



Preface

Flank instability at Mt. Etna

1. Why a special issue on flank instability?

Due to their constant and relatively rapid growth, volcanic edifices are inherently unstable. Flank instability is observed at many polygenetic stratovolcanoes, composite volcanoes and shield volcanoes worldwide. Flank instability may occur suddenly, or develop in a more continuous and subtle way, accelerated by triggering events (magma emplacement, eruptions and earthquakes). Destabilization is usually produced by a combination of circumstances and events. Magma emplacement is the most common triggering factor. However, fault activity, earthquake shakes, weak basement and hydrothermal alteration may also play a significant role in enhancing flank instability (e.g. Keating and McGuire, 2004, and references therein). In turn, instability may induce magma ascent and eruption, mainly through dikes, to such an extent that instability may significantly control the evolution of volcanic edifices and their associated hazards. Therefore, during the lifespan of major composite and shield volcanic edifices, flank instability has significant implications for geologic hazard. In fact, about 20,000 people are estimated to have been killed by historic volcano flank collapses (Siebert et al., 1987). Thus, better understanding of these potentially catastrophic events, with respect to the promoting and triggering factors, is necessary.

Mt. Etna is characterized by one of the best studied and monitored examples of flank instability. This was first inferred by Borgia et al. (1992). Since then, repeated evidence of episodic instability has been documented (e.g., Froger et al., 2001; Acocella et al., 2003; Bonforte and Puglisi, 2003). The extent and frequency of these processes vary widely, from nearly continuous creep-like movements of portions of the flank (areal extent of tens of km²) to the slip, associated with seismicity, of the entire eastern sector of the volcano (areal extent of hundreds of km²). Slip rates vary from mm/yr to m/week. The largest instability events are associated with major eruptions, as during 2002–2003, when the entire eastern flank moved, triggering shallow earthquakes and posing a serious seismic hazard to the inhabited areas. This event has shown how flank dynamics may involve major eruptions, destructive seismic activity and surface fracturing affecting population centers and infrastructure.

Therefore, Mt. Etna provides an appropriate case study to describe and understand how the instability of a volcano may occur, also in relation to volcanic and seismic activity, as well as to estimate the related hazard. Several studies have provided important information on flank instability at Etna, mostly in the last decade, using geodetic (Lundgren et al., 2003; Puglisi et al., 2008; Bonforte et al., 2009; Neri et al., 2009), field (Groppelli and Tibaldi, 1999; Neri et al., 2004), gas monitoring (Neri et al., 2007) and modeling (Walter et al., 2005; Palano et al., 2008) data. However, the lack of crucial information to describe, understand and mitigate flank instability at Etna induced the Italian Department of Civil Defense, with the National

Institute of Geophysics and Volcanology and Italian Universities and Research Institutes, to launch the 2-year-long “Flank” project. The project embraced geological, geophysical, volcanological, modeling and hazard studies, both on the onshore and offshore portions of the unstable edifice (Acocella and Puglisi, 2010). To our knowledge, “Flank” is the first multidisciplinary effort to specifically study flank instability at a volcano. “Flank” has provided a robust scientific basis to understand the structure of the unstable portion and its relations to seismic and volcanic activity. In addition, refined hazards assessment has provided the starting point for an integrated evaluation of flank instability at Etna. Some recent results of “Flank” concern the anatomy of the deformation of the entire edifice (Solaro et al., 2010; Bonforte et al., 2011) or portions of it (Guglielmino et al., 2011; Ruch et al., 2012), including its possible extent at depth (Ruch et al., 2010; Siniscalchi et al., 2012) and offshore (Chiocci et al., 2011), the relationships of flank instability to degassing (Federico et al., 2011) and intrusions (Currenti et al., 2010; Bonaccorso et al., 2011) and the definition of the factors preparing and triggering flank instability (Norini and Acocella, 2011).

The present volume “Flank instability, eruptions, seismicity and hazard: the case of Mt. Etna” completes these researches with a large body of multidisciplinary studies deriving from the “Flank” Project, specifically focused on: a) the geometry and kinematics of the structures characterizing flank instability; b) the causative relationships between flank instability, eruptions and seismicity; c) modeling of flank instability, to understand its causes; and d) the evaluation of the hazard induced by flank instability. These studies, summarized in 15 contributions, have been grouped in the present volume in order to provide the reader interested in flank instability with a comprehensive and updated reference on a well-known and well-monitored case. The idea behind this special volume is in fact to try to cover the most important aspects of the various fields related to flank instability and organize these in a coherent and broad frame. We expect that this volume may be of use not only to study Etna, but may help in understanding and facing flank instability processes at any other volcano.

While the studies here presented certainly represent a significant contribution to flank instability at Mt. Etna, this volume is far from being a conclusive and definitive report, and some important information and evaluations are still needed. These include the deep extent of flank instability below most of the volcano, the longer-term (centuries) relationships to eruptive activity, as well as a more quantitative definition of the possible hazard scenarios.

The studies focused on each of the main topics of the special volume are described below.

