

Dynamics of the December 2002 flank failure and tsunami at Stromboli volcano inferred by volcanological and geophysical observations

A. Bonaccorso, S. Calvari, G. Garfi, L. Lodato, and D. Patanè

Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania, Italy

Received 8 May 2003; revised 12 August 2003; accepted 20 August 2003; published 23 September 2003.

[1] The 2002 effusive flank eruption at Stromboli volcano started on December 28, after several months of strong explosive activity at the summit craters. On December 30, the seismic network recorded two large flank failures and associated tsunami waves. This is the first time that a flank collapse and tsunami, and their associated phenomena, have been recorded by a multi-disciplinary monitoring system. Volcanological and geophysical monitoring, as well as thermal surveys performed immediately before and after the failure, allowed us to define and interpret the sequence of events. The still on-going eruption has provided, for the first time, the opportunity to look into the dynamics of Stromboli's effusive eruptions, flank failure and landslide formation, and their potential hazard. *INDEX TERMS:* 1204 Geodesy and Gravity: Control surveys; 7280 Seismology: Volcano seismology (8419); 8414 Volcanology: Eruption mechanisms; 8419 Volcanology: Eruption monitoring (7280). **Citation:** Bonaccorso, A., S. Calvari, G. Garfi, L. Lodato, and D. Patanè, Dynamics of the December 2002 flank failure and tsunami at Stromboli volcano inferred by volcanological and geophysical observations, *Geophys. Res. Lett.*, 30(18), 1941, doi:10.1029/2003GL017702, 2003.

1. Introduction

[2] Stromboli has had an almost continuous activity during the past 20 centuries, interrupted about twice a year by paroxysmal eruptions. Lava flow output is rare, the previous occurring along the depression of the Sciara del Fuoco (SDF) (Figure 1b) on December 1985 [De Fino *et al.*, 1988]. SDF is a well known unstable sector which has caused about 8 major collapses during the last 13,000 years [Tibaldi, 2001]. Before 30 December 2002, six tsunamis have occurred during the last 120 years: in 1879, 1916, 1919, 1930, 1944, 1954 [Barberi *et al.*, 1993]. The worst hypothetical scenario at this volcano is the collapse of the entire SDF, involving failure of about 1 km³ of rock [Tibaldi, 2001]. This event would move such a large volume of seawater as to have profound effects on the entire Aeolian Archipelago and also on the nearby coasts of southern Italy. The low coast of Stromboli would be hit by the wave, causing severe destruction and extensive damage, as modelled with recent numerical simulations [Tinti *et al.*, 2003a].

[3] On December 30, 2002, a flank collapse of a huge portion of SDF provoked a tsunami causing significant damage to buildings on the eastern coast of the island up to 10 m a.s.l. If a similar event had occurred during the spring-

summer, when that part of the island is densely populated by tourists, it would have had dramatic consequences. Therefore, the partial collapse of the SDF is a major problem and the principal source of hazard posed by the on-going eruption.

[4] In this paper we report details of the phenomena and provide an interpretation of the sequence of events occurring from December 28 (eruption start) to December 30 (flank failure and tsunami).

