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Tornillos at Vulcano: Clues to the dynamics of the hydrothermal system

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A B S T R A C T

The number of tornillo events has recently increased at the Vulcano Island, Italy. While only 15 tornillos were recorded during 2004–2006, 584 events occurred in 2007–2008. They were located just below La Fossa Crater at depths ranging between 0.1 and 1 km b.s.l. During two intervals in 2007–2008 increases in the number of tornillos took place at the same time as temperature and geochemical anomalies were observed. The spectral content of the tornillos, generally characterized by one–two dominant spectral peaks near 6 and 10 Hz, varied over time, with changes also noted in the quality factors. The simplest source mechanism proposed for tornillos is the free eigenvibration of a fluid volume within a crack or a conduit. Based on this model, we propose a causal relationship between the temperature and geochemical anomalies and the increases in numbers of tornillos. As the amount of hydrothermal fluids increases during the anomalies, the upward flux of fluids grows. The consequent changes in the pressure, temperature and dynamics of the system of cracks and conduits result in the generation of tornillos. Based on the fluid-filled crack/conduit model, the shallow depths of the sources and the values of the quality factors, the fluid within the resonant crack/conduit was inferred to be an ash–gas or water droplet–gas mixture. Moreover, the observed variations in the wavefield can be caused by small changes in the location of the source, in the source mechanism, or in the medium in between the source and the seismic station. Finally, another peculiar feature of tornillos is the amplitude modulation that can be explained as a result of a beating phenomenon.

1. Introduction

Tornillo, the Spanish word for screw, refers to a class of seismic events recorded in volcanic areas, which can last up to several minutes. They are characterized by decaying sinusoidal waveforms, screw-like envelope profiles and one, or at most a few, narrow spectral peak. In Japan several names have been used to refer to these particular signals: LC (long-coda) events; BS (banded-spectrum) events; SF (single-frequency) events; and T-type (similarity with a T-square) events (Gomez and Torres, 1997). Some authors include them in the classification long period (LP) events, based both on the spectral content and proposed source process (e.g., Kumagai et al., 2002; Molina et al., 2008). Tornillos (hereafter referred to as TRs) have been observed at many volcanoes such as Galeras (Gomez and Torres, 1997; Seidl and Hellweg, 2003), Puracé (Arcila, 1996; Gomez and Torres, 1997), Tongariro (Hagerty and Benites, 2003), Tatun Volcano Group (Lin et al., 2005), Asama (Shimozuru and Kagiyama, 1989), Cotopaxi (Molina et al., 2008), Papandayan (Triastuty et al., 2006), Kuchinoerabujima (Triastuty et al., 2009) and Katmai National Park (De Angelis, 2006). TRs are recorded during various stages of volcanic activity. They can precede ash eruptions, as at Galeras in 1992–1993 and Asama in 1983 (Gomez et al., 1999). In other cases they occur after eruptions (Tokachi Volcano, Japan, 1989), during seismic swarms (Meakan Volcano, Japan, 1982) or simply during quiescence (Puracè Volcano, Colombia, 1994–1995; Tarumai Volcano, Japan, 1970–1971, 1975) (Gomez et al., 1999). Many different models have been proposed for the physical source of TRs: fluid-filled cracks (Gil-Cruz and Chouet, 1997; Kumagai and Chouet, 1999; Hagerty and Benites, 2003), lumped-parameter models (Julian, 1994), self-excited eddy shedding and turbulent slug flow oscillations (Hellweg, 2000). Moreover, according to Seidl and Hellweg (2003), TRs can be interpreted as the free vibration response of a fluid-filled cavity to a pressure pulse (linear model) or as the initial transient leading into a tremor sequence generated by a nonlinear, self-excited oscillator (nonlinear model).

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Vulcano is the southernmost member of the Aeolian Islands, a volcanic arc in the south-eastern Tyrrhenian Sea in the south of Italy (Fig. 1). It has been active in the last few centuries, erupting calc-alkaline and shoshonitic products (Barberi et al., 1974) and showing an explosive nature with frequent transitions from phreato-magmatic to magmatic activity (Mercalli and Silvestri, 1890; Barberi et al., 1988). A magmatic body was identified at a depth of 2–3 km below La Fossa Crater by geophysical and geochemical studies (Ferrucci et al., 1991; Clocchiatti et al., 1994; Nuccio and Paonita, 2001). Researchers also agree on the presence of a hydrothermal system below La Fossa cone (Chiodini et al., 1993, 1995; Nuccio et al., 1999; Paonita et al., 2002), whose thermodynamic conditions (temperature, pressure and composition) can show large temporal variations (Di Liberto et al., 2002). Since the last eruption in 1888–1890, volcanic activity produces fumarolic emissions varying in intensity and temperature over time. The fumaroles are mainly concentrated at La Fossa Crater (Fig. 1), where the fumarole fields, as well as the steam heated areas, have significantly expanded in the last 20 years (Bukumirovic et al., 1997; Boyce et al., 2007). Based on geochemical studies (Chiodini et al., 1993; Nuccio et al., 1999), the fumarolic emissions of La Fossa Crater are fed by fluids coming from both the magmatic and the hydrothermal system.

