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EDITORIAL

Editorial: Flank dynamics, sector collapses, lahars, and rockfalls: analysis, monitoring, and modelling of small to large scale volcanic slope instability

Federico Di Traglia[1] · **Matteo Roverato**[2] · **Alessandro Bonforte**[3] · **Felix Gross**[4]

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Slope dynamics in volcanic environments comprise a wide spectrum of phenomena, from large lateral collapse to shallow debris remobilization, which may represent a major threat for human communities and infrastructures. Many volcanos built up from the ocean floor and large portions of the volcano edifice are submerged. In these settings, only the edifice's summit can be investigated by terrestrial remote sensing and in-situ approaches. Growth and destruction, including tectonics and gravitational phenomena, affect entire volcano flanks and are not limited to the physical boundary of the sea level but could comprise their subaqueous parts (Urlaub et al. 2018).

Slope instability is a major hazard to local communities and the environment. It affects populations and infrastructure either directly from rockfalls, flows, and avalanches, or through cascading hazards like earthquakes (e.g., Kilauea in 2018, Chen et al. 2019), lateral blasts (e.g., Bezymianny in 1956, Mount St Helens in 1980, and Soufrière Hills in 1997, Belousov et al. 2007), lahars (e.g., Mount St. Helens after the 1980 eruption, Siebert 1984; Major et al. 2000), and tsunamis (e.g., Unzen-Mayuyama in 1792, Sassa et al. 2016; Stromboli in 2002, Bonaccorso et al. 2003; Anak Krakatau in 2018; Grilli et al. 2019; Ye et al. 2020). Since coastal population is increasing globally, hazards from tsunamigenic landslides are expected to further grow in the future. Volcano slope instability has a direct impact on land use, considering the presence of volcanoes that can potentially experience flank-failure inducing also widespread ashfalls and landslides-induced tsunamis in areas where human activities are concentrated.

Volcano slope instability is defined as the condition within a volcanic edifice that destabilizes to a degree sufficient enough to increase the likelihood of structural failure of all or portions of the edifice (Siebert 1996; Voight and Elsworth 1997; de Vries and Davies 2015). Large-scale volcanic edifice collapses have been identified at more than 400 Quaternary volcanoes worldwide, with a global frequency of five large-scale edifice failures per century (Siebert 1984; Dufresne et al. 2020; Siebert and Roverato 2020). Shallower mass movements such as gravel slides or rock falls tend to be more frequent (days–years), have a smaller volume ($< 10^6$ m^3), and smaller impacted areas, whereas larger and less frequent (tens to hundreds of years) landslides ($> 10^6$ m^3) such as rock slides or debris avalanches typically have deeper-seated failure planes and they can travel longer distances, resulting in larger impacted areas (Sosio et al. 2012). Large-scale landslides on volcanic edifices usually comprises two endmembers: volcanic debris avalanches (VDAs), being a sudden single catastrophic event, and slumps, reflecting progressive slope failure (Blahůt et al. 2019). The latter affects volcano with persistent flanks motion and flank deformation (Okubo 2004; Hildenbrand et al. 2012) (Table 1).

Since volcanoes can be affected by steady and/or consistent flank dynamics as creep and/or shallow slope

✉ Federico Di Traglia
federico.ditraglia@unifi.it

Matteo Roverato
matteo.roverato@unige.ch

Alessandro Bonforte
alessandro.bonforte@ingv.it

Felix Gross
felix.gross@ifg.uni-kiel.de

[1] Dipartimento di Scienze Della Terra, Università Degli Studi di Firenze, Via La Pira 4, 50121 Firenze, Italy

[2] Department of Earth Sciences, University of Geneva, 13, Rue des Maraîchers, 1205 Geneva, Switzerland

[3] Osservatorio Etneo, Istituto Nazionale di Geofisica e Vulcanologia- Sezione di Catania, Piazza Roma 2, 95125 Catania, Italy

[4] Christian-Albrechts-Universität zu Kiel, Center for Ocean and Society/Institut für Geowissenschaften, Olshausenstr. 40, D-24118 Kiel, Germany

Table 1 Descriptions and characteristic volume ranges of different volcano slope instability phenomena (modified after Schaefer et al. 2019)

