Dyke emplacement and related hazard in volcanoes with sector collapse: the 2007 Stromboli (Italy) eruption

Marco Neri*, Gianni Lanzafame* & Valerio Acocella°

* Istituto Nazionale di Geofisica e Vulcanologia, Piazza Roma 2, 95123 Catania, Italy (neri@ct.ingv.it)

° Dipartimento Scienze Geologiche Roma Tre, L.S.L. Murialdo 1, 00146 Roma, Italy

Corresponding author: Marco Neri

Abbreviate title: Dyke emplacement and hazard at Stromboli

Abstract

In February 2007, two effusive vents opened along the flank of Sciara del Fuoco (SdF) depression at Stromboli. The summit craters collapsed, obstructing the central conduit, choking the vents and increasing the deformation within SdF. Here a new vent opened, releasing the excess magmatic pressure. The eruption continued, after a summit explosion, until April. The vents were fed by laterally propagating dykes. Vent location is similar to that of the 2002-2003 eruption, fed by dykes triggering landslides, which in turn produced a tsunami. However, the 2007 eruption did not develop landslides, suggesting that their triggering also depends on other factors, (i.e. magmatic pressure).

Journal of the Geological Society
Dyke emplacement and related hazard in volcanoes with sector collapse: the 2007 Stromboli (Italy) eruption
M. NERI, G. LANZAFAME and V. ACOCELLA
Journal of the Geological Society 2008; v. 165; p. 883-886
doi:10.1144/0016-76492008-002

Most eruptions are triggered by dykes (Gudmundsson, 2006). Magma may feed a summit eruption (e.g. Decker, 1987), or emplace, through laterally propagating dykes, along the volcano slopes, reaching considerable distances (Bousquet and Lanzafame, 2001) and triggering hazardous slope instability (e.g. Walter et al., 2005). The path of these dykes is controlled by the topography of the edifice, as prominent scarps (e.g. Fiske and Jackson, 1972). Understanding what controls dyke propagation, as well as identifying any consistency in successive eruptions, is therefore fundamental for hazard mitigation, particularly in volcanoes affected by flank instability.

The island of Stromboli (Italy) is an ideal site for these studies, as it consists of a stratovolcano, rising steeply to ~900 m above sea level (a.s.l.; Figure 1), in near-continuous moderate Strombolian activity. This occurs from an open conduit, NE-SW elongated (Chouet et al., 2003), according to a regional trend (Rosi, 1980; Pasquarè et al., 1993; Falsaperla et al., 1999), feeding 3-4 summit craters at ~750 m a.s.l. (Figure 1). These are located at the top of the Sciara del Fuoco (SdF) scarp, the morphological expression of sector collapses, filled with loose deposits (Tibaldi, 2001). The 2002-2003 eruption was associated with two landslides within SdF, which triggered a tsunami (Bonaccorso et al., 2003; Calvari et al., 2005; Falsaperla et al., 2006). The eruption was induced by the emplacement of two orthogonal dykes, following the trajectories of the gravitational stress, controlled by the topography of the edifice (Acocella et al., 2006). Another eruption, fed by vents opened within the SdF, occurred in 2007; however, in this case no significant landslide developed.

This study considers the evolution of the 2007 eruption, with the aim of defining: a) how magma was emplaced during the eruption; b) any consistency with the 2002-2003 eruption, in terms of deformation pattern and related hazard, to try to evaluate constant features in the recent evolution of Stromboli and to understand magma propagation in stratovolcanoes with sector collapses.

Chronology of the 2007 eruption

After the 2002-2003 eruption, the summit crater area of Stromboli consisted of a single, large depression, NE-SW elongated and several tens of meters deep. Strombolian activity between 2004-2006 progressively filled this depression to its rim. In late 2006 – early 2007, Strombolian activity increased in frequency and intensity (see reports at http://www.ct.ingv.it/).

