Physics and Chemistry of the Earth 63 (2013) 160–169

Contents lists available at SciVerse ScienceDirect

Physics and Chemistry of the Earth

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

# Thermal anomalies in fumaroles at Vulcano island (Italy) and their relationship with seismic activity

Paolo Madonia [a,*], Paola Cusano [b], Iole Serena Diliberto [a], Marianna Cangemi [c]

[a] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Palermo, via Ugo La Malfa 153, 90146 Palermo, Italy
[b] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli, Osservatorio Vesuviano, via Diocleziano 328, Naples, Italy
[c] Dipartimento di Scienze della Terra e del Mare (DiSTeM), Università degli Studi di Palermo, via Archirafi 36, 90123 Palermo, Italy

ARTICLE INFO

*Article history:*
Available online 13 June 2013

*Keywords:*
Crustal transient
Fumarole temperature
Seismic activity
Stress field
Teleseism

ABSTRACT

Fumarole thermal monitoring is a useful tool in the evaluation of volcanic activity, since temperatures strongly relate to the upward flux of magmatic volatiles. Once depurated from meteorological noise, their variations can reflect permeability changes due to crustal stress dynamics eventually associated to seismic activity. In this work, we discuss a fumarole temperature record acquired in the period September 2009–May 2012 at Vulcano island (Italy), during which changes of volcanic state, local seismic activity and teleseisms occurred. Apart from positive thermal anomalies driven by increments in volcanic activity, we observed 3 episodes at least of concurrence between tectonic earthquakes and fumarole temperature increments, with particular reference to the local August 16th, 2010 Lipari earthquake, the March 11th, 2011 Sendai–Honshu (Japan) earthquake and a seismic swarm occurred along the Tindari-Letojanni fault in July–August 2011. We interpreted the seismic-related anomalies as "crustal fluid transients", i.e. signals of volcanogenic vapour flow variations induced by stress-induced permeability changes. From this perspective fumarolic activity can be considered as a tracer of geodynamic instability but, since seismic and volcanic phenomena are in mutual cause-effect relationships, a multidisciplinary observation system is mandatory for correctly addressing thermal data interpretation.



## 1. Introduction

Fumaroles are emissions of water vapour associated to other gaseous species of hydrothermal and/or volcanic origin, both in sub-aerial and underwater environments. According to their emission temperature they will be defined as High ($t > 100$ °C) or Low (100 °C $> t$) Temperature Fumaroles, hereafter referred to as HTF and LTF respectively. Fumarole temperature monitoring is a useful tool in the evaluation of volcanic activity, since it highlights variations related to the discharge rate of deep and hot gases, as observed in many Italian active or quiescent volcanoes like Stromboli island (Brusca et al., 2004; De Gregorio et al., 2007; Rizzo et al., 2009), Vulcano island (Cannata et al., 2012; Diliberto, 2011) or Mt. Etna (Liotta et al., 2012). Moreover, increases in fumarole temperatures were observed in the crater of Volcàn Poàs in 1980, several weeks before a phreatic eruption (Barquero, 1983) or in hot springs at Usu volcano (Abiko, 1988) prior to eruptions. Conversely, long term (years) fumarole temperature decreases are often the most apparent sign of waning volcanic activity (Allen and Zies, 1923; Keith, 1991; Stoiber et al., 1975).

In addition to pure volcanic signal, two other crustal processes are able to influence the thermal regime of fumaroles: permeability changes, due to the dynamics of the stress field acting both at local and regional/subregional scales on a volcanic edifice, and infiltration of meteoric waters (Madonia et al., 2008, and references therein). Whilst the latter represents an environmental noise, stress-induced thermal anomalies are of great interest in monitoring programs, because they are the surface evidence of the tectonic dynamics that may influence volcanic fluid migration. Seismic-induced LTF anomalies were reported by Madonia et al. (2008) at Mt. Vesuvius, where an impressive (ca 45 °C) temperature increase in a fumarole, located on the 1944 crater rim, occurred in August 2005 few weeks before a very shallow earthquake. Moreover, De Gregorio et al. (2007) recorded at Stromboli island isochronous transients in crater rim fumarole temperatures and total dissolved gas pressures (TDGP) in the coastal thermal aquifer, strictly related to volcano-tectonic events.

With the aim of giving new insights in the relationships between fumarole temperature variations and seismic activity, this work compares thermal LTF and HTF data, acquired in the period September 2009–May 2012 at Vulcano island (Aeolian Archipelago, South Mediterranean), with the time distribution of seismic events recorded in this area.

* Corresponding author. Tel.: +39 0916809596; fax: +39 0916809449.
*E-mail address:* p.madonia@pa.ingv.it (P. Madonia).

1474-7065/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.pce.2013.06.001

In our interpretation we followed the crustal transient model proposed by Bernard (2001, and references therein). According to this model, earthquakes and fluid flow anomalies belong to a much larger class of crustal unstable processes called "crustal transients". Transients do not occur in a fixed time sequence, implying a direct cause–effect relationship between different categories of events, nor are their magnitudes reciprocally proportional, i.e. the greater is the magnitude of an earthquake, the greater is a fluid transients (or vice versa). If different transients occur quite contemporarily, and in this specific case earthquakes and fumarole thermal anomalies, they could be symptoms of a wider time–space scale crustal instability. The ability to identify transients driven by the same process is the key for modelling the 'transient—to—transient' triggering processes, i.e. for assessing the predictability of earthquakes whose precursors are fluid transients, or vice versa.

The data shown and discussed hereafter try to give a first, qualitative answer to a basic question in the development of future predictive models: are fumarole thermal anomalies and earthquakes linked to a common crustal instable process?

