Earth and Planetary Science Letters 414 (2015) 58–67

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Evidence of thermal-driven processes triggering the 2005–2014 unrest at Campi Flegrei caldera

Giovanni Chiodini [a,*], Jean Vandemeulebrouck [b,c], Stefano Caliro [a], Luca D'Auria [a], Prospero De Martino [a], Annarita Mangiacapra [a], Zaccaria Petrillo [a]

[a] Istituto Nazionale di Geofisica e Vulcanologia (INGV), Osservatorio Vesuviano, Via Diocleziano 328, Napoli, Italy
[b] Université de Savoie, ISTerre, F-73376 Le Bourget du Lac, France
[c] CNRS, ISTerre, F-73376 Le Bourget du Lac, France

ARTICLE INFO

Article history:
Received 25 June 2014
Received in revised form 17 December 2014
Accepted 9 January 2015
Available online 23 January 2015
Editor: T. Elliott

Keywords:
Campi Flegrei caldera
hydrothermal system
ground deformation
magmatic fluids
caldera unrest

ABSTRACT

An accelerating process of ground deformation that began 10 years ago is currently affecting the Campi Flegrei caldera. The deformation pattern is here explained with the overlapping of two processes: short time pulses that are caused by injection of magmatic fluids into the hydrothermal system; and a long time process of heating of the rock. The short pulses are highlighted by comparison of the residuals of ground deformation (fitted with an accelerating polynomial function) with the fumarolic CO_2/CH_4 and He/CH_4 ratios (which are good geochemical indicators of the arrival of magmatic gases). The two independent datasets show the same sequence of five peaks, with a delay of ∼200 days of the geochemical signal with respect to the geodetic signal. The heating of the hydrothermal system, which parallels the long-period accelerating curve, is inferred by temperature–pressure gas geoindicators. Referring to a recent interpretation that relates variations in the fumarolic inert gas species to open system magma degassing, we infer that the heating is caused by enrichment in water of the magmatic fluids and by an increment in their flux. Heating of the rock caused by magmatic fluids can be a central factor in triggering unrest at calderas.

1. Introduction

The trigger mechanism of unrest at active calderas is one of the most problematic issues of modern volcanology (Newhall and Dzurisin, 1988; Lowenstern et al., 2006; Troise et al., 2006; Gottsmann and Marti, 2008). In particular, magma displacement *versus* hydrothermal dynamics is one of the central questions for an understanding of the signals of several restless calderas on Earth, including, e.g., Yellowstone (Wicks et al., 2006; Lowenstern et al., 2006; Dzurisin et al., 2012), Long Valley (Hill, 2006), Santorini (Parks et al., 2012), Nisyros (Chiodini et al., 2002), and Campi Flegrei. Here we focus on Campi Flegrei caldera (CFc), which is sited in the densely inhabited metropolitan area of Naples (southern Italy; Fig. 1, Napoli). Campi Flegrei caldera has recently given clear signs of potential reawakening (Chiodini et al., 2012) where long time series of geophysical and geochemical data are available. Throughout its history, CFc has alternated between phases of uplift and subsidence over a range of timescales (Rosi et al., 1983; Di Vito et al., 1999; Orsi et al., 2004; Morhange et al., 2006), and it showed evidence of decades-long inflation prior to the last magmatic eruption (the AD 1538 Monte Nuovo eruption; Dvorak and Mastrolorenzo, 1991). The Monte Nuovo eruption was followed by a long period of subsidence, until the early 1950s, when inflation was resumed. This has culminated in two major uplift and seismic episodes ('bradyseisms'), which occurred in 1969–1972 and in 1982–1984, which have shown a total vertical displacement of 3.8 ± 0.2 m (Del Gaudio et al., 2010, and references cited therein). In 1982–1984, the maximum uplift of 1.8 m was accompanied by ∼16 000 shallow earthquakes that affected CFc, which caused the partial evacuation of the heavily populated town of Pozzuoli (Barberi et al., 1984).