On 27 February 2007, ~13.00 GMT, a lava flow erupted from the northern base of the summit crater area. Immediately after, an eruptive fissure propagated downslope along a NE-SW alignment (vent 1 in Figure 1) vigorously feeding effusive activity at 650-600 m a.s.l. On the evening of the same day, the fissure propagated further downslope, varying its strike (from NE-SW to NW-SE) and becoming parallel to the northern rim of the SdF collapse depression. At ~18.30 GMT a new vent opened at ~400 m a.s.l., (vent 2 in Figure 1); soon after, vent 1 terminated its activity (Barberi and Rosi, 2007). On 28 February morning, surface fractures arranged with a horseshoe-like shape and NW-SE aligned were observed at vent 2 (Fig. 1). Contemporaneously, the uppermost fracture system collapsed, forming a NE-SW trending graben-like feature ~130 m wide and >30 m deep, partly resulting from a translational component towards NW of the seaside adjoining block (Figure 1).

During the first two days, the eruption was characterized by a peak in the effusion rate of ~21-22 $m^3 s^{-1}$ (Spinetti et al., 2007; “a” in Figure 2).

Starting from early of March, the summit crater conduit underwent the progressive collapse of its internal walls, enlarging the summit crater area (“b” in Figure 2). On 8 March, vent 2 interrupted its activity. At the same time, a progressive, significant inflation of the upper portion of SdF was registered by the Stromboli monitoring network (http://www.ct.ingv.it/stromboli2007/main.htm). On 9 March, vent 2 reactivated and, in addition, a new eruptive vent opened at ~500 m a.s.l., (vent 3 in Figure 1) ~350 m to the SSW of vent 1. Immediately after, the inflation monitored within SdF started to fade. Vent 3 ceased to erupt after about one day, whereas vent 2 continued its effusive activity. An explosion at the summit craters was observed on 15 March, 20:38 GMT (Figure 2). The related ejecta were found down to ~300 m a.s.l., on the eastern and southern slopes of the volcano. No other significant collapse affected the summit area after the 15 March explosion (see panel “b” in Figure 2).

The eruption ended in the night between 2 and 3 of April, following the progressive decrease of magma output from the 400 m vent. The eruption lasted 35 days, emitting, considering the effusion rate from satellite data measured by Spinetti et al. (2007), ~$8.9\pm1.5 \times 10^6$ m^3 of magma, with an average rate of ~2.9 ± 0.5 $m^3 s^{-1}$.

Feeding system and dynamics of the 2007 eruption

As suggested by the downslope propagation of the NE-SW strike fissure to the north of the summit crater area, vent 1 was fed by a laterally propagating NE-SW dyke, originated from the upper portion of the central conduit. Lateral propagation occurs once the magma within the upper conduit reaches enough pressure to overcome the resistance of the surrounding walls (Bousquet and Lanzafame, 2001). Indeed, the dyke propagated laterally downslope without significant seismicity and was not accompanied by strong explosive activity. The NW-SE aligned horseshoe-shaped cracks, located immediately to the SE of vent 2 (Figure 1) may have been induced by the opening of the vent. However, the relationships between vent 1 and 2 are not unequivocal on the field, since lacking continuity in the fractures at surface or of any intermediate vent. Similarly, the origin of vent 3 and its relationships with vents 1 and 2 are also unclear from field data alone. Therefore, despite the evidence that vent 1 is dyke-fed, the definition of the feeding system of vents 2 and 3 is debatable.

To try to understand their origin, we use results from analogue models simulating dyke emplacement within a volcano with a flank depression. Colored water (magma analogue) is injected within gelatine (volcano analogue), to form dykes. These experiments were partly published in Acocella and Tibaldi (2005), where the details on the apparatus and scaling are reported. The injection of water along the depression axis, on the upper edge of the scarp, forms a dyke. This propagates laterally, progressively varying its strike, becoming parallel to the wall of the depression (Figure 3, a to c) and extruding (red circle in Figure 3c) next to the depression scarp. The injection of water along the depression axis, but further from the scarp, forms another dyke. This propagates laterally, migrating towards the centre of the depression, subparallel to the depression axis (Figure 3 d to e) and extrudes (red circle in Figure 3e). The experiments suggest that the location of extrusion within a volcano with a flank depression is controlled by: 1) the location of provenience of magma; 2) the morphology of the depression. In any case, the extrusion occurs through the lateral propagation of dykes. At Stromboli, the depression is related with a sector collapse and the dykes propagate following the inner rim of the SdF, if fed along the collapse axis from the upper rim of the depression, they propagate within the collapse. These different behaviors result from the deflection of the stress trajectories at the sides of the depression (Acocella and Tibaldi, 2005).

