Journal of Volcanology and Geothermal Research 177 (2008) 1035–1044

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Hydrothermal origin for sustained Long-Period (LP) activity at Campi Flegrei Volcanic Complex, Italy

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ARTICLE INFO

Article history:
Received 1 April 2008
Accepted 27 July 2008
Available online 3 August 2008

Keywords:
Campi Flegrei caldera
Long-Period earthquakes
crack model
Sompi method
gas composition

ABSTRACT

We present a detailed analysis of the source properties of Long-Period (LP) signals recorded at Campi Flegrei Caldera (Italy) during the last (2005–2006) mini-uplift episode. Moment Tensor inversion via full-waveform modelling of broad-band seismograms indicates a crack-like source with a significant volumetric component. From auto-regressive modelling of the signal's tail we evaluate the dominant frequency and the attenuation factor of the oscillating source. Considering the acoustic properties of a fluid-filled crack, these values are consistent with the resonant oscillations of a crack filled by a water–gas mixture at variable gas–volume fraction. For these fluids, the crack size would be on the order of 40–420 m, a size range which is consistent with the spatial spreading of LP hypocenters. Analysis of temporally-correlated time series of seismological and geochemical data indicates that climaxing of LP activity was preceded by swarms of volcano-tectonic (VT) events and rapidly followed by a consistent increase of both thermal emissions and gas fluxes recorded at the surface (1 month — 2/3 days, respectively). Following these observations, we propose a conceptual model where VT activity increases permeability of the medium, thus favouring fluid mobility. As a consequence, the hydrothermal system experiences pressure perturbations able to trigger its resonant, LP oscillations.

1. Introduction

Campi Flegrei (CF) volcanic complex hosts a nested caldera and is located in a densely populated area (1.5 million inhabitants) to the west of Naples, Southern Italy. Its magmatic system is still active, as testified by the 1538 AD Monte Nuovo eruption (Di Vito et al., 1999); the recent bradyseismic episodes in 1969–1972 and 1982–1984 that have generated a net uplift of 3.5 m around the town of Pozzuoli, and the widespread occurrence of fumaroles and thermal springs. The combination of dense urbanization and a very active volcanic system results in a high volcanic threat in the area. Since the large (about 1.7 m; Berrino et al., 1984) 1983–1984 vertical ground deformation event, the area has been subjected to a general subsidence, interspersed by minor uplift episodes in 1989, 1994, 2000 and 2005–2006. A characteristic of these movements is that seismicity always accompanies the uplift phases, while subsidence occurs aseismically (Saccorotti et al., 2001). Despite the small amount of net uplift (5 cm), the 2005–2006 deformation episode was accompanied by the largest release of seismic energy observed since 1985. In addition, remarkable swarms of Long-Period (LP) signals occurred, accounting for some 800 events in total, spanning a 6-day-long period starting on October 23, 2006. This latter observation has been considered with particular concern, as the occurrence of Long-Period signals in volcanic/hydrothermal areas is indicative of a source mechanism associated with fluid-rock interaction, and could thus represent an indicator of renewing volcanic activity (e.g., Chouet, 1996a, 2003).

In a previous paper (Saccorotti et al., 2007; hereafter referred to as S07) we presented an extended analysis of location and temporal evolution for both VT and LP seismicity that accompanied the 2005–2006 uplift episode (see Fig. 1). The main results gained from this previous work are synthesized as follows:

1. VT seismicity starts in coincidence with, and occurs throughout, the uplift phase. It consists of 269, low-magnitude (Md<2) events, 83 of which were successfully located. These hypocenters are mainly clustered beneath the Solfatara-Accademia area (Fig. 1), at depths ranging between 1 and 4 km b.s.l.;
2. The time occurrence of VT seismicity does not exhibit any clear evolutionary pattern for which concerns both magnitude and source depth;
3. Precise, absolute locations of LP signals indicate a source area located beneath the southern border of the Solfatara Crater, at depths of about 500 m b.s.l.;
4. Several evidences, including (a) comparison with spectra from background noise, (b) comparison with spectra from VT events sharing common locations, and (c) the particle motion orbits, indicating a wavefield dominated by P-waves, suggest that the marked spectral peaks exhibited by LP signals actually reflect a source

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0377-0273/$ – see front matter
doi:10.1016/j.jvolgeores.2008.07.019