2. The geometry and kinematics of the unstable flank at Mt. Etna

Recent geodetic studies developed in the frame of “Flank” and describe the overall deformation pattern of Mt. Etna during the

last two decades (Solaro et al., 2010) and in the 1992–2000 period (Bonforte et al., 2011). These geodetic data, matched with those from previous geological and geophysical studies, have allowed Azzaro et al., 2013a–this issue, to propose a synthetic structural model of both the onshore and offshore portions of the volcano. Such a model may be a reference for future modeling studies of Mt. Etna.

While defining the structure at the volcano scale, the importance for detailed studies of specific areas of the unstable eastern flank was manifested. These areas mainly include its northern and southern boundaries. The Pernicana Fault System marks the northern and most active limit of the unstable eastern flank, with an extent of ~20 km, from the NE Rift to the seaside. It has been repeatedly activated during major rifting events from the NE Rift, to which it is kinematically connected (Groppelli and Tibaldi, 1999). Therefore, the Pernicana Fault System can be considered as a gauge of any instability occurring on the eastern flank of the volcano, and studying and monitoring its activity provide first-order insights on flank instability and how this may be affected by shallow intrusions. Alparone et al., 2013–this issue, provide the first attempt to specifically define the seismic behavior of the Fault, relocating the seismic events occurring in the last decade. The very shallow seismicity (with maximum depth of 3 km below sea level) is clustered into two main zones, separated by an area with very low rate of earthquakes occurrence, but characterized by the highest seismic energy release. The fault plane solutions confirm the transtensive motion of the fault observed at the surface.

On the southern border of the eastern flank, several structures accompany instability. InSAR data from the last two decades show that these structures have been mostly active, even though with irregular behavior (Frøger et al., 2001; Neri et al., 2007; Solaro et al., 2010; Bonforte et al., 2011). Their activity and slip rate could be influenced by the internal magma dynamics, if characterized by general inflation or dike emplacement (Solaro et al., 2010). Bonforte et al., 2013a–this issue, provide a detailed analysis of the main structural features of the fault systems of the southern part of the eastern unstable flank, using soil gases and SAR measurements. SAR, CO₂ and Radon measurements reveal the precise location of the active fractures on the flank. Gas measurements are especially useful at higher altitudes, where the SAR signal becomes poor. This study is an example of the potential of coupling InSAR with soil gas prospecting methods in detecting hidden active structures.

Many of the faults on the southeastern unstable flank are located in urban areas. An example of a detailed multidisciplinary study of one of the most active of these faults, the Trecastagni Fault, is given in Bonforte et al., 2013b–this issue. The activity of this fault between 2005 and 2009 is studied by means of SAR, leveling and extensimeter data. The results show that the accumulated stress is periodically released seismically; this illustrates how faults in volcanic areas may be characterized by much higher slip rates and activity than those in tectonic settings, thus providing excellent proxies to understand the longer-term seismicity of regional faults.

The offshore continuation of structures reflecting flank instability has been a puzzling topic in the last decade, as no studies were available. The recent bathymetric data of Chiocci et al. (2011) provided important insights, even though at the shallow level. However, the multichannel seismic reflection profiles data of Argnani et al., 2013–this issue, some of which with high resolution, reveal for the first time the buried structural features of the offshore portion of Etna. While there is no significant evidence for the offshore continuation of the major faults characterizing the onshore slip of the flank, there is an offshore bulge bounded by a thrust fault that may have been magma-induced.

3. Causative relationships between flank instability, magmatism and seismicity at Mt. Etna

The definition of the relationships between flank instability, magmatism and seismicity is a crucial topic at Mt. Etna, especially for any multi-hazard assessment. While some general relationships between flank slip and eruptive activity have been proposed (Groppelli and Tibaldi, 1999; Acocella et al., 2003; Walter et al., 2005; Currenti et al., 2010), a more comprehensive analysis has been lacking.

A first important point is how to use and interpret monitoring data to detect any variation in the magmatic state of the volcano. The study of Di Salvo et al., 2013–this issue, addresses this topic using multivariate analysis of geophysical and geochemical data from 1996 to 2003, a period which includes major variations in the magmatic behavior of the volcano. This novel approach uses time series segmentation and self-organizing map techniques to show how the monitoring data may detect the transition from summit to flank eruptions. This information can be used to carry out a more careful evaluation of the state of a volcano and to define potential hazard assessments. The period investigated in Di Salvo et al., 2013–this issue, is crucial to understand flank instability at Etna, particularly during the change of the magmatic system in the 2001 and 2002–2003 major eruptions.

To better understand flank dynamics, Corsaro et al., 2013–this issue, investigate the petrologic processes in the shallow plumbing system of Mt. Etna between 1995 and 2005, including the two major eruptions. The authors find that, from 1995 to July 2001, magmatic processes did not significantly influence flank movement. By contrast, the onset of the 2001 flank eruption led to an acceleration of the movement as a consequence of the ascent, of a primitive, volatile-rich magma from a deeper (~10 km b.s.l.) reservoir. It is thus proposed that the intrusion of magma in the plumbing system may play a role in accelerating flank instability.

