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How to cope with volcano flank dynamics? A conceptual model behind possible scenarios for Mt. Etna

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ABSTRACT

Volcano flank dynamics poses a serious hazard, also involving the inhabited lower slopes. Mt. Etna is a well-studied unstable volcano, and a significant amount of data has been collected on the dynamics of its eastern and southern flanks. We first propose a conceptual model to describe and explain flank dynamics at Etna; we identify the preconditions, as due to the differential unbuttressing conditions at the volcano base, and the triggering factors, as shallow magmatic sources (dikes, reservoirs). Evidence and parameters and/or observations for flank dynamics are listed, summarizing the 1994–2010 period of activity. Based on this, we then propose a set of scenarios possibly occurring in case of unrest of the unstable flanks of Mt. Etna. Flank unrest is a variation in the steady state condition of the volcano flanks, possibly accompanied by significant ground deformation, seismicity and eruptions. The scenarios may provide a general reference and recommendation in case of five types of multi-hazard processes related (either as a cause or effect) to flank dynamics: 1) edifice inflation; 2) emplacement of dikes along the NE and/or S rifts; 3) seismicity along Pernicana Fault System; 4) seismicity on the S sector; 5) seismicity along Timpe Fault System. Each scenario is analyzed and recommendations are given. The scenarios may or may not be related to each other, in the sense that the probability of occurrence of one scenario may or may not be contingent or dependent upon the prior occurrence of another. These scenarios provide a qualitative analysis of the multi-hazard processes related to flank dynamics; a more quantitative (*i.e.* probabilistic) characterization is under consideration.

1. Introduction

Volcanic edifices result from the repeated emplacement of magmatic products in a limited area, usually within time spans of $<10^5$ years. As a consequence of this relatively rapid construction, any edifice with significant height (on the order of 10^3 m) can become unable to support its own load. This may result in the instability of one or more sectors of the volcano. In many cases, destabilization is produced by a combination of circumstances and events, rather than a single cause (Voight and Elsworth, 1997). Magma emplacement is largely the most common triggering factor, in the form of both dikes (Dieterich, 1988; Delaney et al., 1998; Elsworth and Day, 1999; Tibaldi, 2001; Acocella et al., 2006), or viscous intrusions (Voight et al., 1981; Voight and Elsworth, 1997; Belousov et al., 1999; Richards and Villeneuve, 2001). Flank dynamics can in turn also initiate volcanic activity (Alvarado and Soto, 2002; Acocella et al., 2003; Neri et al., 2005; Neri and Acocella, 2006), generating a feedback mechanism between flank dynamics and magmatism (McGuire and Pullen, 1989; McGuire et al., 1990; Walter et al., 2005). Other common triggers are fault activity (Hall et al., 1999; Walter et al., 2005) and seismic shaking (Ando, 1979; Acocella et al., 2003), whereas the presence of a weak basement (Borgia et al., 1992; Morgan et al., 2000; Borgia and van Wyk de Vries, 2003) and hydrothermal alteration (Lopez and Williams, 1993; Reid et al., 2001) usually constitutes preconditioning processes.

Flank dynamics may occur suddenly, leaving limited possibility for its prediction. This is the case, for instance, of many volcanic islands, whose catastrophic failure may trigger tsunamis (Keating and McGuire, 2004). In other cases, flank dynamics is more continuous and the possible correlation with other impending events (magma emplacement, eruptions and earthquakes) may help in predicting accelerated flank dynamics and therefore to adopt solutions/interventions to reduce the related hazard (*e.g.* Voight et al., 1981). Such a possibility may be significantly enhanced by an *a priori* adequate knowledge of the (1) structure (geometry and kinematics) of the unstable flank, (2) the mechanisms and processes responsible for the instability, (3) the general relationships among various dynamic processes (magma emplacement, eruptions, earthquakes) occurring on the volcano.

Mt. Etna (Italy) provides a suitable example to study flank dynamics at an active volcano. Its recent past was characterized by significant

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flank collapses, as the Valle del Bove (VdB) scar, formed at approximately 10 ka (Calvari et al., 2004). However, there is no evidence of similar catastrophic events in the last 8 ky (Calvari et al., 2004). The current structure of its unstable flanks is widely known, especially at the surface (*e.g.* Rust and Neri, 1996; Froger et al., 2001; Acocella and Neri, 2003; Solaro et al., 2010; Bonforte et al., 2011). The mechanisms and processes responsible for flank dynamics have been widely analyzed, as due to a weak basement (Borgia et al., 1992; Tibaldi and Groppelli, 2002; Solaro et al., 2010), the differential buttressing conditions at the volcano base (Froger et al., 2001; Solaro et al., 2011), the seaward growth of an intrusive complex at depth (Tibaldi and Groppelli, 2002) and shallow magma emplacement (Acocella et al., 2003; Puglisi et al., 2008; Neri et al., 2009; Ruch et al., 2010). In addition, the possible cause–effect relationships among magmatism, seismicity and flank dynamics, especially occurring in the last 2 decades, have also been highlighted (Acocella et al., 2003; Walter et al., 2005; Currenti et al., 2008; Puglisi et al., 2008; Neri et al., 2009). All these studies have permitted to define the onshore areal extent of the unstable flank, the velocity of its portions, as well as the possible mechanisms triggering flank dynamics (Neri et al., 2009; Solaro et al., 2010; Bonforte et al., 2011; Norini and Acocella, 2011).