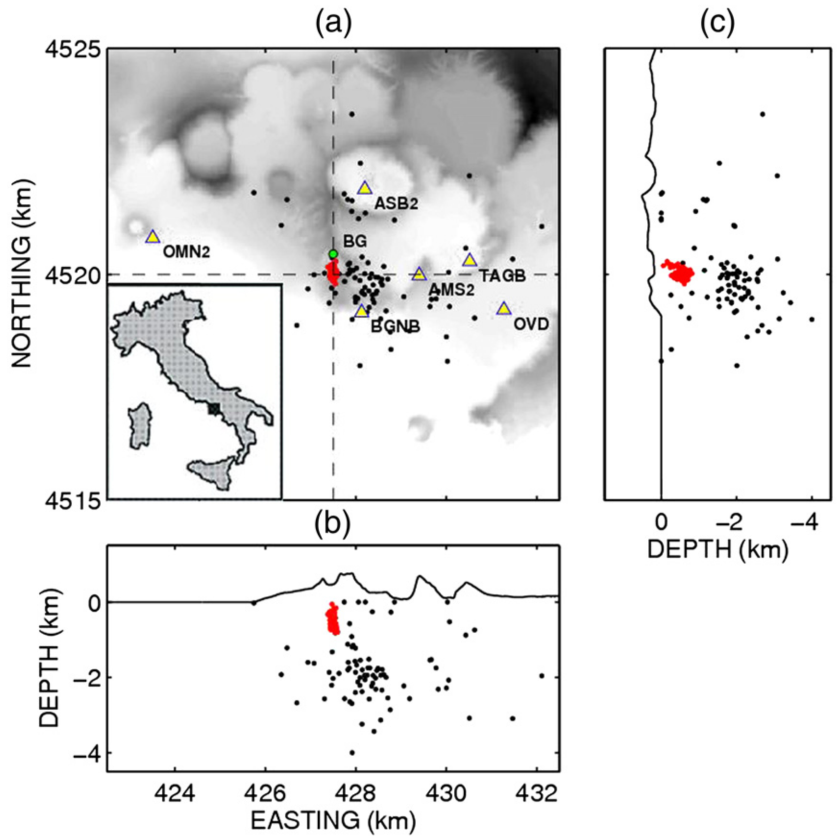

Fig. 1. LP and VT location. (a) Map of Campi Flegrei Caldera, with location of LP and VT epicenters (red and black dots, respectively). The inset at the lower left marks location of the study area with respect to Italy. Yellow triangles mark the broad-band stations used for this study. The green dot indicates the location of Bocca Grande (BG) fumarole, at the NE margin of the Solfatara Crater. The two dashed lines mark the surface trace of the vertical EW and NS cross-sections used for projecting the LP and VT hypocenters displayed in (b) and (c), respectively. In these two latter panels, topography is vertically exaggerated by a factor 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

effect. Based on these data, S07 postulated the acoustic resonance of a fluid-filled cavity as the most likely source process of these signals;

5. Relationship between the occurrence of VT and LP signals suggests that a cause-effect link exists between the two phenomena. The 6-day-long LP activity occurred right after the most significant step in the VT energy release. LP signals and most VT events share the same epicentral region, but VT hypocenters are significantly deeper (1–3 km b.s.l.).

Over the past few years, integration of geophysical and geochemical data provided useful insights into the dynamics of hydrothermal aquifers at collapsed calderas (e.g., Campi Flegrei: Todesco, 2005; Battaglia et al., 2006; Yellowstone: Tikku et al., 2006; Nisyros: Gottsmann et al., 2007). Following these studies, this work aims at providing a coherent picture about the dynamics of the Solfatara hydrothermal system during the 2005–2006 awakening episode, from integration of source analysis of LP seismicity and geochemical parameters observed at the surface.

The paper is structured as follows: first, we conduct a Moment Tensor inversion via full-waveform modelling in order to gain insight into the LP source geometry and setting. Then, we use an auto-regressive approach to precisely determine the spectral content and attenuation factor of LP recordings. Using Chouet's (1988) crack model, we interpret these data in terms of source dimension and composition of the fluids contained therein.

Eventually, we compare the time series of seismicity with those related to gas outflux and soil temperature. From these data, we find that the typical VT–LP successions are rapidly followed by delayed (on the order of a few days) increases of gas flux at the ground surface. These observations enable us to propose a final model in which the VT fracturing process locally increases the permeability of the medium, thus facilitating underground fluid migration. This process would induce the transient pressurization of the shallow hydrothermal system, in turn causing its resonant, LP oscillations and increased fluid flux at surface.

2. Moment Tensor inversion

In order to characterize the source dynamics of the LP-swarm occurred beneath the Campi Flegrei caldera at the end of 2006, we performed a Moment Tensor inversion adopting a full-waveform modelling procedure. For the inversion, we used stacked signals obtained after aligning and stacking 183 events pertaining to a cluster of similar events (Cluster 1 in S07). Such process was applied only to data from the digital, broad-band stations (see Fig. 1), thus resulting in a set of six, three-component seismograms. An initial hypocenter is fixed at the centroid of the LP cluster (40–49.67N, 14–08.44E, 0.5 km b.s.l.). For the inversion procedure of body waves, we selected a 2-second-long portion of the signals, corrected for the site effect, starting at the first arrival, P-wave onset. We calculated the Green's functions using the Reflectivity Method expressed as Wave Number Integration (Kawase and Aki, 1989; Herrmann, 2002). For this calculation, we used a 1D velocity model derived by the 3D structure obtained in a recent tomographic experiment (Judenherc and Zollo, 2004). The source-time function is given by a 1-s-long parabolic function, consistent with the LP dominant frequency peaked at around 0.8 Hz (S07). Both signals and Green functions are filtered in the frequency band 0.2–1.0 Hz.

In S07 the earthquakes that occurred on October 19–30, 2006 were classified as LP events on the basis of the waveforms and spectral contents (lack of clear S-wave arrival, spindle-shaped waveforms and