The experiments suggest an explanation for the origin and location of vents 2 and 3 at Stromboli. Vent 2 may be due to the further downslope propagation of the dyke feeding vent 1. The variation in the direction of the dyke feeding vents 1 and 2 results from the deflection of the topography-induced $\sigma 1$ trajectory along the SdF rim. This hypothesis is supported by the fact that vent 1 ended its activity when vent 2 opened, suggesting a common feeding. Vent 3 results from the lateral propagation of a different dyke, originating below the collapse, possibly within the central conduit below the craters. This dyke migrated toward the centre of SdF, along a subradial path, not affected by the topographic effect of the SdF walls, since these were too distant from the dyke source. The distribution of vents during the 2007 eruption appears thus controlled by two laterally propagating dykes: a dyke fed by the upper portion of the central conduit, propagating with a curved path along the SdF rim, and a NW-SE dyke fed by the central conduit (Figure 4).

Therefore, the dynamics of the eruption appear as follows. At the eruption onset, magma filled the summit craters, triggering the NE-SW fissure, feeding vent 1 and, subsequently, vent 2. The rapid drainage of magma from the central conduit (see panel "c"; Fig. 2) caused the collapse of the internal walls of the conduit, producing its temporary, partial obstruction for a few hours, on 8 March. This induced an overpressure inside the conduit, inflating the upper SdF. The collapse of a wide portion of SdF seemed incipient, when the overpressure at the dyke tip produced a bulge at surface, enhancing landslides. The reactivation of the vent 2, as well as the temporary propagation of a NW-SE striking new dyke, ~100 m below and within the summit conduit (Figure 4), released the internal magmatic pressure, terminating the surface deformation. The major explosion of 15 March was probably due to the arrival of a new batch of non-degassed magma (Corsaro et al., 2007), in the context of a vanishing supply, enhanced by the partial obstruction of the conduit. This explosion significantly enlarged the summit crater area, expelling the previously collapsed material.

Comparison with the 2002-2003 eruption and hazard implications

Vent 1 of the 2007 eruption is in the same location as vent "a" in 2002-2003 (Fig. 1), which was also dyke-fed (Acocella et al., 2006). However, in 2007 the dyke propagated further downslope, to 400 m a.s.l. Similarly to 2002-2003, this feeding system has been the most active. Vent 3 is located along the same alignment as vents "b-f" of 2002-2003 (Figure 1), which were intermittently fed by a NW-SE striking dyke. Therefore, in both eruptions the vents in this central portion of SdF were fed by NW-SE striking dykes.

The consistency in the location of vents and the propagation path of the dykes in the 2002-2003 and 2007 eruptions is evident (Fig. 4). Therefore, lateral dyke propagation, as controlled by the topography of the volcano and shaped by the presence of SdF, represents a constant feature of the shallow feeding system of the recent Stromboli eruptions. Minor differences between the two eruptions are listed here. a) The extent of the NE-SW dyke (significantly longer in 2007, changing its direction to NW-SE). b) The number of vents related to the NE-SW dyke and their duration of activity (one in 2007 lasting ~1 day, >five in 2002-2003 lasting ~50 days). These differences may be due to variations in the magmatic supply and geometry of the central conduit, at times obstructed in 2007. c) Despite the similar feeding system, no catastrophic landslide occurred in 2007. This does not seem to be related to any difference in the topography of SdF; in fact, the landslide scarp of 2002-2003 was already filled before the 2007 eruption (Falsaperla et al., 2006). A more feasible explanation for the lack of catastrophic landslides is related to the lower magmatic pressures developed at the tip of the NW-SE striking dyke. This is supported by the fact that only one vent opened for a very few hours, unlike 2002-2003, when 5 vents were active for several weeks. Moreover, the re-opening of vent 2 may have dissipated the accumulating pressures below SdF, preventing any catastrophic collapse.

