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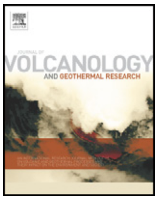

Understanding Etna flank instability through numerical models

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ABSTRACT

As many active volcanoes, Mount Etna shows clear evidence of flank instability, and different mechanisms were suggested to explain this flank dynamics, based on the recorded deformation pattern and character. Shallow and deep deformations, mainly associated with both eruptive and seismic events, are concentrated along recognised fracture and fault systems, mobilising the eastern and south-eastern flank of the volcano. Several interacting causes were postulated to control the phenomenon, including gravity force, magma ascent along the feeding system, and a very complex local and/or regional tectonic activity. Nevertheless, the complexity of such dynamics is still an open subject of research and being the volcano flanks heavily urbanised, the comprehension of the gravitative dynamics is a major issue for public safety and civil protection. The present research explores the effects of the main geological features (in particular the role of the subetnean clays, interposed between the Apennine–Maghrebian flysch and the volcanic products) and the role of weakness zones, identified by fracture and fault systems, on the slope instability process. The effects of magma intrusions are also investigated. The problem is addressed by integrating field data, laboratory tests and numerical modelling. A bi- and tri-dimensional stress–strain analysis was performed by a finite difference numerical code (FLAC and FLAC^{3D}), mainly aimed at evaluating the relationship among geological features, volcano-tectonic structures and magmatic activity in controlling the deformation processes. The analyses are well supported by dedicated structural–mechanical field surveys, which allowed to estimate the rock mass strength and deformability parameters. To take into account the uncertainties which inevitably occur in a so complicated model, many efforts were done in performing a sensitivity analysis along a WNW–ESE section crossing the volcano summit and the Valle del Bove depression. This was mainly devoted to evaluate the effect of topography, geometry and rheological behaviour of the structural units. The 3D numerical model, extended 40 × 60 km, was implemented to simulate the volcano deformation pattern. First, the role of the Pleistocene subetnean clays was investigated, then, two "structural weakness zones" – the Pernicana Fault system and the NE rift – were introduced and their effects on the flank instability evaluated. Two extreme hydrogeological conditions, drained and undrained, were analysed. The results are expressed in terms of stress–strain field, displacement pattern, plasticity states and shear strain increments. Two main instability mechanisms were identified: one at shallow depth, with the sliding surface located inside the subetnean Quaternary clay, and another deep-seated mechanism with a not continuous and less evident sliding surface, developed inside the Apennine–Maghrebian Chain flysch, bordered by active structures. Both mechanisms contribute to explain the present deformation pattern and some of the main structures of the Etna flank. The effect of magma pressure exerted on the active dyke walls during eruptions was then simulated and relations between magmatic activity and flank instability were preliminarily investigated.

1. Introduction

An increasing number of volcanoes are being recognised to have experienced large flank instability processes leading to sector collapse. These volcano collapses are giant landslides that involve entire sectors of a volcanic edifice. When such events occur, cubic kilometres of rocks are suddenly mobilised in the form of devastating debris avalanches that reach areas tens of kilometres away from the source (Siebert, 1984). The effects can also strike farther because the debris avalanche deposits can be reworked into debris flows and lahars. The direct hazard and risk associated with sector collapses could be very high, especially at island and coastal volcanoes where tsunamis could be generated (Siebert, 1992). Additionally, the derived hazards could be due to changes in volcanic activity, such as rapid decompression of the plumbing system, which can lead to lateral blast eruptions, magma pathway migration with opening of eruptive vents in new areas, and changes in magma chemistry with the consequential possibility of greater explosive activity (Siebert, 1996).

Different factors that could influence edifice instability and possible causes of volcano failure have been proposed (Elsworth and Voight,

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1996; McGuire, 1996; Siebert, 2002). These factors include static conditions, such as volcano mass, hydrothermalisation, slope gradients; dynamic factors such as seismicity and magma push due to intrusions; and exogenous processes such as sea-level variations at island/coastal volcanoes, glacial melting at glaciated volcanoes, etc. In this context, Mt. Etna (Italy), which has an unstable eastern flank, is a perfect natural laboratory where several possible variables can be investigated due to the inherent complexity of the area, the availability of several different studies and applied methodologies in the literature, and the well-documented and visible present-day flank instability processes.

The present work contributes to the understanding of the factors that guide the instability of the eastern flank of Mt. Etna. The approach described here is based on a holistic view of the problem by integrating different field and laboratory methodologies. We carried out a 2D and 3D stress–strain numerical analysis with a more detailed constraint on the rock succession based on field and laboratory geotechnical data.

This study explores the effects of the main geological features, particularly the role of the subetnean clays, interposed between the Apennine–Maghrebian flysch and the volcanic products (Di Stefano and Branca, 2002), and the role of weakness zones, identified by fracture and fault systems, on the slope instability process. The effects of magma intrusions are also preliminarily investigated.

The modelling results can be regarded as the effect of the deformation history of the volcano, simulating its past stress–strain evolution from a 3D perspective. The reconstruction of this evolution was performed by taking into account the rheological contrasts of the main geological units, the presence of existing structural elements, and the role of magma pressure along the feeding system. We then compared the resulting stress and strain fields with the main gravitational and volcano-tectonic features of the volcano flank.