2. Geodynamic and Structural Framework

[5] Stromboli is a composite volcano, ~3 km high, whose top lies at 924 m a.s.l. Thus, most of the volcanic edifice extends below sea level. The island is located at the NE end of the Aeolian Archipelago (Figure 1a), a volcanic arc related to a Benioff zone dipping NW beneath the Tyrrhenian sea [Barberi *et al.*, 1974]. The morphology of the NW flank of the volcano is dominated by the SDF (Figure 1b), attributed to a giant collapse and landslide [Pasquarè *et al.*, 1993]. Spreading along a NW direction is due to preferential dyke emplacement following the NE-SW regional tectonic trend, which is the zone of main weakness of the volcanic edifice. Bathymetric studies indicate that the SDF extends below sea level to a depth of about 1700 m [Romagnoli *et al.*, 1993]. The majority of dykes, eruptive fissures and parasitic vents are concentrated along a NE-SW regional trend. Recent geophysical evidence [Bonaccorso, 1998; Falsaperla *et al.*, 1999] confirm geological and volcanological observations [Pasquarè *et al.*, 1993; Tibaldi, 2001] on the regional stress field, which is still active along the NE-SW structural direction. Seismicity is usually very shallow (<1 km) and associated with eruptive activity. Volcanic tremor and explosion-quakes are related to the fluido-dynamics of magma within the conduits. Tectonic earthquakes due to shear-failure of rocks are rarely recorded [Falsaperla and Spampinato, 1999], suggesting a free pathway for magma ascent. The source of tremor and explosions is concentrated at depths shallower than 200 m beneath the summit craters, as inferred by analyses from small-aperture seismic arrays [Chouet *et al.*, 1997; Saccorotti and Del Pezzo, 2000]. A further constraint from broad-band seismic data confirms that most of the energy radiated by the source originates within a small volume located at ~100 m depth beneath the SDF [Chouet *et al.*, 2003].

3. December 28 Eruption and December 30 Flank Failure

[6] Since May 2002, increasing explosive activity at the summit craters was recorded by the INGV-CT web-camera

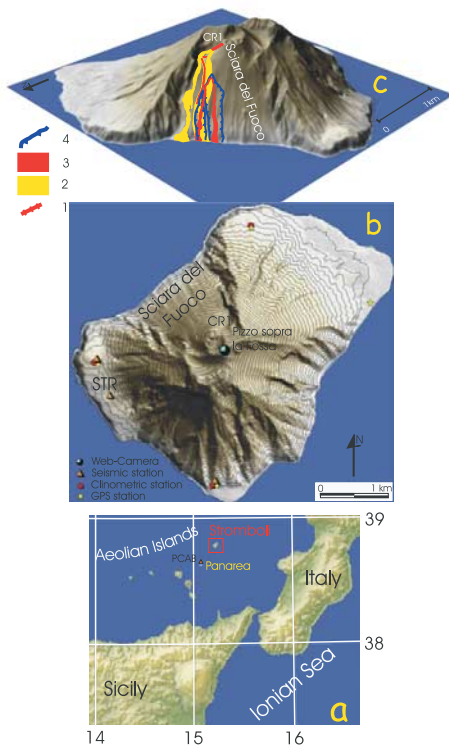


Figure 1. (a) Map of southern Italy and the Aeolian Islands. (b) Topographic map of Stromboli, showing location of the summit web camera, and seismic, clinometric and GPS stations. (c) DEM of the island of Stromboli, showing (1) the Dec. 28, 2002 eruptive fissure opened at the north-eastern base of Crater 1 (CR1), (2) the lava flows of Dec. 28, together with (3) the lava flows spread on Dec. 29 and 30 by the two vents at ~ 500 and ~ 600 m elevation, and (4) the boundaries of the two scars left over by the failure events of Dec. 30.

located at Il Pizzo Sopra La Fossa (Figure 1b), 100 m above the craters. Strombolian activity was very intense since May 2002, and lava level within the craters was very high on November, when an overflow from the N rim of Crater 2 formed a small lava flow which spread in the upper SDF. Increased strombolian activity and a greater frequency of explosion-quakes was associated with the explosions occurred on early December, when frequency of the explosions and heights of ejecta were particularly intense at Crater 1, the NE crater. On 28 December the height of ejecta reached 200 m above Crater 1, and the wide shape of explosions suggested magma very close to the crater rim. Frequency of explosions and heights of ejecta increased, and at 18:30 (local time = GMT + 1) on 28 December activity culminated with the opening of a NE-trending eruptive fissure, about 300 m long (Figure 1c). This broke the northern wall of Crater 1, displacing NW the upper eastern wall of the SDF. Two lava flows came out from the base and middle of the fissure (Figure 1c). The flows covered a very steep, unstable surface composed of loose lava blocks, scoria and debris. Within 30 minutes the first flow reached the sea, about 1.1 km away. The lava flows covered a 400 m wide area at the shoreline, but were about 100 m wide along the steep SDF walls. No geophysical precursors were noted prior to the onset of the

eruption. In particular, the INGV-CT permanent GPS network, which records a six hours data session per day, did not show significant changes in the benchmark positions before and after the eruption onset. Only a small increase of volcanic tremor amplitude accompanied the onset of lava flow emission.