Therefore, the two eruptions show how a similar feeding system, with different magmatic pressures, can be activated with different consequences, triggering catastrophic landslides or not (Apuani et al., 2005). As most eruptions are commonly fed by dykes (Gudmundsson, 2006, and references therein), often controlled by the volcano topography (Fiske and Jackson, 1972; Bousquet and Lanzafame, 2001), the specific configuration of the summit craters, within a sector collapse filled by debris deposits at Stromboli, continues to pose an additional, serious hazard deriving from dyke emplacement during future eruptions. This hazardous situation is shared by those active volcanoes characterized by unstable and/or steep flanks, as well as by the proximity to the sea or lakes. In fact, here the hazard directly deriving from the eruption may couple with that deriving from the triggering of landslides, collapses or even tsunamis.

Acknowledgments

We are grateful to the colleagues who worked with us during the 2007 Stromboli eruption, particularly to F. Barberi, A. Bonaccorso, S. Calvari, G. Giordano and M. Rosi. The Authors are grateful to the pilots and technicians of the helicopters of the Dipartimento Protezione Civile, Italy, which helped us for acquisition of aerial photography. We thank A. Tibaldi for his helpful review. S. Conway improved the English. Work funded by INGV and Dipartimento Protezione Civile, Italy, project INGV-DPC V2.

References

Acocella, V. & Tibaldi A. 2005. Dyke propagation driven by volcano collapse: a general model tested at Stromboli, Italy. *Geophysical Research Letters,* **32***,* L08308, doi:10.1029/2004GL022248.

Acocella, V., Neri M. & Scarlato P. 2006. Understanding shallow magma emplacement at volcanoes: orthogonal feeder dykes during the 2002-2003 Stromboli (Italy) eruption. *Geophysical Research Letters,* **33***,* L17310, doi:10.1029/2006GL026862.

Apuani*,* T., Corazzato C., Cancelli A*. &* Tibaldi A*.* 2005. Stability of a collapsing volcano (Stromboli, Italy): Limit equilibrium analysis and numerical modelling. *Journal of Volcanology and Geothermal Research,* **194**, 191-210.

Barberi, F. & Rosi M. 2007. The chronology of the 2007 Stromboli eruption and the activity of the scientific synthesis group. In: *The 2007 Eruption of Stromboli (Italy)*, XXIV IUGG General Assembly, Perugia (Italy) 2-16 July 2007.

Bousquet, J.C. & Lanzafame G. 2001. Nouvelle interprétation des fractures des éruptions latérales de l'Etna: conséquences pour son cadre tectonique. *Bulletin de la Société Géologique de France,* **172**, 455-467.

Bonaccorso, A., Calvari S., Garfì G., Lodato L. & Patanè D. 2003. Dynamics of the December 2002 flank failure and tsunami at Stromboli volcano inferred by volcanological and geophysical observations. *Geophysical Research Letters,* **30**(18)*,* 1941, doi:10.1029/2003GL017702.

Calvari, S., Spampinato L., Lodato L., Harris A.J.L., Patrick M.R., Dehn J., Burton M.R. & Andronico D. 2005. Chronology and complex volcanic processes during the 2002-2003 flank eruption at Stromboli volcano (Italy) reconstructed from direct observations and surveys with a handheld thermal camera. *Journal of Geophysical Research,* **110***,* B02201, doi:1029/2004JB003129.

Chouet, B., Dawson P., Ohminato T., Martini M., Saccorotti G., Giudicepietro F., De Luca G., Milana G. & Scarpa R. 2003. Source mechanisms of explosions at Stromboli Volcano, Italy, determined from moment-tensor inversions of very-long-period data. *Journal of Geophysical Research,* **108**(B7), B07301, doi:1029/2002JB001919.

Corsaro, R.A., Bertagnini A., Boari E., Freda C., Landi P., Metrich N., Miraglia L., Petrone C.M., Polacci M., Pompilio M., Tesoro R. & Tommasini S. 2007. Petrochemical composition of the products erupted during the February-April 2007 eruption at Stromboli volcano. In: *The 2007 Eruption of Stromboli (Italy)*, XXIV IUGG General Assembly, Perugia (Italy) 2-16 July 2007.

