Journal of Volcanology and Geothermal Research 199 (2011) 153–164

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

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

Dike emplacement and flank instability at Mount Etna: Constraints from a poro-elastic-model of flank collapse

M. Battaglia [a,*], M. Di Bari [b], V. Acocella [c], M. Neri [d]

[a] Department of Earth Sciences, Sapienza, University of Rome, Italy
[b] Department of Geology and Geophysics, University of Bari, Italy
[c] Dipartimento di Scienze Geologiche, Università Roma Tre, Roma, Italy
[d] Istituto Nazionale di Geofisica e Vulcanologia, Catania, Italy

ARTICLE INFO

Article history:
Received 12 April 2010
Accepted 3 November 2010
Available online 12 November 2010

Keywords:
Etna
dike intrusion
flank instability
poro-elasticity
analytical modelling

ABSTRACT

Many volcanic edifices are subject to flank failure, usually produced by a combination of events, rather than any single process. From a dynamic point of view, the cause of collapse can be divided into factors that contribute to an increase in shear stress, and factors that contribute to the reduction in the friction coefficient μ of a potential basal failure plane. We study the potential for flank failure at Mount Etna considering a schematic section of the eastern flank, approximated by a wedge-like block. For such geometry, we perform a (steady state) limit equilibrium analysis: the resolution of the forces parallel to the possible basal failure plane allows us to determine the total force acting on the potentially unstable wedge. An estimate of the relative strength of these forces suggests that, in first approximation, the stability is controlled primarily by the balance between block weight, lithostatic load and magmatic forces. Any other force (sea load, hydrostatic uplift, and the uplift due to mechanical and thermal pore-fluid pressure) may be considered of second order. To study the model sensitivity, we let the inferred slope α of the basal surface failure vary between $-10°$ and $10°$, and consider three possible scenarios: no magma loading, magmastatic load, and magmastatic load with magma overpressure. We use error propagation to include in our analysis the uncertainties in the estimates of the mechanics and geometrical parameters controlling the block equilibrium. When there is no magma loading, the ratio between destabilizing and stabilizing forces is usually smaller than the coefficient of friction of the basal failure plane. In the absence of an initiating mechanism, and with the nominal values of the coefficient of friction $\mu = 0.7 \pm 0.1$ proposed, the representative wedge will remain stable or continue to move at constant speed. In presence of magmastatic forces, the influence of the lateral restraint decreases. If we consider the magmastatic load only, the block will remain stable (or continue to move at constant speed), unless the transient mechanical and thermal pressurization significantly decrease the friction coefficient, increasing the instability of the flank wedge for $\alpha > 5°$ (seaward dipping decollement). When the magma overpressure contribution is included in the equilibrium analysis, the ratio between destabilizing and stabilizing forces is of the same order or larger than the coefficient of friction of the basal failure plane, and the block will become unstable (or accelerate), especially in the case of the reduction in friction coefficient. Finally, our work suggests that the major challenge in studying flank instability at Mount Etna is not the lack of an appropriate physical model, but the limited knowledge of the mechanical and geometrical parameters describing the block equilibrium.

1. Introduction

Massive, destructive edifice collapses have dramatically sculpted hundreds of stratovolcanoes, including Mount St. Helens and Augustine (United States), la Soufrière volcano (Guadalupe), Merapi (Indonesia), Mount Bandai (Japan) and Mount Etna (Italy) (Acocella, 2005, and references therein). Although destabilizing shallow intrusion of magma into the edifice accompanies most collapses (e.g., Mount St. Helens), others have occurred without eruption of juvenile magmatic materials (e.g., Bandai volcano; Reid, 2004).

Flank instability seems to be independent of volcanoes composition, shape and geodynamic setting. The instabilities are characterized by different velocities of the mobilized mass, from creep-like movements (velocity of 10^{-9}–10^{-10} m/s; Froger et al., 2001), to catastrophic fast-moving landslides (velocity ~10^2 m/s; Voight et al., 1981). Instabilities may occur suddenly (Cervelli et al., 2002) or consist of accelerated movements within prolonged periods of creeping of the volcano flank (Neri et al., 2004). Mobilized volumes

* Corresponding author.
E-mail address: mbattaglia@uniroma1.it (M. Battaglia).

