Journal of Volcanology and Geothermal Research 245–246 (2012) 149–158

Contents lists available at SciVerse ScienceDirect

Journal of Volcanology and Geothermal Research

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

Triggering mechanisms of static stress on Mount Etna volcano. An application of the boundary element method

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ARTICLE INFO

Article history:
Received 8 February 2012
Accepted 19 August 2012
Available online 28 August 2012

Keywords:
Numerical modeling
Coulomb stress changes
Volcano dynamics
Mount Etna volcano
Magmatic activity

ABSTRACT

In the last 30 years, numerous eruptions and associated deformation episodes have occurred at Mt. Etna volcano. Datasets recorded by continuous monitoring of these episodes provide a unique opportunity to study the relationships between volcanism, flank instability and faulting activity. We have investigated the stress triggering mechanism between magmatic reservoir inflation, intrusive episodes and flank dynamics. Using three-dimensional numerical Boundary Elements Models we simulated volcano-tectonic events and calculated Coulomb stress changes. Using this modeling approach, we analyzed four realistic scenarios that are representative of recent kinematics occurring at Mt. Etna. The main results obtained highlight how (1) the inflation of a deep spherical magma source transfers elastic stress to a sliding plane and faults, (2) the opening of the NE Rift and S Rift (to a less efficient extent) favors movements of the instable sector and may encourage seismicity on the eastern flank faults, and (3) flank instability may trigger the uprising of magma. Defining the effects of the elastic stress transfer and relationships among the main forces acting on volcano, may help to forecast possible eruption scenarios during future episodes of unrest at Mount Etna and provide an important tool for decision makers during volcanic emergencies involving the highly populated areas of the volcano.

1. Introduction

Active volcanoes in densely populated areas represent a primary hazard that requires an operative and well-timed interaction between research institutions and civil defence authorities during unrest episodes. Consequently, involved researchers are encouraged to tune up affordable methods that can provide realistic scenarios of the eruptive evolution in near real-time.

Mount Etna dynamics is the result of a complex interplay between magma ascent in the plumbing system, dike emplacement, tectonic uplift, faulting and flank instability. Many studies have highlighted that at Mount Etna increases in static stress induced by dike intrusions bring faults closer to failure (Gresta et al., 2005). More recently, the pressurization of a magmatic reservoir was considered to trigger 1997–1998 Mount Etna seismic swarms as a consequence of stress redistribution (Bonanno et al., 2011).

The increase in collected seismic and deformation measurements and the rapid growth of computational power have enabled improving investigations into the relationship between faulting, flank dynamics and magmatic activity using numerical modeling. Walter et al. (2005) modeled the 2002–2003 Mt. Etna eruption by means of Boundary Element Method, evaluating the influence of four different sources on the kinematics of the volcano's eastern flank. They found a feedback relationship between flank movements and intrusive processes. The numerical models suggest that magmatic activity (inflation of a reservoir and emplacement of dikes) encourages motion of the eastern flank, which, in turn, promotes magma to rise up to shallower levels within the volcano. Currenti et al. (2008) performed a Finite Element Modeling approach to evaluate ground deformation and the resulting stress redistributions in response to magmatic processes occurring during the 2002–2003 Etna eruption. They found that the changes in the state of stress generated by the southern dike produce an extensional stress field that favors magma propagation along the north-east Rift. The static stress changes computed onto the Timpe Fault System and the Pernicana Fault indicate that the magma intrusions on the southern and northeastern flanks prompted these seismogenic structures to slip. In this paper, we will use numerical simulations to hypothesize four realistic scenarios at Mt Etna in which one source at a time is active. Coulomb stress changes will be computed on three dimensional fault surfaces in order to investigate the interaction between intrusion/eruptive episodes, tectonic activity and flank instability. The method used requires a processing time of some tens of minutes and is thus suitable for a near real-time application in order to forecast the evolution of future unrest episodes.

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http://dx.doi.org/10.1016/j.jvolgeores.2012.08.012

2. Etna volcano setting

Mount Etna is a Quaternary basaltic stratovolcano located on the east coast of Sicily. It stands between two first-order tectonic elements: the Apenninic–Maghrebian Chain and the Hyblean Foreland (inset of Fig. 1). The northern and western sectors of the volcano lie over metamorphic and sedimentary rocks belonging to the frontal nappes system of the Apenninic–Maghrebian Chain, whereas the southern and eastern sectors overlie marine clays of Quaternary age, deposited on the flexured margin of the northward-dipping downgoing Hyblean Foreland (Lentini, 1982) (inset of Fig. 1).

2.1. Volcanic activity

Recent volcanic activity of Mount Etna is characterized by eruptions at the four summit craters, and by fissure eruptions and dike intrusions at the rift zones oriented NE, south and west. During the last 400 years, about half of the eruptions occurred along the rift zones through fissures opened on the volcano flanks (Behncke and Neri, 2003). These fissures are usually related to the lateral intrusion of dikes radiating from a shallow magma conduit system.