Decker, R.W. 1987. *Dynamics of Hawaiian volcanoes: an overview*. United States Geological Survey, Surveillance Professional Paper, **1350***,* 997-1018.

Falsaperla, S., Lanzafame G., Longo V. & Spampinato S. 1999. Regional stress field in the area of Stromboli (Italy): insights into structural data and crustal tectonic earthquakes. *Journal of Volcanology and Geothermal Research,* **88**, 147-166.

Falsaperla, S., Neri M., Pecora E. & Spampinato S. 2006. Multidisciplinary Study of Flank Instability Phenomena at Stromboli Volcano, Italy. *Geophysical Research Letters,* **33***,* L09304, doi:10.1029/2006GL025940.

Fiske, R.S. & Jackson E.D. 1972. *Orientation and growth of Hawaiian volcanic rifts.* Proceedings of the Royal Society of London*,* **329***,* 299-326.

Gudmundsson, A. 2006. How local stresses control magma-chamber ruptures, dyke injections, and eruptions in composite volcanoes. *Earth Science Reviews,* **79***,* 1-31.

Pasquaré, G., Francalanci L., Garduño V.H. & Tibaldi, A. 1993. Structure and geologic evolution of the Stromboli volcano, Aeolian Island, Italy. *Acta Vulcanologica,* **3**, 79-89.

Rosi, M. 1980. The Island of Stromboli. *Rendiconti della Società Italiana di Mineralogia e Petrologia,* **36**, 345-368.

Spinetti, C., Buongiorno M. F., Doumaz F., Musacchio M., Lombardo V., Harris A., Steffke A. & Amici S. 2007. *Rapporto eruzione Stromboli 9-16Marzo 2007*. INGV Sezione CNT-LABTEL e Università delle Hawaii - HIGP/SOEST, World Wide Web Address: http://www.ct.ingv.it/Report/BollettinoCNT_160307_Stromboli%20(2).pdf.

Tibaldi, A. 2001. Multiple sector collapses at Stromboli volcano, Italy: how they work. *Bulletin of Volcanology,* **63**(2-3), 112-125.

Walter, T.R., Troll V.R., Cailleau B., Belousov A., Schmincke H.U., Amelung F. & Bogaard P. 2005. Rift zone reorganization through flank instability in ocean island volcanoes: an example from Tenerife, Canary Islands. *Bulletin of Volcanology,* **67**(4), 281-291, doi:10.1007/s00445-004-0352-z.