0377-0273/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jvolgeores.2010.11.005

vary enormously, even at the same volcano: in general, significant collapses commonly mobilize volumes of 10^8–10^{11} m^3 (Carracedo et al., 1999; Day et al., 1999; Hall et al., 1999; Masson et al., 2002). The larger the volume of the mobilized mass, the lower is the frequency of collapse (McGuire, 1996).

Several factors have been proposed to trigger the instability of volcanoes. These may act independently, or, more commonly, simultaneously. Magma emplacement is possibly the most common triggering factor, mainly in the form of dike emplacement (Delaney et al., 1998; Elsworth and Day, 1999; Tibaldi, 2001; Acocella et al., 2003; Walter et al., 2005; Acocella and Neri, 2009). Dike emplacement may induce static and dynamic effects on the stability of the flank of a volcano. From a dynamic point of view, the emplacement of the dike displaces the host rock away and, if buttressing is limited, the displacement effect may propagate to a significant part of the volcano (Delaney and Delinger, 1999; Cervelli et al., 2002; Acocella et al., 2003). From a static point of view, the effect of a dike is to increase the magmastatic force of the magmatic column, represented by the dike itself, and to increase the pore pressures in the groundwater within the volcano, which may induce failure (Elsworth and Voight, 1992). In particular, consideration of field and seismic evidence, together with simple calculations, indicate that reductions in the strength, or in the effective friction coefficient, of volcanic materials are mainly due to the effect of high pore-fluid pressure relative to confining pressure, produced by a variety of mechanisms (Day, 1996): heating of confined pore water by intrusions (e.g., Elsworth and Voight, 1995); degassing of intrusions; discharges of highly pressurized fluids from depth through clastic dykes; and by deformation associated with dike intrusion (e.g., Elsworth and Voight, 1992).

Sector collapses characterize the evolution of Mt. Etna, as testified by the Valle del Bove scar and by the occurrence of local Pleistocene and Holocene debris-avalanche and debris-flow deposits exposed on the eastern flanks of the volcano (Borgia et al., 1992; Rust and Neri, 1996; Groppelli and Tibaldi, 1999; Neri et al., 2005, 2009). Despite the large amount of studies and an acceptable definition of the surface deformation induced by flank instability, a quantitative analysis of the static effects of dike injection on flank instability, in particular on the role played by pore-fluid pressurization, has been lacking.

Here, we study how the emplacement of dikes in one of the Mount Etna rift zones can promote flank failure. We consider the efficacy of shallow edifice intrusion, and mechanical and thermal pore-fluid pressurization, to destabilize large regions of the volcano (e.g., Elsworth and Day, 1999). To determine the factors controlling flank failure at Mount Etna, we have performed a limit equilibrium analysis (Elsworth and Voight, 1995). Pore pressures developed by mechanical and thermal effects are readily evaluated using simple, but rigorous, models. Mechanically induced pore-fluid pressures are evaluated through an analogy with a moving line dislocation within a saturated porous-elastic medium (Elsworth and Voight, 1992). Thermally induced pore-fluid pressures are evaluated from a one-dimensional advective–diffusive solution for low Peclet transport, representing behaviour around a plane feeder dyke of infinite extent (Delaney, 1982; Elsworth and Voight, 1995). A key part of our analysis is to understand how the uncertainty in our knowledge of the geometrical and physical parameters of Mount Etna may influence the evaluation of the potential for flank failure.

2. Mount Etna

Mount Etna (Fig. 1) is a 3329 m high and ~40×60 km wide volcano, formed in the last 200 Ka (Romano, 1982; Corsaro et al., 2002; Branca et al., 2008, and references therein; Neri et al., 2008). Three prominent rift zones, characterized by eruptive fissures and parasitic cones radiating from the volcano summit (Acocella and Neri, 2003), are currently active on Etna: the Northeast, South and West Rifts. Much of the current volcanism here is characterized by the lateral movement of magma radiating from the central conduit (Allard et al., 2006; Acocella and Neri, 2009).