Category	Volume	Description
Deep-seated slope deformations evolving into debris avalanches	$> 10^7$ m^3	Large-scale deformation of an unstable volcano flank, manifested by scarps, benches, cracks, trenches and bulges, but may lack a fully defined rupture surface Evolving into extremely rapid, massive, flow-like motion of fragmented rock and volcaniclastics
Rock (rotational or planar) slide evolving into rock avalanches	$\approx 10^6$–10^8 m^3	Sliding of a mass of rock on a rotational or planar rupture surface that is not structurally controlled Evolving into extremely rapid, massive, flow-like motion of fragmented rock
Rock fall evolving into dry gravel/debris flows	$< 10^6$ m^3 (typically $< 10^5$ m^3)	Detachment, fall, rolling, and bouncing of rock Evolving into (generally) rapid flow-like movement of loose, dry, sorted or unsorted granular material, and without excess pore pressure
Gravel/debris slide evolving into dry gravel/debris flows	$< 10^6$ m^3 (typically $< 10^5$ m^3)	Sliding of a mass of granular material on a shallow, planar surface Evolving into (generally) rapid flow-like movement of loose dry, sorted or unsorted granular material, and without excess pore pressure

Terminology based on classifications from Hungr et al. (2014)

processes (material erosion and remobilization), flank movement can be categorized as:

(i) Persistent flank motion, typically deep-seated, steady-state movement of large sectors of a volcano edifice due to interaction between gravity and magma dynamics (Poland et al. 2017), sometimes referred to as “volcanic spreading” (Borgia et al. 1992; Merle and Borgia 1996);

(ii) Transient flank motion (i.e. flank “unrest”), considered the precursor to catastrophic collapses, associated with intrusive processes, co-eruptive deformation, seismic shaking, or other relatively rapid increases in shear stress (de Vries and Davies 2015);

(iii) Surficial slope motion, or shallow motion such as material erosion and remobilization of volcaniclastic and lava material (Schaefer et al. 2019).

In general, failures controlled by shear forces (e.g., slides) have a limit equilibrium condition between the shear stress (τ) and the shear strength (s): namely the factor of safety $F = s/$. (Reid et al. 2000; Schaefer et al. 2019). The shear strength s is defined by the Coulomb-Terzaghi failure rule $s = c + \left(\sigma_n - u\right)tan\varphi$, where c is cohesion, σ_n is the normal stress, u is the pore-water pressure acting on the shear surface, and ϕ is the angle of internal friction. An increase in the shear stress (e.g., from slope over-steepening, dynamic loading from dike intrusion or seismic shaking) or a reduction in the shear strength (e.g., from hydrothermal alteration or increase in pore fluid pressure) can lead to a sudden drop in F and abrupt acceleration of the flank of the volcano.

Slope failure may occur in response to active deformation (magma intrusion, gas overpressure, substrate spreading) or may result over a long period of time due to over-steepening, over-loading, or peripheral erosion (Fig. 1; Voight and Elsworth 1997; Reid et al. 2000, 2001; Apuani et al. 2005; Borselli et al. 2011; Schaefer et al. 2013; Roberti et al. 2018; Roverato et al. 2020). The role of magmatic intrusions is twofold, involving both driving and resisting forces (Voight and Elsworth 1997).

Primary, slope stability is diminished by magma-static and magma overpressures that accompany intrusion in instable flanks. Moreover, excess pore pressures in potential failure zones can be generated as a result of intrusion-related mechanical or thermal straining of the rock-fluid medium, pressurized retrograde boiling in high level magma chambers, or hydrothermal fluid circulation (Voight and Elsworth 1997; Bonaccorso et al. 2010; Borselli et al. 2011; Harris et al. 2012). In addition, tectonic activity can generate earthquakes that may aid slope instability through inertial forces and shaking-induced pore pressure generation, reducing the sliding resistance. The destabilizing influence of mechanically induced pore pressures is maximized as the intruded width, or corresponding overpressure, of the intrusion is increased. The destabilizing influence of thermally induced pore pressures is conditioned by the severity of thermal forcing, ratios of thermal and hydraulic diffusivities, and the time required for the fluid pressure disturbance to propagate outwards from the intrusion. Failure initiation does not imply sustained failure; in some cases, enhancement of pore pressures through deviatoric shearing, frictional heating, or run-out over compressible

