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Insights into fluid circulation across the Pernicana Fault (Mt. Etna, Italy) and implications for flank instability

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ABSTRACT

We conducted geophysical–geochemical measurements on a ~2 km N–S profile cutting across the Pernicana Fault, one of the most active tectonic features on the NE flank of Mt. Etna. The profile passes from the unstable E flank of the volcano (to the south) to the stable N flank and significant fluctuations in electrical resistivity, self-potential, and soil gas emissions (CO_2, Rn and Th) are found. The detailed multidisciplinary analysis reveals a complex interplay between the structural setting, uprising hydrothermal fluids, meteoric fluids percolating downwards, ground permeability, and surface topography. In particular, the recovered fluid circulation model highlights that the southern sector is heavily fractured and faulted, allowing the formation of convective hydrothermal cells. Although the existence of a hydrothermal system in a volcanic area does not surprise, these results have great implications in terms of flank dynamics at Mt. Etna. Indeed, the hydrothermal activity, interacting with the Pernicana Fault activity, could enhance the flank instability. Our approach should be further extended along the full extent of the boundary between the stable and unstable sectors of Etna for a better evaluation of the geohazard in this active tectonic area.

1. Introduction

In recent years, a growing number of researchers have published detailed geophysical investigations of complex structural settings. DC resistivity and self-potential (SP) imaging methods have proven to be well suited for the geophysical characterization of active faulted areas and volcanic environments (e.g. Diaferia et al., 2006; Revil et al., 2008).

A parallel body of literature documents the close relationship between soil gas emissions and fault dynamics related to seismic or volcanic activity. Soil gas prospecting has become a powerful tool for monitoring volcanic activity and understanding fluid–fault coupling processes during earthquakes (Neri et al., 2006).

Whereas single-parameter approaches are unlikely to be effective at characterizing dynamic and structurally complex natural systems, multidisciplinary studies can be highly useful. This paper takes a statistical approach to integrating multidisciplinary data (resistivity, SP, soil gas emissions and geo-structural survey) on a volcanically and tectonically active region.

2. The Etna case study

We focus our attention on Mt. Etna (eastern Sicily, Italy), one of the most active volcanoes in the world (Fig. 1; Neri et al., 2008) located at the front of the Apennine–Maghrebian Chain (Lentini, 1982). This volcano is affected by spreading of its E and S flanks (Bonforte and Puglisi, 2006; Neri et al., 2009, and reference therein). The unstable sector (inset in Fig. 1) is confined to the N by the E–W-striking Pernicana Fault System (PFS) and at the SW margin by the N–S-striking Ragalna Fault System (RFS; Rust et al., 2005).

The PFS develops eastward from the NE Rift down to the Ionian coastline, over a length of ~18 km. Between 1000 and 1500 m of elevation above sea level (asl), the transtensive PFS is characterized by a scarp reaching a maximum height of 70–80 m. At lower elevations (from 700–800 m asl down to the coast), the PFS is characterized by left-lateral faults with a dextral en-enchelon configuration. Shallow (<2–3 km) seismic activity ($2<M<3.5$; Allard et al., 2006) characterizes the W part of the PFS, and aseismic creep characterizes the E portion.

The PFS is kinematically linked, via a feedback mechanism, to magma intrusions and eruptions occurring on the NE Rift (Neri et al., 2009). On a larger scale, the spreading that affects the unstable sector is thought to be triggered by magmatic activity (Allard et al., 2006).

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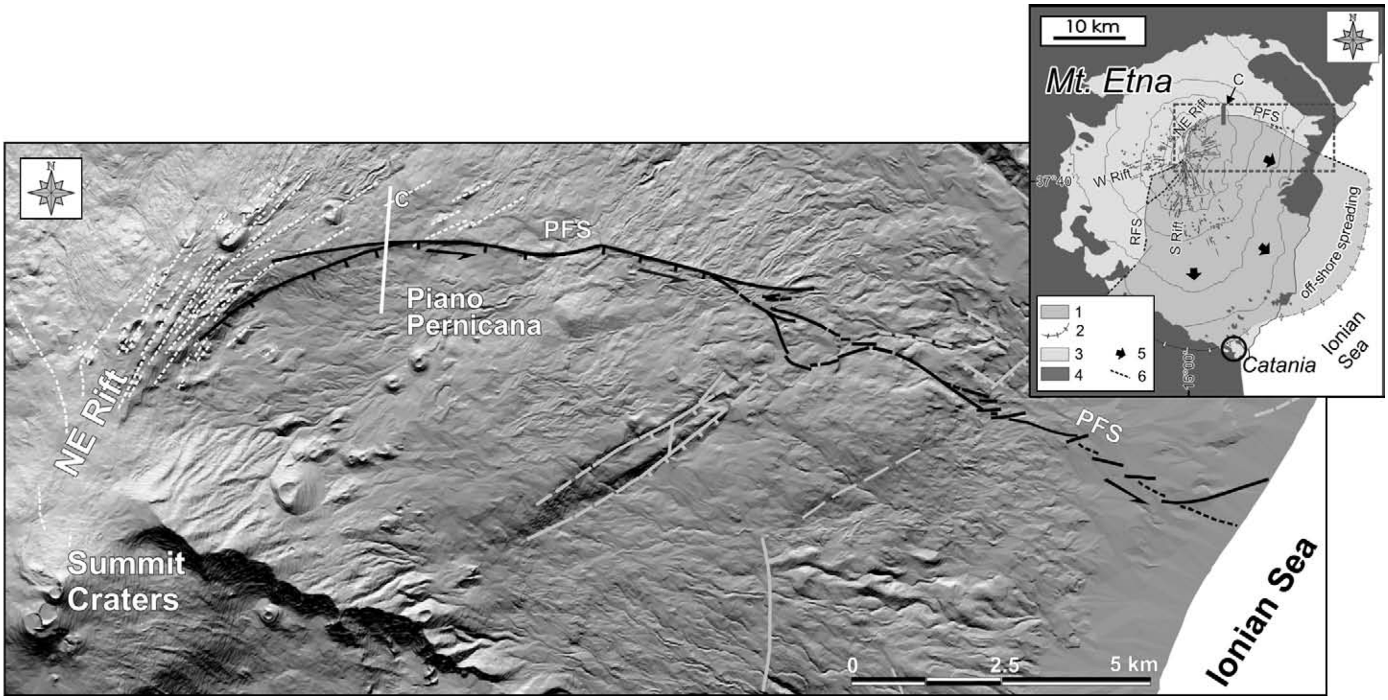