## 2. Tectonics, volcanology and seismicity of the studied area

The Aeolian Archipelago represents the emerged part of a submarine volcanic arc located between the Southern Tyrrhenean Sea back-arc basin (Marsili oceanic basin) and the Calabrian Arc fore-arc region (Fig. 1), a Hercynian belt affected by Late Quaternary extensional tectonics and uplift (Boccaletti et al. 1984). It can be subdivided into three sectors with different structural and tectonic evolution (De Astis et al., 2003): (i) the western sector (Alicudi and Filicudi islands), where volcanic activity started at about 1.3 My (Gillot, 1987) and ended at about 30–40 Ky, with seismicity mainly linked to the WNW–ESE Sisifo Fault System, showing strike slip to oblique focal solutions with a main NNW–SSE compression (Pondrelli et al., 2004, 2006); (ii) the eastern sector (Panarea and Stromboli islands), where the present active volcanism started 0.8 My ago, is affected by a prevailing NE–SW strike-slip fault system; (iii) the central sector (Salina, Lipari and Vulcano islands), where the volcanism began at 0.4 My (Beccaluva et al., 1985) and is still active at Lipari (last eruption dated 729 A.D.) and Vulcano (1888–90 A.D.) (Keller, 1980).

These three volcanoes are aligned along a lithospheric NNW–SSE fault system, the Aeolian–Tindari-Letojanni Fault System, a regional zone of brittle deformation extending from the Aeolian islands to the Ionian sea at the transition between the ongoing shortening (western Sicily) and extensional (eastern Sicily and southern Calabria) domains related to the Africa–Europe convergence process. Lanzafame and Bousquet (1997) named this fault the "Aeolian–Maltese" system, interpreting it as the northward prolongation of the Maltese escarpment that traverses the eastern flank of Mt. Etna. Its off-shore segment, in the Tyrrhenean Sea, shows right-lateral to oblique kinematics along which seismicity is roughly aligned (e.g. Billi et al., 2006; Neri et al., 2003, 2005).

In particular, Vulcano island is also characterized by NE–SW and N–S trending normal structures which accommodate the horizontal movements of the main system (Mazzuoli et al., 1995). Dikes, vents and eruptive fissures are aligned along these two oblique trends (De Astis et al., 2003; Mazzuoli et al., 1995; Ventura et al., 1999). The morphology of the island (Fig. 2) is characterized by two main volcanotectonic depressions: the "Piano" Caldera (about 350 m a.s.l.), which occupies the southeastern sector of the island, and the "La Fossa" Caldera (0–50 m a.s.l.), located in the north-western sector. The "La Fossa" cone (391 m a.s.l.; last eruptive phase 1888–1890 A.D.) occupies the central sector of the caldera, while the lava platform and pyroclastic cones of Vulcanello form the northern corner of the island. Since the last eruption, Vulcano island has been characterized by fumarolic activity, mainly concentrated in the inner northern flank of La Fossa cone (HTF up to 700 °C during periodic volcanic unrests) and in two secondary peripheral fields, located close to the sea in the northern and southern sectors of the island (Fig. 2). According to Badalam-

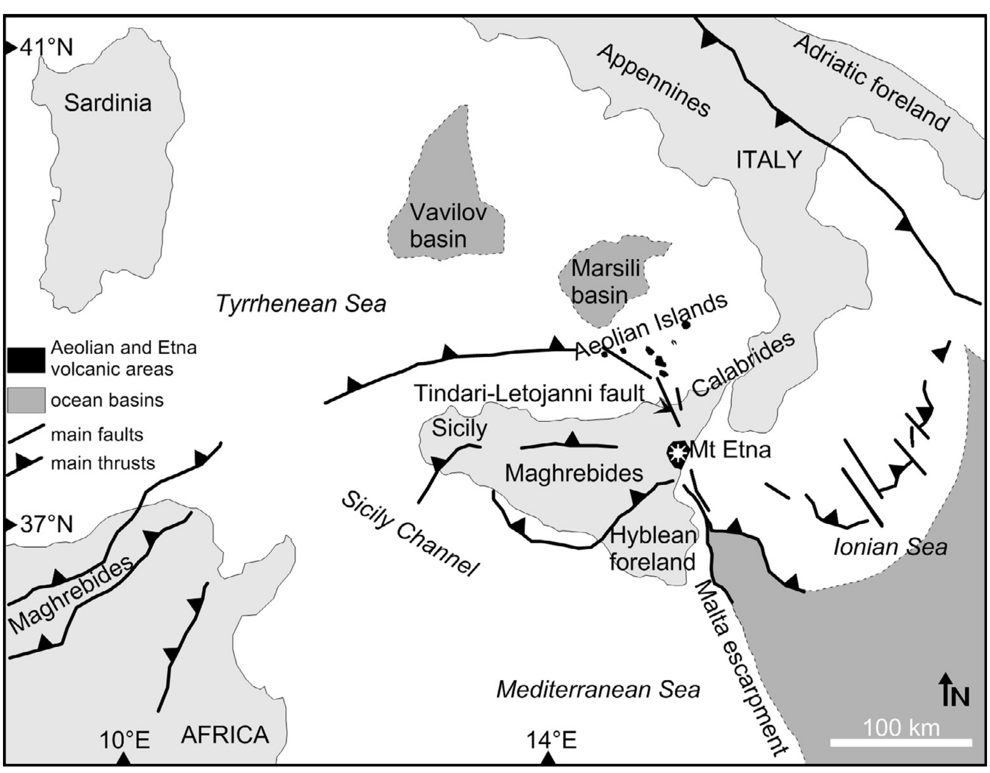


**Fig. 1.** Tectonic map of the South Thyrrenean sector (modified after Billi et al., 2006).