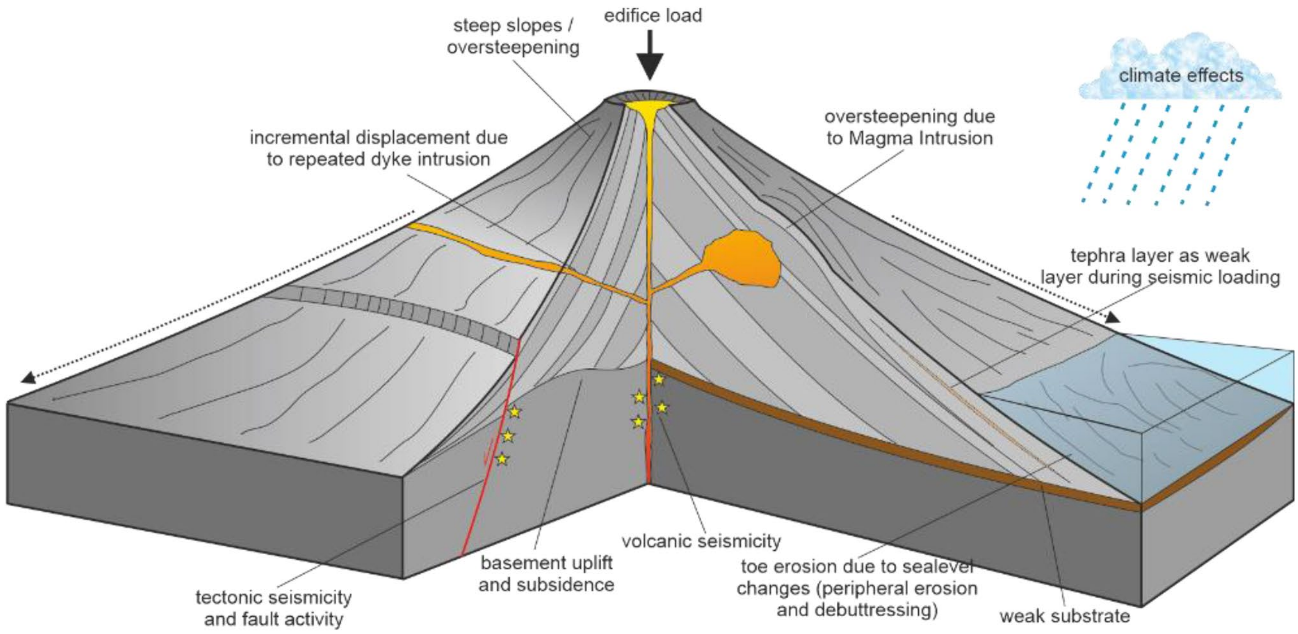

Fig. 1 Preconditioning, triggers and drivers of flank instability

saturated alluvium or marine sediments may be necessary following slide initiation to maintain the impetus of flank failure for long run-out (Voight and Elsworth 1997).

The interpretation and evaluation of such events is challenged by the complex and evolving interactions of tectonic, magmatic, fluid, and gravitational processes. The moving masses can behave in different ways depending on the depth of the detachment, water content and flow rheology and can demonstrate different modes from deep flank spreading or collapse to shallow granular or viscous flows. Water plays an important role in the transport and emplacement mechanisms of flows, enhancing their run-out and destructive power, as well as the pore pressure can increase favour the failure on local faults and deep detachment layers. Many volcanoes worldwide are located in tropical, high-precipitation environments or are covered by snow or glaciers, which exacerbates the potential for landslides, lahars and debris avalanches. In many cases, volcano flanks continue below sea level and are often affected by terrestrial volcano built-up and activity. Hence, subaqueous volcano flanks can be prone to mass wasting and consecutive tsunamis. A holistic understanding of flank dynamics and its consequences is therefore essential for the establishment of disaster risk reduction measures in volcanic and peri-volcanic environments.

The four papers belonging to this Special Issue present an updated general overview of the progress in volcanic slope instability analysis, monitoring, and modelling from multi-disciplinary efforts, from slope to edifice and regional scale. The topics discussed range from the geological/volcanological evolution of a Quaternary silicic volcanic complex (Shiribetsu) in Japan (Goto et al. 2020), the analysis of two very famous case studies for tsunamigenic landslides at Stromboli (Italy; Casalbore et al. 2020) and Ritter island (Papua Nuova Guinea, Karstens et al. 2020), to studies of grain-size distribution and sedimentological features of volcaniclastic mass flows (Makris et al. 2020).

Goto et al. described the geology and eruptive history of the Shiribetsu Quaternary silicic volcanic complex in Hokkaido (Japan). In this area, the authors recognized a debris avalanche deposit generated by a sector collapse occurred at West Shiribetsu at 50–60 ka.

Casalbore et al. analysed the role of different triggering mechanisms in controlling the occurrence and size of submarine slope failures at Stromboli, based on the integration of 11 years (2002–2013) of morpho-bathymetric data, comprising the 30th December 2002 tsunamigenic landslides.

Karstens et al. presented 3D seismic interpretations and sedimentological analyses of Ritter Island, highlighting both the deformations that occurred before the 1888 volcanic sector collapse and the different phases of the collapse itself. These data were used to reconstruct the landslide-induced tsunami and the new results are in agreement with historic eyewitness accounts.

The study of Makris et al. is based on the review of the grain-size distribution and sedimentological features of nine volcanic debris avalanche deposits and eight lahar deposits. The evidence of particles comminution in debris avalanches deposits support previous studies suggesting that the percentage of large proportions of fine particles, remains a valid candidate factor for their high mobility.

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