Fig. 1. Map showing the location of the studied profile (c) on Mt. Etna. PFS = Pernicana Fault System (black lines). Dashed white lines represent the main eruptive fissures in the NE Rift area. The inset on the upper right shows (1) the extent of the unstable sector; (2) the off-shore boundary of the spreading area; (3) the stable sector of the volcano; (4) a sedimentary rock outcropping around the volcano; (5) the directions of movement of the sliding sectors; and (6) an inferred extension of the PFS and the Ragalna Fault System (RFS).

In this work we study the western portion of the PFS, just to the W of Piano Pernicana. In October 2006, electrical tomography, self-potential and soil gas emission (CO_2 efflux, ^{222}Rn and ^{220}Rn activities) measurements were performed along a 2 km-long axis perpendicular to the PFS (line “c” in Fig. 1), at an altitude of about 1500 m asl. All measurement points were spaced every 20 m along the same profile and referenced to the southernmost point. These datasets are analyzed and discussed both individually and in conjunction, to better interpret their variability and reveal mutual relationships.

3. Field surveys

3.1. Electrical resistivity tomography

Electrical resistivity tomography (ERT) measurements were carried out using a computer-controlled system. Ninety-six electrodes were laid out along a 1920 m straight line. In order to fully exploit the multi-electrode system, three sets of measurements were obtained using dipole–dipole, Wenner–Schlumberger and non-standard arrays. To enhance the resolution and the penetration depth of the resulting 2-D resistivity model (Dahlin and Zhou, 2004, Stummer et al., 2004), the whole dataset was jointly inverted with the RES2DINV code (Loke and Barker, 1996). Surface topography was included in the inversion process.

The resulting 2D resistivity model (RMS = 8.2), shown at the bottom of Fig. 2, has several important features. The uppermost 200 m is structurally complex, with resistivity values ranging from 1000 to 50000 ohm m, in accordance with the presence of a volcanic cover (lava flows and tephra). The southern side of the Pernicana Fault is characterized by strong lateral resistivity gradients. Here, three relative conductive anomalies reach the surface at 320 m, 620 m, and 940 m along the profile (measured from S to N) where surface evidences mark the presence of the main faulted zones. On the hanging wall of these, the highest resistivity values occur in correspondence with structurally depressed zones filled by unconsolidated, highly porous volcaniclastic products. Conversely, the northern side of the Pernicana Fault is characterized, in the uppermost 200 m, by a relatively conductive body (resistivity of about 3000 ohm m) lying between two more resistive layers with resistivities of > 8000 ohm m. This resistant–conductive–resistant shallow sequence is quite parallel to the topography, suggesting fluid drainage within the volcanic cover (see thin dashed arrows in stable block in Fig. 4).

The lower layer, between 200 and 400 m below ground level, is more conductive with resistivity values decreasing sharply from N to S, passing from about 3000 to 300 ohm m.

The 2D model highlights strong resistivity contrasts ranging over more than two orders of magnitude. According to previous works (Neri and Rossi 2002 and references therein), in the investigated area the thickness of the Etnean volcanic products is about 600 m, thus our resistivity model lies within this geological unit. In this context, the lower resistivity values are compatible with the presence of fluids within permeable zones. In the following sections, we explore whether the resistivity anomalies are linked to processes occurring at depth (e.g., hydrothermal system) or to shallow features and/or processes acting on the shallow drainage channels within the volcanic cover (e.g., topography, and ground water flow).

3.2. Self-potential

Natural electric potentials can be generated by a number of sources, such as electrokinetic activity, thermoelectric effects and geochemical processes (Corwin and Hoover, 1979). In active tectonic areas, SP anomalies are often related to heat-triggered phenomena. For this reason SP measurements are becoming increasingly popular in studies of thermal and hydrothermal activity (e.g. Finizola et al., 2004). As the current density depends on water conductivity, this investigation method is also very effective in the study of hydrodynamic flow systems.