The effect of the major 2002–2003 eruption on the degassing system of the volcano has been also investigated using data between 2001 and 2005. Giammanco et al., 2013–this issue, show that the SO₂ and CO₂ variations in this period are largely influenced by the acceleration of spreading in 2002, which may have triggered a progressively deeper depressurization in the central conduit. In addition, by integrating geochemical and structural data, previous degassing models developed at Mt. Etna have been updated to advance the understanding of recent eruptive events.

These studies confirm the importance of petrologic and gas geochemistry information in understanding flank instability.

4. The causes: modeling flank instability at Mt. Etna

To better understand the factors triggering flank instability at depth, “Flank” has used numerical and analog models. These have focused on the causative relationships between flank instability and on several potentially destabilizing factors, both at the volcano scale and the local scale, focusing on key structures.

A more extensive set of analog models than that of Norini and Acocella (2011), matched with recent InSAR observations (Solaro et al., 2010), allowed Acocella et al., 2013–this volume, to evaluate the hierarchy of factors controlling flank instability at Etna. While the long-term regional tectonic activity is fundamental to provide an asymmetric morphology below the volcano, on the shorter term, magmatic intrusion has a primary destabilizing role, followed, to a lesser extent, by the spreading induced by the volcano load. This comparative study of the preparing and triggering factors of flank instability may enhance a better understanding also of less studied or poorly known flank instabilities at volcanoes worldwide.

A similar systematic approach was used by Apuani et al., 2013–this issue, through numerical models, testing in particular the role of

topography, geometry, hydrogeology and rheology of the structural units. Two main instability mechanisms were identified: one at shallow depth, with the sliding surface located inside the subbent Quaternary clay, and another deep-seated mechanism with a discontinuous and less evident sliding surface, developed inside the Apennine–Maghrebian Chain flysch in the basement. Both mechanisms contribute to explain the present deformation pattern and some of the main structures of the Etna flank.

More detailed numerical models, based on seismicity and geodetic data from the last decades, investigated the behavior of the Pernicana Fault, as representative of the instability of the northern portion of the eastern flank of the volcano (Bonaccorso et al., 2013–this issue). The results show that the pressurization of an intermediate storage and the traction exerted by the eastern flank sliding contribute to the seismicity along the Pernicana Fault, even without preceding an immediate eruption. Instead, the seismicity along the Pernicana Fault related to the intrusions inside the northern sector of the volcano would represent a potential early-warning for an impending eruption at Mt. Etna. This study, aiming at clarifying the relationships between flank slip and magma emplacement, provides constraints to better understand instabilities also at other volcanoes.

5. Flank instability induced hazard at Mt. Etna

The final part of this special volume is devoted at better defining the hazards deriving from flank instability at Mt. Etna, to provide the Italian Civil Defense with semi-operative information.

From a general point of view, Acocella and Puglisi, 2013–this volume, propose a conceptual model and, using geologic, geophysical, geodetic, geochemical and petrological observations from the last two decades, define possible scenarios related to flank instability at Mt. Etna in the near future. These scenarios may provide a general qualitative reference and recommendation in the case of five types of multi-hazard processes related (either as a cause or effect) to flank dynamics. These scenarios constitute the first attempt ever made on any volcano to face flank instability. It is expected that similar attempts will be made on other unstable volcanoes where the mechanisms for flank unrest are sufficiently understood.

The other two papers from Azzaro et al., 2013b,c–this volume, both concern the probabilistic seismic hazard assessment at Mt. Etna, possibly the biggest concern in the case of flank instability. The importance of the local seismogenic sources in the mid-short term is analyzed by: (i) generating different maps based on an extended historical earthquake catalog and a new probabilistic attenuation model (Azzaro et al., (b)); (ii) comparing them with the estimates of earthquake occurrence on the faults with higher seismic potential, considering also a time-dependent perspective (Azzaro et al., (c)). In particular, Azzaro et al., (b) apply a probabilistic procedure to model the attenuation of the macroseismic intensity in the Mt. Etna region, which allows estimating probabilistic seismic scenarios. This study also considers the anisotropic decay (elliptical) of the intensity due to a linear source. Azzaro et al., (c) first assess the hazard in terms of macroseismic intensity and represent the occurrence probability calculated for different exposure times both on maps and at fault scale. In addition, occurrence probability of major events at the fault scale has been investigated by statistics on intertimes. Two faults are identified as the most probable sources to be activated in the 2013–2017 period. This result represents a useful indication to establish priority criteria for actions aimed at reducing seismic risk at a local scale.

Finally, the need to archive, handle and readily use all the available structural information related to flank instability at Mt. Etna has allowed to propose a pilot-GIS database of the active faults of Mt. Etna (Barreca et al., 2013–this issue). This database collects, organizes and shares all currently available information on the active faults of the volcano. Furthermore, its structure is open to the collection of

further data coming from future improvements. By layering additional user-specific geographic information and managing the proposed database, a great diversity of hazard and vulnerability maps can be produced. This is the backbone for a comprehensive geographical database of fault systems, universally applicable to other sites.

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