For all these reasons, Mt. Etna may be considered as a reasonably known unstable volcano, where the hazard deriving from flank dynamics may be evaluated. Flank dynamics at Mt. Etna is continuous, characterized by the near constant downward movement and diffuse shallow seismicity of the eastern and southern flanks. Not considering any catastrophic failure of parts of the edifice, historically not experienced on Mt. Etna, here we focus on the episodes of acceleration of such dynamics, which we refer to as flank unrest. Flank unrest may be related to hazardous conditions (flank eruptions, shallow seismicity, surface fracturing), responsible for large economic damages and casualties in the last centuries. On these premises, this study uses the existing amount of information on flank dynamics at Mt. Etna, largely due to the multidisciplinary monitoring system expanded during the last two decades, to provide five types of multi-hazard processes related (either as a cause or effect) to the dynamics of the flanks of the volcano. To our knowledge, this study constitutes the first integrated attempt to evaluate flank dynamics on an active volcano and provide a semi-operative tool to mitigate its effects. We expect that such an operational-oriented approach on flank instability may be a reference attempt to be considered also at other unstable volcanoes. This study has been performed in the frame of a 2-year Italian project (named FLANK), devoted at understanding flank dynamics

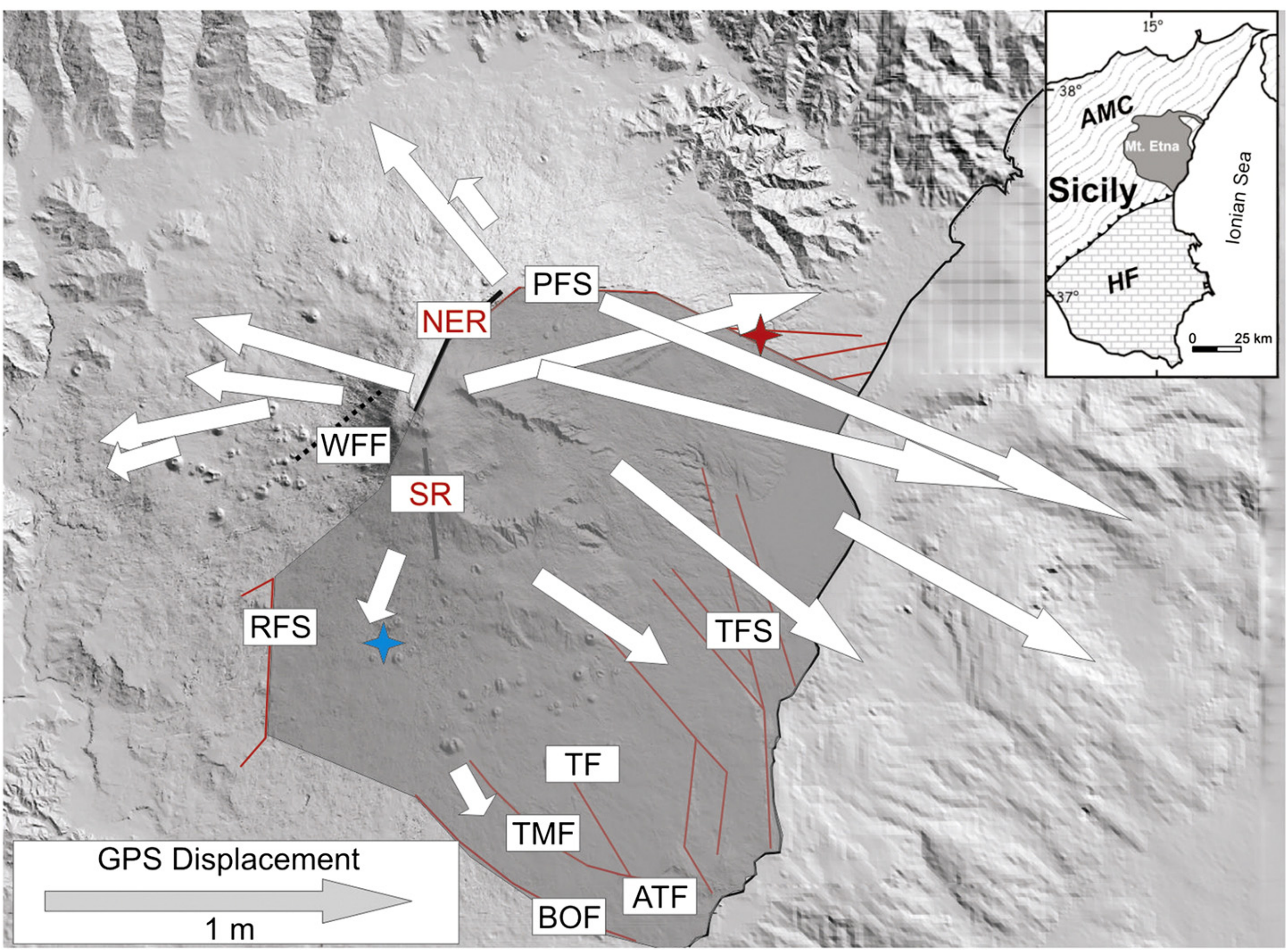

Fig. 1. Topography and bathymetry of Mount Etna area. The most unstable flank is highlighted in darker gray. The vectors represent the total displacements between 1993 and 2006 recorded at selected benchmarks (located at the beginning of each vector arrow) of the GPS network. The map also shows the location of the main faults, volcanic features and other relevant sites discussed in the text: Pernicana Fault System (PFS); Ragalna Fault System (RFS); Belpasso–Ognina Fault (BOF); Tremestieri–Mascalucia Fault (TMF), Trecastagni Fault (TF); Aci Trezza Fault (ATF); Timpe Fault System (TFS); Western Flank Fault (WFF); NE Rift (NER); South Rift (SR). The blue star indicates the location of M. Parmentelli; the red star indicates the Presa area.