Since 1985, CFc has been slowly subsiding, which has been interrupted by a few minor uplift events. In 2005, there was new inflation, which accelerated and reached a maximum vertical displacement of about 23 cm by June 2014. This last stage was accompanied by weak seismicity, by a strong increase in fumarolic activity (Fig. 2), and by important compositional variations in the fumarolic effluents, which were interpreted as increased contributions from a magmatic source (Chiodini et al., 2012, and references therein). For instance, these phenomena induced the Italian Civil

* Corresponding author. Tel.: +39 081 6108448; fax: +39 081 6100811.
E-mail address: giovanni.chiodini@ingv.it (G. Chiodini).

http://dx.doi.org/10.1016/j.epsl.2015.01.012

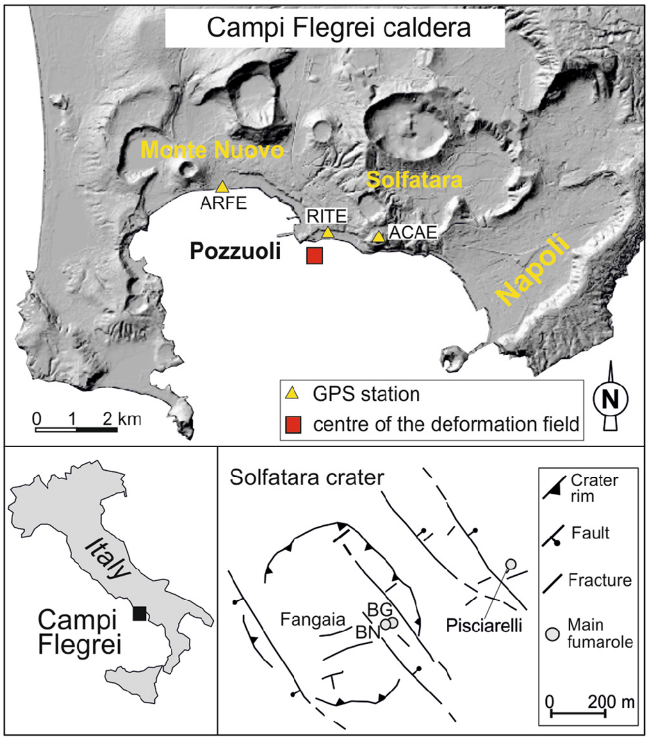

Fig. 1. Location of Campi Flegrei caldera, Solfatara crater, and the main fumaroles. The map also shows the position of the CGPS stations referred to in the text, and the deformation field during 2005–2014.

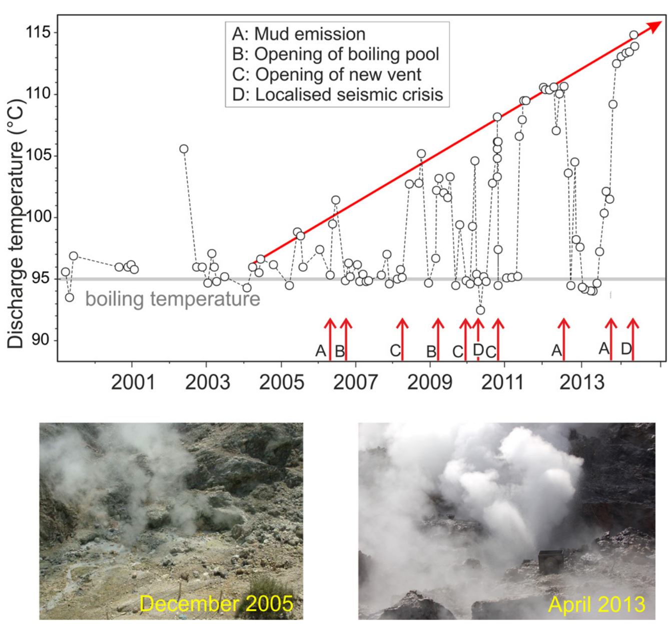

Fig. 2. Time series of discharge temperatures at Pisciarelli fumarole, and chronogram of localized phenomena that have affected the hydrothermal site (red arrow). The two pictures highlight the strong increase in fumarolic flow rate from 2005 to 2013. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Defence to change the state of Campi Flegrei from the green level (quiet) to the yellow level (scientific attention).

