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Interaction of volcano-tectonic fault with magma storage, intrusion and flank instability: A thirty years study at Mt. Etna volcano

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ABSTRACT

We investigated the relationship between the occurrence of earthquakes along the main volcano-tectonic structures and periods of volcanic unrest at Mt. Etna. We focused our study on the Pernicana Fault System (PFS), one of the most outstanding tectonic structures delineating the northern border of the sliding eastern flank of Etna volcano. During recent decades several flank eruptions have occurred at Mt. Etna and sometimes PFS released seismicity before the eruptive events, while in other cases there have been earthquakes that did not precede any eruption. To highlight a possible relation between PFS ruptures and volcanic unrest, we took into account the most energetic earthquakes ($M \geq 3.5$) occurring in the last three decades (1980–2010), and considered the volcano deformation sources previously inferred by inverting geodetic data recorded during the several flank eruptions in this time interval. The estimates of stress redistribution on the PFS due to different volcano sources, such as the magma storage, the dike intrusions and the sliding eastern flank, were studied by implementing 3D numerical models that also consider the presence of topography and medium heterogeneity. Our results show that the pressurization of an intermediate storage and the traction exerted by the eastern flank sliding contribute to the seismicity along the PFS even without preceding an immediate eruption. Instead, the seismicity along the PFS related to the intrusions inside the northern sector of the volcano would represent a potential early-warning for an impending eruption at Mt. Etna.

1. Introduction

Volcanic eruptions are often temporarily and spatially related to the occurrence of earthquakes. Time and space correlations between these two phenomena have been observed in numerous regions of the world (e.g. Nostro et al., 1998; Hill et al., 2002, and references therein; Manga and Brodsky, 2006). Several studies have shown that static stress changes exerted by the volcanic activity to faults or by the earthquakes to the volcanoes may have promoted seismic events or volcanic eruptions. A volcanic system, which has reached a critical state, can be perturbed by stress changes caused by earthquakes occurring nearby (e.g. Hill et al., 2002, and references therein). Changes in stress conditions in the volcano-tectonic structure can be promoted by recharging phases that last several years before an eruption, as well as by magma intrusions that occur in a short time (from months to hours) before volcanic eruptions (e.g. Marzocchi et al., 2002, 2004; Eggert and Walter, 2009).

Relationships between the activation of tectonic structures, earthquake swarms, and volcanic eruptions have also been documented on Etna volcano (Gresta et al., 2005; Walter et al., 2005; Feuillet et al., 2006; Currenti et al., 2008a). The remarkable series of seismic and volcanic events that occurred on Etna during the last three decades has offered a unique opportunity to improve our understanding on the structural setting, recharging mechanism and seismic response to better assess the seismic and volcanic hazard in so highly exposed and populated regions (Fig. 1). Understanding the relations between these processes could provide a helpful contribution for a correct evaluation of volcano unrest and a timely prediction of volcanic scenarios that are of great interest to hazard managers during an eruption.

In particular, the seismic swarms in the western flank of Mt. Etna, recorded at depth from 10 to 0 km below sea level, have been interpreted as a response of the medium to the intrusive episodes occurring across the volcano-genetic NNW–SSE structural trend. This precursor behavior has been analyzed for the seismicity recorded in the months preceding the 1991–93 flank eruption (Bonaccorso et al., 1996), the January 1998 seismic swarm associated with the intrusion leading to the February–November 1999 eruption (Bonaccorso and Patanè, 2001), and the April 2001 swarm preceding the eccentric intrusion of the July 2001 eruption (Bonaccorso et al., 2004).

In the northern sector, along the Pernicana Fault System (PFS) (Fig. 1), frequent seismicity is recorded having a controversial relationship with the volcano activity and with the several flank eruptions that have taken place in the last decades (Table 1). The PFS is one of the most active and the most well-defined tectonic structures on Etna, and it borders the northern limit of the sliding eastern flank of the volcano (Rasà et al., 1996; Azzaro et al., 2001; Neri et