As in most active volcanoes around the world, Vulcano is also characterized by an ample variety of seismic signals. Since all these signals at Vulcano are “transients,” that is, are limited in time, we call them earthquakes or seismic events. Here the different types of these earthquakes are briefly classified, mainly on the basis of waveforms and spectral contents, and their similarities or differences with the most recent classifications of seismic signals in volcanic areas (e.g., Chouet, 1996; McNutt, 2005; Wassermann, 2009) are shown. The first group of events comprises the volcano-tectonic (VT) earthquakes, characterized by high-frequency content (>5 Hz), low magnitude (generally $M \leq 2.5$) and clear P and S phases (Aubert and Alparone, 2000). Similar to the VT earthquakes defined in other classifications (e.g., Wassermann, 2009), they are originated by shear failure caused by stress buildup and resulting in a slip on a fault plane. The other earthquakes were associated with the shallow dynamics of the hydrothermal system (focal depth, generally <1 km b.s.l.) and grouped into three classes (Alparone et al., 2010): long period, high-frequency and monochromatic events. The first ones are characterized by a spectral content mainly ranging between ~0.5 and 5 Hz and are similar to the long period events (also called low-frequency events) observed at most volcanoes (Chouet, 1996; McNutt, 2005). They are associated with the resonance of cracks (or conduits) filled with hydrothermal fluid (Alparone et al., 2010). The high-frequency events show a wide frequency range and seismic energy between 5 and 25 Hz. They differ from the aforementioned VT earthquakes because of the emergent onsets and the poorly defined P and S phases and thus are very similar to VT-B or shallow VT events introduced by Wassermann (2009). Moreover, similar to the VT

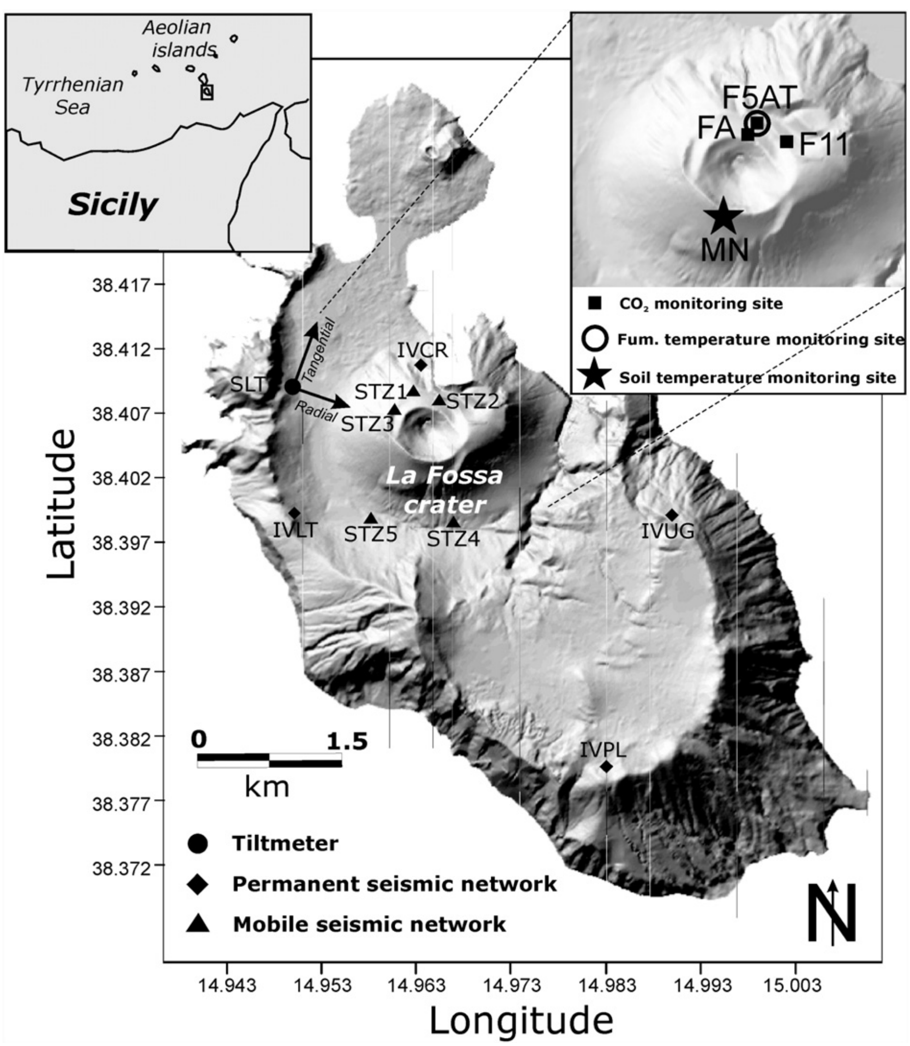

Fig. 1. Sketch map of the Vulcano Island showing the location of the seismic stations belonging to the permanent and mobile networks and tiltmeter used in this work (see the key in the lower left corner). In the upper right corner an inset with the location of the monitoring sites of CO_2, fumarole temperature and soil temperature is reported.