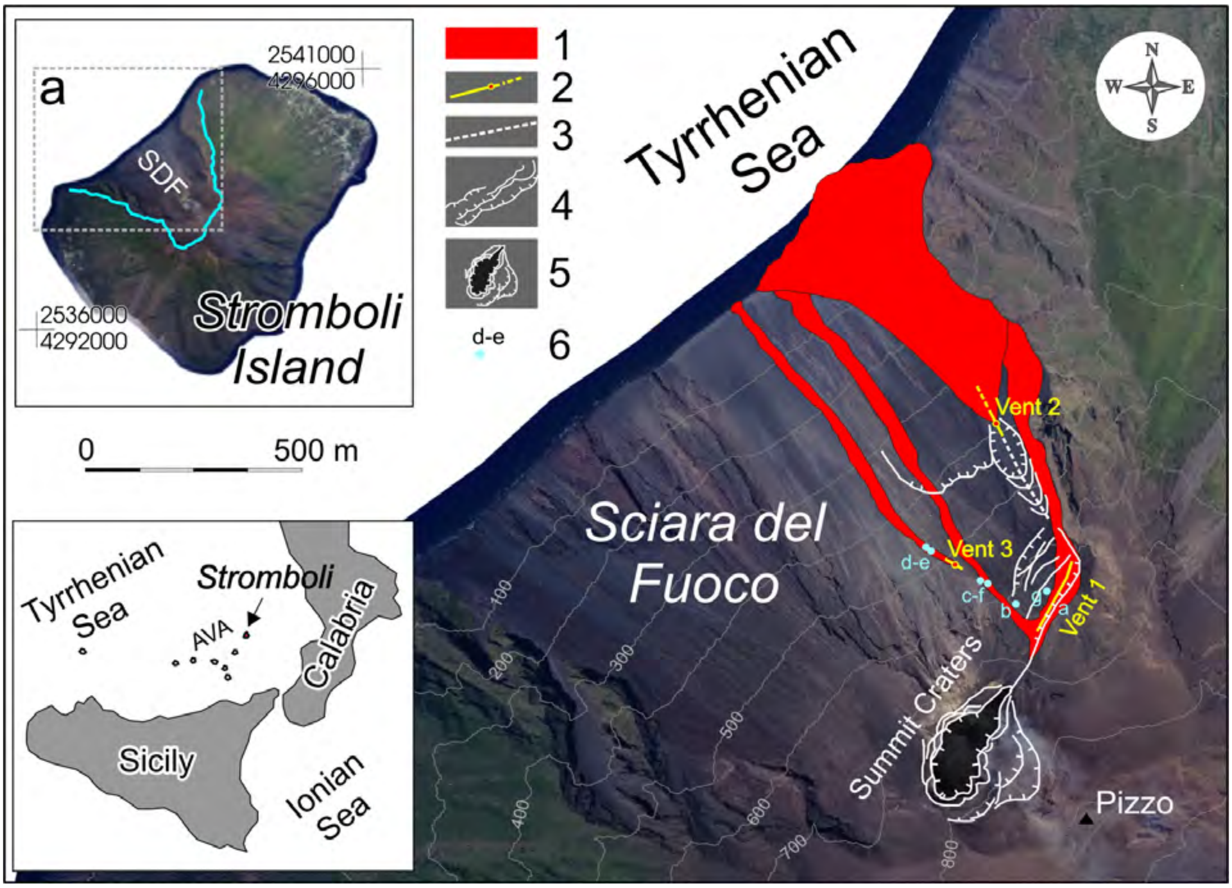

Figure 1 – Studied area (insets; AVA = Aeolian volcanic arc) and main features of the 2007 Stromboli eruption. Digital orthophoto (February, 6, 2003, Italian Civil Protection). 1) 2007 lava flows; 2) 2007 eruptive vents (vent 1, 2 and 3); 3) trace of the 2007 dyke feeding vent 2; 4) Main fracture fields in 2007 (bars indicate the downthrown side); 5) Surface cracks bordering the summit collapsed area in 2007; 6) Names (*a* to *g*) of the 2002-2003 main vents.