2. Geological setting and structural background

Mt. Etna is located in a seismically active region astride the complex tectonic zone which marks the boundary between the African and European plates (Fig. 1A) (McKenzie, 1970; Barberi et al., 1973; Lentini, 1982; Doglioni et al., 2001). The volcano, Europe's largest and most active, has risen rapidly to an elevation of over 3300 m from a succession of overlapping central vents and associated flank eruptions approximately in the last 200 ka (Branca et al., 2011a, and references therein). The northern and western parts of the volcano overlie a pre-existing topography developed in metamorphic and sedimentary rocks belonging to the Apennine–Maghrebian Chain, a southward verging system of thrusted nappes. The southern and eastern flanks of the edifice overlie marine Pleistocene clays that have accumulated in the foredeep created on the tectonically depressed northern margin of the northward-dipping downgoing African plate (Lentini, 1982). This geological background must have predisposed the edifice to complex instability phenomena.

The eastern flank of the volcano has undergone a long history of aseismic and seismic deformations accompanied by seaward motions

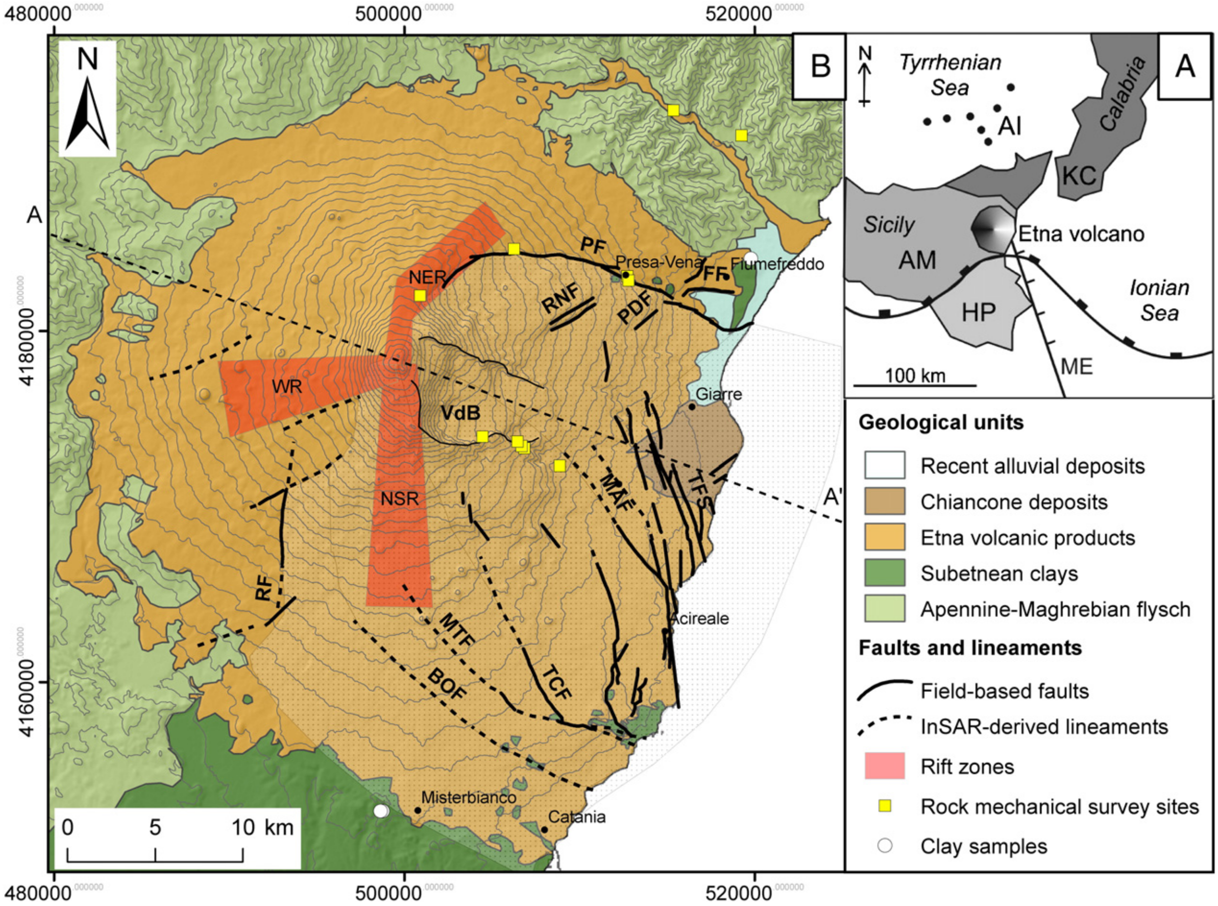

Fig. 1. (A) Location of Mt. Etna and geodynamic setting (after Lentini et al., 2006). HP—Hyblean Plateau, AM—Apennine–Maghrebian Chain, KC—Kabilo–Calabride Chain, AI—Aeolian Islands, ME—Malta Escarpment. (B) Simplified geological–structural sketch map of Etna volcano. Geological units redrawn after Neri and Rossi (2002) and Rust et al. (2005). Major and minor structures (from Neri et al., 2007; Branca et al., 2011b; Azzaro et al., 2012, and references therein), including GPS-InSAR-derived lineaments (from Ruch et al., 2010; Solaro et al., 2010; Bonforte et al., 2011): TFS—Timpe Fault system, PF—Pernicana Fault, PDF—Piedimonte Fault, FF—Fiumefreddo Fault, RNF—Ripe della Naca Faults, RF—Ragalna Fault, MAF—Santa Maria degli Ammalati Fault, MTF—Mascalucia–Tremestieri Fault, TCF—Trecastagni Fault, BOF—Belpasso–Ognina Fault. NER—North–East Rift, NSR—North–South Rift, WR—West Rift; VdB—Valle del Bove depression. Sampling sites of subetnean clays are indicated, as well as location of rock mechanical survey sites. Unstable portion of the volcano (stippled overlay) after Solaro et al., 2010 and Bonforte et al., 2011. SRTM90 DEM from srtm.csi.cgiar.org. A–A′ locates the trace of the geological–technical cross-section of Fig. 2A.