[7] The opening of the eruptive fissure caused a complete drainage of the craters, which collapsed forming an elongate

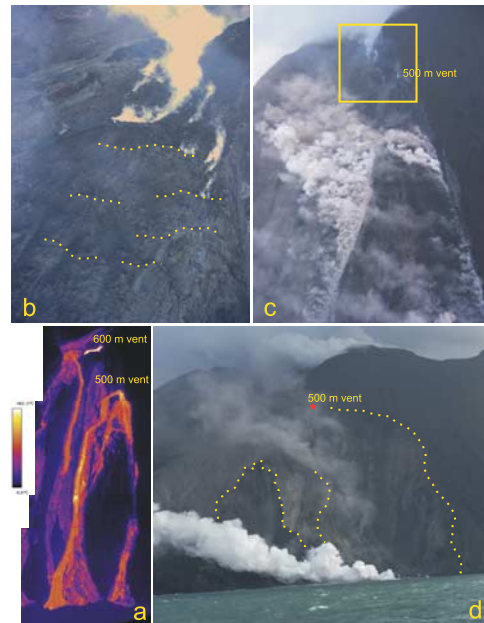


Figure 2. (a) Thermal images along the Sciara del Fuoco recorded on Dec. 30, 2002 at about 11:30 local time. View is from NW. The step-like portion of Figure 2b is the black, cold area between the 600 m and the 500 m vents. Blue colour (yellow lava flow in Figure 1c) represents the Dec. 28, inactive flows; red is the Dec. 29, inactive flows started from the ~ 600 m and ~ 500 m vents; white is the lava flow fed from the ~ 600 m vent, active on the morning of Dec. 30, and yellow-orange is the low-effusion rate lava flows spreading from the ~ 500 m vent, which are black and crusted over in Figure 2c. (b) Photo taken on 2nd January 2003 showing the NE base of Crater 1. View is from NW. Note the eruptive fissure on the upper part of the image, and a number of step-like blocks (bounded by yellow dotted lines) moved down slope and displaced NW by the opening of the eruptive fissure. (c) Photo of the upper Sciara del Fuoco taken on Dec. 30, 2002 at $\sim 11:30$ am (local time), less than 2 hours before the major failures. View is from NW. The two smoking lines bound the detachment surface that gave rise to the large landslides. The yellow square shows area of photo (b). The approximate position of the ~ 500 m vent is also represented. (d) Landslide scars along the Sciara del Fuoco after the major failure events. Photo taken on Dec. 31, view is from NW. The position of the ~ 500 m vent is shown by a red star, and outlines of the landslide scars by dotted yellow lines. The white vapour column rising from the sea is due to water vaporisation triggered by lava entering the sea. Note that no ash emission is taking place from the summit craters, in the upper margin of the photo.