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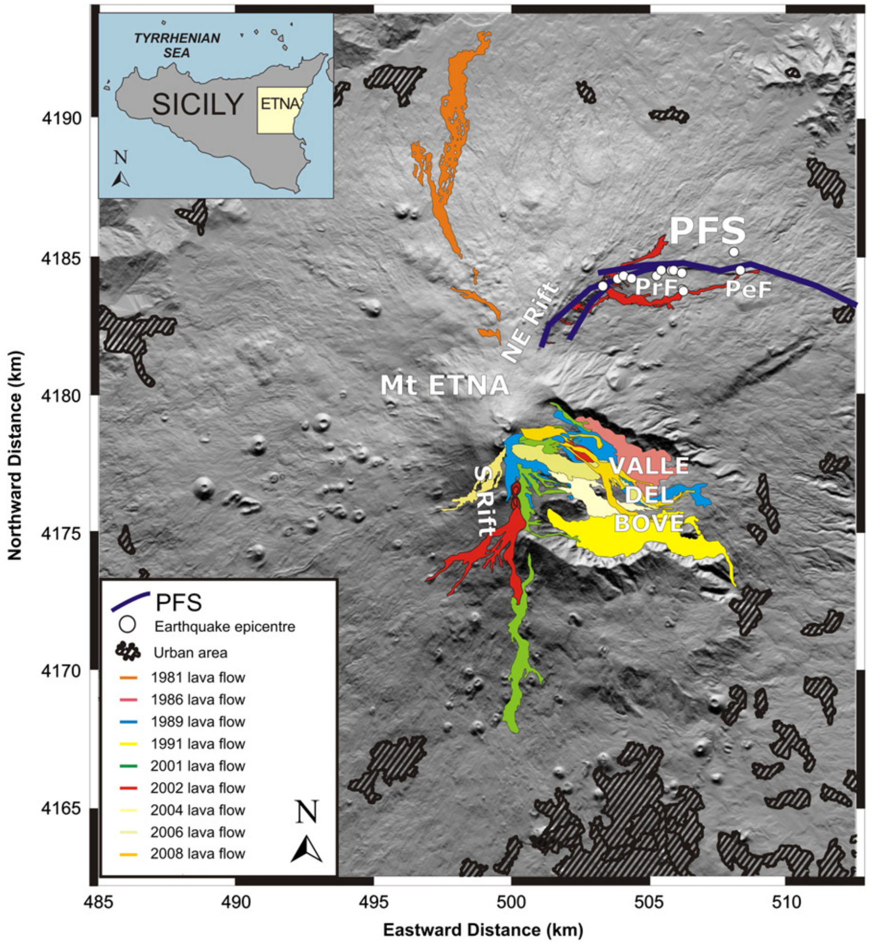

Fig. 1. Shaded relief map of Mt. Etna with the structural lineaments of the Pernicana Fault System (PFS. NE-Rift = North-East Rift; PrF = Provenzana fault; PeF = Pernicana fault; S Rift = South Rift. The inset at the top left shows the location of Etna volcano in Sicily. The main lava flows occurring in the last three decades are shown (Behncke et al., 2005; Allard et al., 2006). The white circles represent the epicenter of the $M_L \geq 3.5$ earthquakes along PFS in 1980–2010 from Azzaro (1997) and Azzaro et al. (2006). The seismic events were available from http://www.ct.ingv.it/ufs/macro/ and http://www.ct.ingv.it/ufs/analisti web-sites. Geographical coordinates are expressed in UTM projection, zone 33 N.

al., 2003; Acocella and Neri, 2005; Rust et al., 2005; Palano et al., 2006; Bonforte et al., 2007). The PFS has released seismicity several times before eruptive events but on several other occasions there have been earthquakes that did not precede any eruption. Based on elastic stress transfer considerations, Feuillet et al. (2006) supported the idea that at Etna the volcanic sources and active faults located nearby the volcano are mechanically coupled. Different studies have been conducted on static stress changes caused by some recent eruptions at Etna. Gresta et al. (2005) examined stress field perturbations caused on the PFS by two dike intrusions leading to eruptions: i) the 1981 intrusion in the northern flank and ii) the 2001 intrusion in the southern flank. In both cases, the Coulomb stress was calculated treating the intrusions as uniform dislocation in a homogeneous elastic space by using Coulomb 2.5 software (King et al., 1994). In agreement with the observed seismicity pattern, Gresta et al. (2005) showed that the first case favored earthquakes on PFS, while the second one did not. Walter et al. (2005) studied stress transfer associated to the events (intrusion, seismicity and flank movement) of the 2002–03 eruption characterized by a double intrusion in the southern and north-eastern sector, respectively. They used a 3D boundary element program Poly3D (Thomas, 1993) for calculating the static stress within a homogeneous and isotropic media. The stress was generated by volcano inflating reservoir and magma intrusions associated with the 2002 eruption. They showed that the inflation of a reservoir, the eastern flank movement and the emplacement of dikes in the northern rift zone encourage the rise of magma to shallower levels and the faulting along the PFS. However, Walter et al. (2005) did not constrain the sources of the stress through geodetic data, and further they did not include the heterogeneities of the medium that instead strongly affect the amplitude of the static stress changes. Currenti et al. (2008a) overcame these simplifications and provided a more realistic model by using the Finite Element Method (FEM). They showed that southern flank intrusion was able to produce an extensional stress field that could have favored magma-filled fracture propagation along the north-east rift, and confirmed that PFS was encouraged to slip by the 2002–03 double intrusion. Recently, Currenti et al. (2010), through a FEM inversion of a slip distribution model, gave evidence that the M 3.7 earthquakes record on 22 September 2002 along the central part of the PFS was activated under the action of an initial magma intrusion along the NE Rift, where the 2002–03 eruption took place just one month later. This earthquake was interpreted as a precursor of the eruption and encouraged us to investigate the possible relationships of the PFS with the volcanic processes. However, the precursor behavior on PFS did not occur for all the flank eruptions and the earthquakes on PFS occurred also without preceding an eruption (Table 2). This is an apparently controversial point in which we decided to look into. Therefore, the key point of this study is to investigate how different sources such as magma storage, intrusions and flank instability interact with seismic episodes on PFS.

In this work, after a brief description of the structural setting of Mt. Etna and the role of PFS and its most energetic seismic events, we outline the flank eruptions in the last three decades and the modeled sources obtained from previous studies on deformation