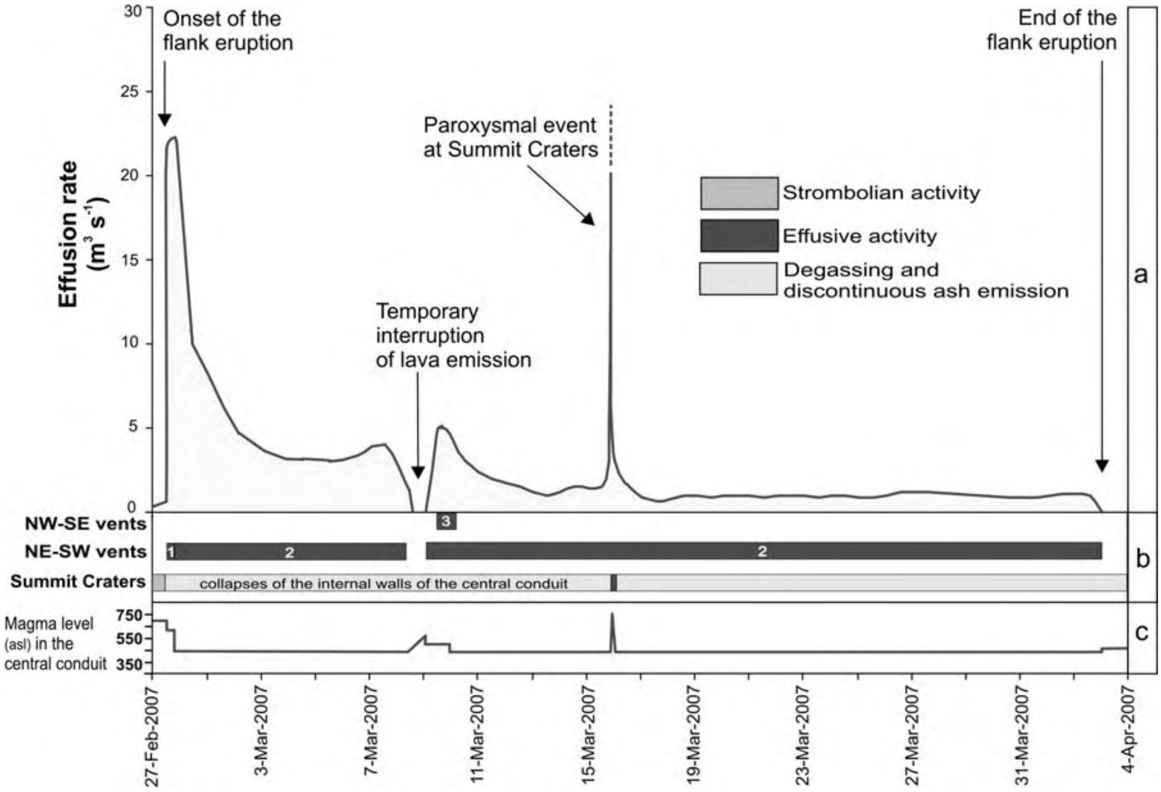

Figure 2 – Chronology of the 2007 events. Effusion rates (a) are calculated using the effusion rate from satellite data measured by Spinetti et al. (2007). (b) =Periods of activity at vents 1-2-3. (c) = Magma level within the central conduit, interpreted from the collected data (error of ±50 m).