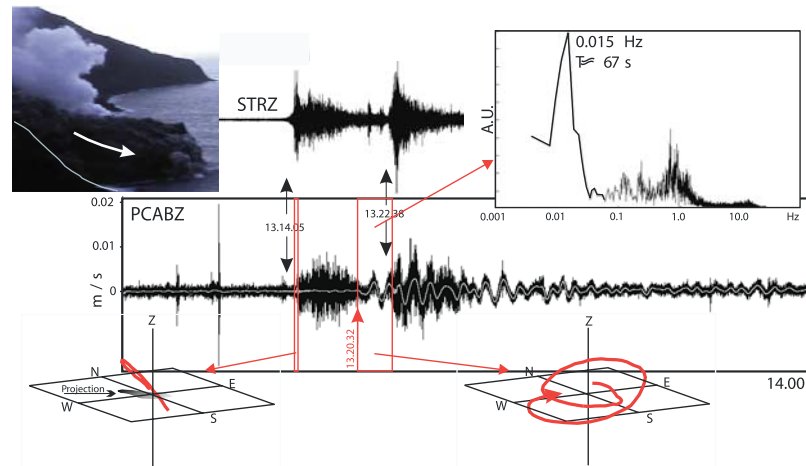


Figure 3. Seismic signals of vibrations associated with the Dec. 30 landslides along the Sciara del Fuoco, as recorded at two stations installed at Stromboli (STR) and at Panarea island (PCAB) (see Figure 1 for location). A gradual increase of signal amplitude characterizes the onset of the two main seismic events recorded at the short-period station of STR. This increase indicates a progressive detachment of the two rock bodies (Figure 2d). Seismogram recorded at the broad-band (60 s) station of PCAB shows the effect of sea waves of the tsunami. (top left, from a video taken by Massimo Pompilio, INGV-CT, and published on the www.ct.ingv.it web site). Using a low-pass filter at 10 s (white seismogram inside PCAB black seismogram) we can detect the onset (13:20:32 local time) of the sea wave oscillation at Panarea, which occurred about 6 minutes after the first landslide (13:14:05), and shows a predominant period of about 67 s (see spectrum at top right). Particle motion of the waves packet immediately follow the onset of the event and of the first part of the long period waves following the arrival of the tsunami is also shown.

depression. At least 12 hours passed before new flows came out from two vents at about 600 m and 500 m elevation (Figure 2a), during which a number of seaward-directed steps formed along the SDF (Figure 2b).

[8] In the early morning of December 29, the lava flows along the SDF were no longer being fed, and a helicopter-borne thermal survey showed transversal, horizontal cracks on the surface. The fractures probably were the first evidence of the ongoing failure process. Effusive activity resumed in the afternoon of Dec. 29, and a thermal survey on the morning of Dec. 30 revealed lava flows from two vents at about 500 and 600 m along the SDF wall (Figure 2a). Comparison between photos and thermal images taken on the morning of Dec. 30 (Figures 2a and 2c) shows hot surfaces, concave down slope, that developed along the cracks cutting the Dec. 28 flows (see Figure 1c for comparison). The thermal survey performed at $\sim 11:30$ a.m. on 30 December allowed us to collect unique data showing the formation of the cracks contouring the upper part of the flank which were to fail two hours later. Considering that the magma come out from the two 500 and 600 m vents and that no explosive activity was observed at summit, the ash emission from the entire fracture lines, where the magma did not come out, was instead caused by frictional sliding rather than explosive activity (Figure 2c). This aspect revealed the dynamics of their formation, which started from the upper eastern part of the SDF walls at about 500 m elevation and propagated down slope. During the 20 minutes of the survey, fractures also opened to the west, from about 500 m down slope, and spread defining the boundary of the landslide scar that formed a few hours later (Figure 1c). The mass of rock contained within the fractures did not move as a unique landslide, perhaps as a consequence of more competent rocks in the middle of the

surface, causing the failure of two distinct rock bodies (Figure 2d). Seismic records from the INGV-CT permanent network (Figure 3) did not show precursor signals of the landslide. Instead, they showed the timing of landslide propagation into the sea.

[9] Seismic signals associated with the two different landslides were observed at the short-period (1 s) stations located on Stromboli island (Figure 1b), which showed a gradual increase of signal amplitude and their onset can be detected at 13:14:05 and at 13:22:38 respectively (Figure 3). A temporary array of three 3-component digital seismic stations, equipped with broad-band (60 s) sensors and installed at Panarea island, 20 km away from Stromboli, recorded the effect of the tsunami. The long period seismogram at PCAB station (Figure 3) showed that the tsunami arrived after about 6 minutes. It is noteworthy that this timing is coherent with the computer-based tsunami modelling propagation carried out by *Tinti et al.* [2003b]. Moreover, when Panarea seismograms are low-pass filtered with a cut-off period of 10 s we can observe: *i*) a waves packet, which may correspond to Love waves due to the NW horizontal force induced by the first landslide. In fact, the particle motion analysis shows that this waves packet is linearly polarized on the transverse NW direction (hodogram on the left of Figure 3); *ii*) six minutes after the first landslide and before the arrival of the second, we can detect the onset (13:20:32) of the sea wave oscillation at Panarea. In this case very long period (67 s) waves are observed. They are characterized by a large and substantial ellipsoidal motion (in this case it's nearly a circle), which is mostly horizontal and not vertical as expected for the Rayleigh wave. In order to better characterize these surface wave arrivals, further studies (e.g. polarization and dispersion analysis) are however necessary.