Important results obtained during recent decades, mainly due to the rapid improvement in the seismic and deformation monitoring networks, have identified the main tectonic structures and the paths along which the magma rises beneath Mount Etna. Seismic tomographic images define the basement of Mount Etna as characterized by a main upper and middle crustal intrusion complex, with high V_p values (High Velocity Body; HVB), whose top is located at about 4 km below sea level (b.s.l.), beneath the southeastern flank of Mount Etna (e.g., Aloisi et al., 2002; Chiarabba et al., 2004; Patanè et al., 2006). In recent years, magma intrusions have ascended along the western boundary of the HVB, as documented by ground deformation and seismic studies (e.g., Bonforte et al., 2008; Puglisi et al., 2008 and references therein). It is noteworthy that the lack of evidence for large magmatic storage volumes strongly supports the idea that, during its ascent along the western boundary of the HVB, the magma is stored as a plexus of dikes or sills, as suggested by Armienti et al. (1989) to justify the typical polybaric evolution of the magmas within the plumbing system of Mount Etna (Corsaro and Pompilio, 2004).

2.2. Structural framework

The shallow geodynamic behavior of Mount Etna seems to be controlled by the flank instability processes causing the seaward sliding of the volcano eastern side as a result of a complex interaction between regional tectonic stresses, gravity forces acting on the volcanic edifice and the dike-induced rifting (Neri et al., 1991; Borgia et al., 1992; Lo Giudice and Rasà, 1992; McGuire, 1996; Rasà et al., 1996). Although the published models propose different explanations of the origin and depth of the flank movement, they all agree in identifying the Pernicana Fault system, PF (Fig. 1) as the northern boundary of the unstable sector. This is a transtensive fault with left lateral movement. It is characterized by a high slip rate from 10 to 28 mm/year with shallow (<3.5 km) and moderate seismic activity ($2<M<4.5$) (Azzaro, 1997; Azzaro et al., 2001). The PF activity is kinematically connected to the episodic opening and eruptions of the nearby NE Rift (Fig. 1) (Neri et al., 1991; Gardunõ et al., 1997; Tibaldi and Groppelli, 2002; Acocella and Neri, 2003; Acocella et al., 2003). The southern part of the western boundary of the unstable sector is represented by the South Rift (Rasà et al., 1996) joining, southeastward, with the Tremestieri–Trecastagni fault system TTF (Fig. 1). This fault system is made up of a number of NNW–SSE striking faults showing evident right-lateral displacement and is also characterized by very shallow seismicity, with typical focal depths of 1–2 km. Other tectonic lineaments dissect the southern and south-eastern sectors of the volcano, such as the Timpe Fault system (STF1 and STF2), San Leonardello Fault (SLF), Moscarello Fault (MF) and Santa Venerina Fault (SVF) (Fig. 1).

Most of these faults have high sliprates from 1.0 to 2.7 mm/year (Azzaro, 2004; Puglisi et al., 2008), partly due to shallow seismicity (Lo Giudice and Rasà, 1992; Montalto et al., 1996). Instrumental data, according to historical and macroseismic information (Azzaro, 1999), indicate that more than 80% of earthquakes are shallower than 5 km (Gresta et al., 1990), which, despite their moderate magnitude, have

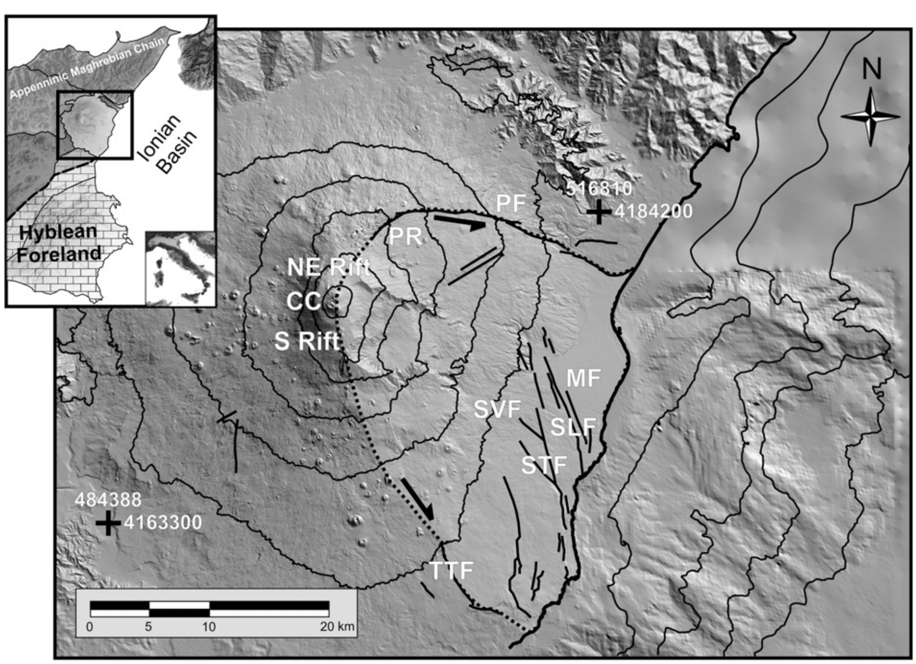

Fig. 1. Structural sketch map of Mount Etna: Provenzana Fault (PR); Pernicana fault (PF); Santa Venerina fault (SVF); Timpe fault system STF; Moscarello fault (MF); Tremestieri–Trecastagni fault (TTF); San Leonardello Fault (SLF); Central Craters (CC); South Rift and North - East Rift are also indicated. In the upper inset, the location of Mount Etna in the central Mediterranean area and a simplified geological map of eastern Sicily are also reported. The INGV-G-DEM is in the WGS84 reference system and the projection is UTM33.