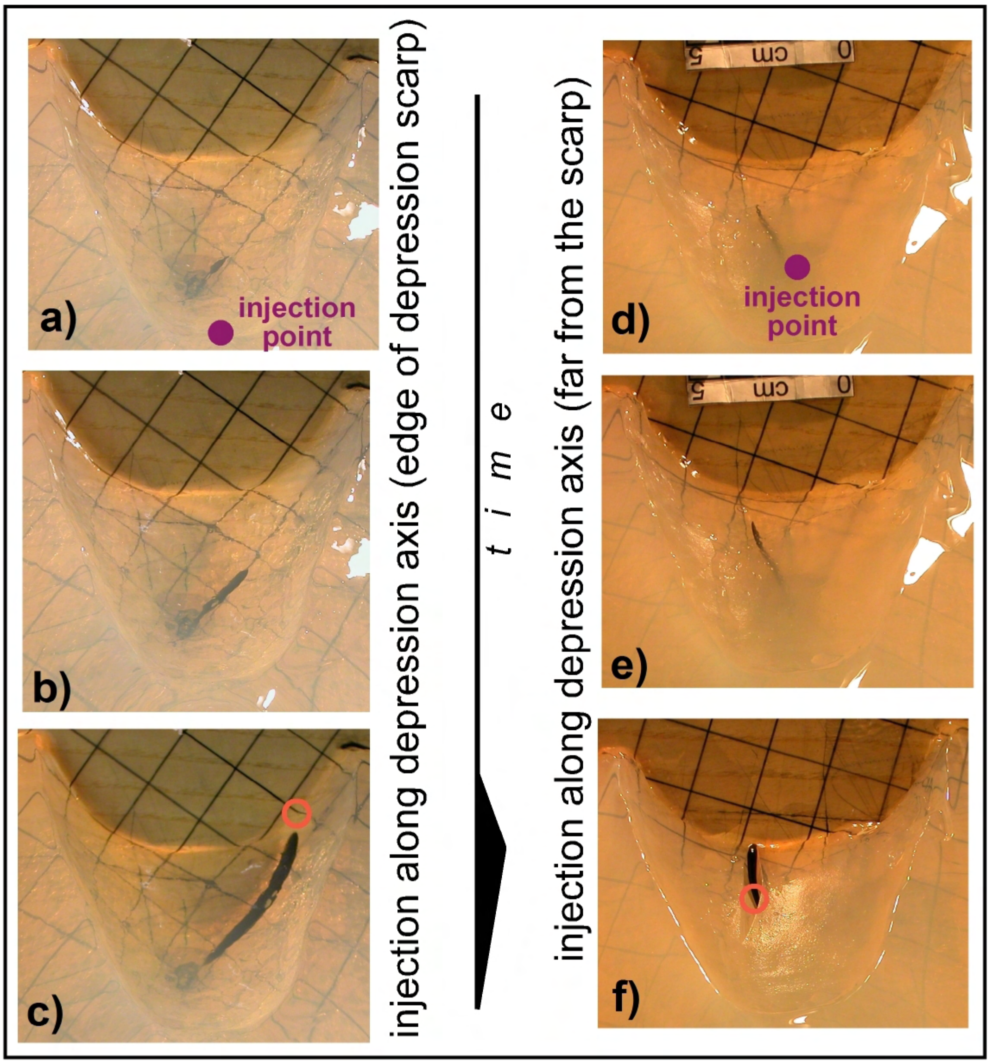

Figure 3 – Analogue models of dyke emplacement within a cone with a depression. a to c: map view of the propagation path of a dyke resulting from injecting black water along the depression axis, on the edge of the scarp; the dyke propagates following the inner side of the scarp, extruding in the red circle in c. d to e: map view of the propagation path of a dyke resulting from injection along the depression axis, far from the scarp; the dyke propagates and extrudes within the scarp centre (red circle in f). Exact position of injection is taken from section views of the models and then projected on the map views in a and d, to avoid any distortion. This distorsion in map view explains the apparent discrepancy between the drawn (purple dot) and the visible injection point.

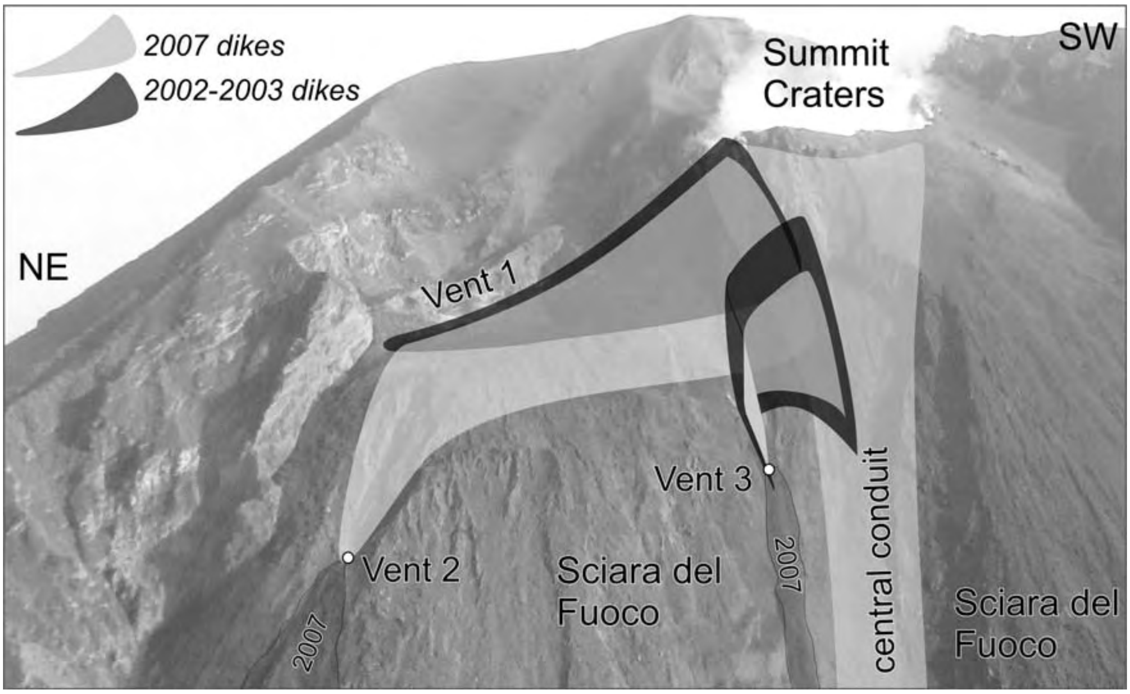

Figure 4 – 3D reconstruction of the dykes feeding the 2002-2003 and 2007 eruptions.