Several studies have highlighted the extensive sliding of the eastern and southern sectors of the volcano towards E and S, respectively (Borgia et al. 1992, 2000; Lo Giudice and Rasà 1992; Rust and Neri 1996; Froger et al. 2001; Neri et al., 2004, 2005, 2009). Flank instability is partly triggered by volcanic activity, as for example observed during the dike-fed 2001 and 2002–2003 eruptions, when a significant part of the E flank slipped eastward, locally reaching displacement rates of m/month (Behncke and Neri, 2003; Neri et al., 2004, 2009; Walter et al., 2005; Allard et al., 2006; Carbone et al., 2009).

The mobile eastern portion is bordered, to the north, by the E–W trending transtensive Pernicana fault system (PFS), with a left lateral–normal motion (Acocella and Neri, 2005 and references therein). The sliding southern sector is confined, to the west, by the N–S trending Ragalna fault system (RFS), with a predominant dextral–normal motion (Neri et al., 2007 and references therein). The spreading front is in part characterized by compression, forming an anticline, which involves the sub-volcanic sediments at the southern base of the volcano (Borgia et al. 1992; 2000; Froger et al., 2001; Neri et al., 2009; Solaro et al., 2010).

Little is known on the continuation of the unstable flank at depth, in particular on the existence, location and geometry of any decollement surface confining the sliding mass. The existence of the decollement has been largely postulated from indirect constraints (stratigraphic, structural, seismic or modelling constraints; Borgia et al., 1992; Tibaldi and Groppelli, 2002; Neri et al., 2004; Bonforte and Puglisi, 2006; Bonforte et al., 2008, 2009; Puglisi et al., 2008; Ruch et al., 2010), so that no direct evidence has been provided so far. Its location has been inferred to lie somewhere between 1–2 km a.s.l. and 6 km b.s.l. (Kieffer, 1985; Borgia et al., 1992; Lo Giudice and Rasà, 1992; Bousquet and Lanzafame; 2001; Neri et al., 2004; Ruch et al., 2010), with the possible occurrence also of multiple discontinuities (Tibaldi and Groppelli 2002; Bonforte and Puglisi, 2006; Bonforte et al., 2008; Puglisi et al., 2008; Bonforte et al., 2009). Finally, the geometry of the decollement(s) is also subject of debate, as different studies postulate the presence of a W-dipping (Borgia et al., 1992; Neri et al., 2004) or of a E-dipping surface (Tibaldi and Groppelli 2002; Rust et al., 2005; Bonforte and Puglisi, 2006; Bonforte et al., 2008, 2009; Puglisi et al., 2008; Ruch et al., 2010).

The role of the pore pressures on flank instability has not been considered at Etna so far. Available constraints suggest the presence of an open aquifer limited to the volcanic pile (which reaches a maximum depth of 1 km a.s.l. under the volcano summit; Rust and Neri, 1996), whose top is characterized by an inclination of ~3° (C. Federico, personal communication). No information is available on the presence and extent of other aquifers within the sedimentary basement, deeper than 1 km a.s.l.

3. Forces involved in flank failure

Flank failure is usually produced by a combination of events, rather than any single process. From a mechanical point of view, the cause of collapse can be divided into factors that contribute to an increase in shear stress, and factors that contribute to the reduction in the friction coefficient μ, or shear strength, of a potential basal failure plane (Voight and Elsworth, 1997).

To determine the factors controlling flank failure at Mt. Etna, we have performed a limit equilibrium analysis (Elsworth and Voight, 1995). We first determine the forces involved in the volcano flank failure, then we evaluate the force budget. Many of the mathematic details of the steady state model presented below are discussed in depth by Elsworth and Voight (1992, 1995 and 1996) and in the