The first part of this study aims to illustrate the main features of this hydrothermal system. Then, we investigate the possible causes of the new unrest at CFc, by comparison of the long time series of the Solfatara fumarole composition with ground deformation data obtained from the continuous GPS network (De Martino et al., 2014).

1.1. The hydrothermal system that feeds Solfatara

A conceptual geochemical model of the hydrothermal system that feeds the fumaroles of Solfatara based on fumarole effluent composition was first proposed by Cioni et al. (1984), and then refined by Cioni et al. (1989), Chiodini et al. (1996, 2001, 2010), Chiodini and Marini (1998), and Caliro et al. (2007). According to the most comprehensive work of Caliro et al. (2007), hot gases separate from the magma at depth, ascend toward the surface, mix with boiling meteoric water to form a gas plume that feeds fumaroles and diffuse soil degassing at Solfatara. This geochemical interpretation has been supported by numerous physical–numerical simulations that have been published in the last 10 2years (Chiodini et al., 2003, 2012; Todesco et al., 2003; Todesco, 2009; Rinaldi et al., 2010; Petrillo et al., 2013). All of the models have consisted of injection at depth beneath Solfatara crater (1.5–2.5 km) of a hot CO_2–water mixture, where its flux is constrained by the surface hydrothermal flux measured at Solfatara. All of the simulations have been performed with the TOUGH2 code (Pruess, 1991) under steady-state conditions, and they have returned the presence of a gas plume that vertically connects the deep injection zone to the surface.

Together with geochemical interpretations and simulation results, other independent data highlight the presence of a gas plume in the subsoil of Solfatara crater:

- The total CO_2 release from diffuse degassing processes at Solfatara and its surroundings ($\sim$1.4 km^2; Fig. 3a) was estimated at 1000 t/d to 1500 t/d from 1998 to 2010 (Chiodini et al., 2010). In addition, recent measurements of gas flux from the three main fumaroles of Solfatara that were performed in January 2013 indicated a total CO_2 output of up to $\sim$600 t/d (Aiuppa et al., 2013). The total CO_2 flux of 1500 t/d to 2000 t/d was obtained by summing the fumarole fluxes and the diffuse emission, and this has to be considered as a minimum estimation of the total hydrothermal CO_2 output, because it does not consider the flux of the numerous smaller fumarolic discharges that have never been measured. Such high hydrothermal CO_2 flux is more compatible with the presence in the subsoil of a large zone where there is a gas phase (i.e., the gas plume), rather than with a boiling process of a liquid, which would require unreasonable amounts of boiling water. For example, at Yellowstone, high diffuse CO_2 fluxes of the same magnitude as at Solfatara (i.e., $\sim\mathrm{kg\,m^{-2}\,d^{-1}}$), are normally found in vapor-dominated hydrothermal areas (i.e., acid–sulfate areas), while relatively low diffuse CO_2 fluxes are observed in areas that are dominated by thermal liquid discharges (e.g., alkaline-chloride areas) (Werner and Brantley, 2003).
- At Solfatara, the aquifer is anomalously high for both the water table height (Fig. 3b) and the water temperature (Fig. 3c), with temperatures up to boiling point (Petrillo et al., 2013). These anomalies are due to the large amounts of condensates, which are of the order of thousands of tons per day, and which locally recharge and heat the groundwater system (Bruno et al., 2007; Petrillo et al., 2013). The height of the water level indicates that a pressurized gas plume sustains the aquifer here. Similar observations of aquifers saturated with hot water condensing from an underlying gas reservoir have been reported for vapor-saturated hydrothermal systems in Yellowstone (Zohdy et al., 1973) and at Waimangu, New Zealand (Legaz et al., 2009).
- The S-wave seismic velocity (*Vs*) models (data from Battaglia et al., 2008; Zollo et al., 2006; Fig. 3d) clearly delineate a vertical, roughly cylindrical, high-*Vs* structure that extends from the surface close to Solfatara crater, down to at least 1.5 km. This *Vs* anomaly is unique in the shallower part of CFc, and