th 2009 - July 28th 2010 (Fig.2a,c) displayed at both sites a classic pattern of environmental temperature variations (periodic long-term seasonal variations, and short-term daily variations) disrupted by rainfall events. At the GC site no temperature variation could be associated with the 2009 seismic swarm. At PN site, however, only a weak variation of the signal coincided with changes in the seismicity, although there was no clear evidence to support this. In contrast, the temperature gradients calculated between 70 and 10 cm depths displayed a strong seasonality at both sites, preventing any possibility of clearly detecting disruptions related to hydrothermal activity (Fig.2b,d). In fact, despite we can note changes in temperature gradient coinciding with variations of R2 at both sites, other changes of same amplitude in temperature gradient also appears outside the seismic swarm period. This means that changes in temperature gradient are not exclusively related to hydrothermal system disruptions and they remain unclear due to a low signal to noise ratio.

In order to determine if the 2009 seismic swarm influenced the heat transfer modalities inside La Fossa cone, we computed a linear regression of temperature versus depth and R2 at each site and time interval. The aim of this analysis was to discriminate the conductive dominated heat transfer from a more convective one . The former is characterized by a linear gradient giving R2 close to 1 while the latter by a non-linear gradient giving lower R2 values.

Applying an R2 analysis to our vertical temperature profiles, presented in Figure 2a,c, we obtained the results shown in Figure 2b,d. On both GC and PN sites, significant anomalous spikes of R^2 coincide with the seismic swarm, showing an obvious disruption in the hydrothermal fluid flow.

DISCUSSION

The comparison between the temperature raw data and the R2 variations obtained in the same dataset displays striking results because no temperature anomaly is obvious in the raw data during the period of seismic swarm. The main external parameters influencing the superficial soil temperature were daily and seasonal temperature variations and contrast between sunshine and cloudy periods. Each one of these parameters is related to pure heat conduction in the soil, hence exhibit a R^2 close to 1 despite substantial changes in temperature. These three external parameters have a different influence on temperature values measured by each individual sensor, as shown by the temperature gradient variations (Fig. 2b,d). Conversely they do not significantly affect the heat transfer modality (conductive/convective) of the heat toward the surface, which is mainly driven by the energy released at depth by the hydrothermal system. Although these external processes strongly modify the temperature values, they do not disrupt the linearity of the temperature gradient as a function of depth. In this sense, the

R^2 analysis constitutes an excellent filter for these external parameters and allows for extracting variations related to convective heat transfer of deep origin.

Among the external parameters influencing temperature values, rainfall deserves some additional explanation. Indeed, a rainfall corresponds to an injection of a cold fluid into the soil, which decreases the temperature and makes the top of the condensation zone deeper . As a consequence, the thickness of the conductive zone located above the condensation level increases, as well as R^2. It can take from several days to a few weeks before temperature disruption induced by a rainfall vanishes and the temperatures come back to their initial values (Chiodini et al., 2005; Peltier et al., 2012). The duration of the disruption depends on the intensity of the rain and on the geothermal energy released from the soil. Although rain events appear to have more significant consequences on the convective component, it is interesting to note that the external parameters previously described (seasonal and diurnal variations and strong sunshine periods) do not disrupt the signal toward a more convective end member. Therefore, a decrease of R^2 is basically the result of an increase in the advective hydrothermal fluid flow toward the surface.

Moreover, unlike remote techniques used for temperature detection (e.g. IR-camera or IR-channel of satellite images), cloudy weather has no adverse effect on the acquisition of soil temperature data, representing a real advantage in thermal monitoring of active volcanoes.

It is worth noting that the seismic swarm began 9 days before the decrease of R^2 values, September 29th and October 8th respectively. This time delay suggests that the disruption of the hydrothermal fluid flow at the surface could be a consequence of the seismic swarm. In fact, small perturbations temporarily increasing the pore pressure can modify the effective normal stress and trigger seismicity. This phenomenon and others fracturing processes (due to alteration of rock to secondary minerals with reducing the shear stress required to initiate fracturing and/or increases of temperatures in the rock with consequently rock fracture) are also able to enhance the rock vertical permeability, thus favoring the rise of fluids (Cannata et al., 2012 and references therein).

CONCLUSIONS

Our results indicate that monitoring the linearity of the vertical temperature profiles at shallow depths (up to 70cm) – hence changes from conductive to convective heat transfer in near surface – is an efficient tool for the identification of volcanic unrest associated with a disruption of a hydrothermal system. The installation of such a simple temperature monitoring device could be considered by volcano observatories because it gives fundamental information on changes of heat transfer modality not highlighted by ordinary thermal monitoring. Moreover, data processing can be easily integrated in a real time monitoring for surveillance purposes. An increase of the hydrothermal activity can be related to pressurization and/or permeability changes inside the edifice, potentially leading to explosive activity. Such information is of prime importance for eruption forecasting and hazard assessment and, ultimately, volcanic risk mitigation.

ACKNOWLEDGMENTS

This work has been supported by the University of La Réunion-IPGP and CNRS-INSU project, and one month IPGP “Invited Researcher” program for T. Ricci in the Laboratoire GéoSciences Réunion. S. Barde-Cabusson was funded by JAE-Doc Program (JAEDoc_09_01319). The authors thank B. Suski and M. S. Davis for constructive comments concerning the manuscript and U. Sistometro for field assistance. Comments from the reviewers N. Fournier, D. Hasterok and G. Chiodini greatly improved the manuscript. This is IPGP contribution number 3524. Data are freely available from the authors upon request.

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FIGURE CAPTIONS

Figure 1. Location of crater boundaries, temperature data loggers, seismic network, and hypocenters of the 2009 seismic crisis at La Fossa cone of Vulcano. a) Location of the two temperature data logger over the soil temperature map (measured at 30 cm depth). “Pa” stands for Palizzi, “FV” stands for Forgia Vecchia, and “PC” stands for Pietre Cotte. “IVCR” locates the INGV permanent seismic station of La Fossa cone. b) Location of the INGV permanent seismic stations (green triangles) operating at Vulcano Island, used to locate the hypocenters of the 2009 seismic crisis, and of the seismic events (red squares) during the 2009 seismic crisis at La Fossa cone.

Figure 2. Temperature variations, Coefficient of determination R^2, and seismic events. a,c**)** Raw data of the temperature measured at 10, 30, 50, and 70 cm depth at Gran Cratere and Punte Nere during the period May 12th 2009 - July 28th 2010. b,d) Coefficient of determination (R^2) (in red) and temperature gradient between 70 and 10 cm depth (in black and yellow) calculated on the two temperature data sets for the same period. e) Number of seismic events recorded at IVCR station with the relative cumulative curves. The green area represents the period of seismic crisis evidenced by the cumulative curve of seismicity. The coefficient of determination allows distinguishing the evolution from a conductive to a convective heat transfer induced by a disruption of the hydrothermal system during the seismic crisis.

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