[10] This was the first instrumental record of a tsunami at Stromboli. The two landslides detached from the SDF walls with a 8 minute interval (Figure 3). The resulting scar was up to several tens of meters deep into the volcanic edifice (Figure 2d). Many minor sub-aerial collapses and landslides occurred along the Sciara del Fuoco in the following hours, days and months, as documented by the INGV-CT seismic network. All these seismic events share with the two major landslides a common spectral character and a low frequency content, which is generally <6–8 Hz.

4. Discussion

[11] On December 28, lava output occurred because the magma level within the conduit rose to the crater rim. Magma pressure caused the opening of a fissure on the NE flank of Crater 1. The opening of the fissure caused a NW displacement of the upper SE portion of the SDF, causing a step-like breaking of the wall, and the opening of downward concave cracks, clearly visible both on photos and thermal images (Figures 2a and 2b). These cracks exposed the shallow feeding system of the two vents of 500 m and 600 m that opened along the SDF between 29 and 30 December. Therefore, our hypothesis is that the two vents were not located along a new eruptive fissure. We maintain that they formed at the intersection between the steps caused by initial detachment of the SDF wall, and the shallow feeding system of the volcano, located just a few tens of meters below this zone [Chouet *et al.*, 2003]. Passive magma spilling from the deepest part of the landslide scar, from the 500 m vent (Figure 2d), resulted from the intersection between the upper feeder conduit and the new topographic surface, which became deeper towards the crater zone due to the landslide scar.

[12] On 30 December, when the landslides and tsunami occurred: *i*) ground deformation did not detect any landslide-triggering intrusion; *ii*) before and during the failures there was no volcanic or tectonic seismicity; *iii*) seismicity was not the trigger, but the effect of the landslides, recording vibrations caused by sliding under gravity along the SDF; *iv*) the seismic events at 13:15 and 13:22 marked the time when detachments from the surface occurred. Both sliding surfaces reached the sea causing erosion of the shoreline. This suggests that landslides scar extended also below sea level.

[13] During a further helicopter-borne thermal survey performed a few hours after failures, a large ash cloud spreading eastward from the SDF hampered viewing of the scar morphology. The small landslides, still going on along the SDF, produced the ash cloud. The ash was wet, since it was mixed with steam from seawater vaporization during phreatic explosions triggered by the hot lava entering the sea (Figure 2d). Photos and thermal images during helicopter flight revealed the following: (1) no eruptive activity was present at the summit craters of the volcano, suggesting complete drainage of the upper feeder conduit; (2) no ash cloud was coming out from the summit craters, confirming that no summit explosive activity was associated with the collapse; (3) lava output from the ~500 m vent along the SDF was very low, suggesting passive drainage of the feeder system as a consequence of its intersection with the failure surface; (4) two separate sliding planes were

observed along the SDF wall, having estimated volumes of 0.6×10^6 and 5×10^6 m³ (Figure 2d); (5) the two sliding surfaces involved only the westernmost of the 28 December lava flows (Figure 1c), implying that extra weight on the SDF caused by emplacement of the new lava flows was not the primary cause of failure; this also suggests that intrinsic instability of the SDF surface might have been the trigger of its failure.

[14] Seismic records have shown that further minor landslides followed the main one during the next days. Given these conditions, it cannot be excluded that another major failure might happen in the near future.

[15] **Acknowledgments.** We wish to thank G. Bertolaso and the Italian Department of Civil Protection for the great support to our activities; the helicopter pilots of Civil Protection and Air Walsler, whose expertise and courage allowed us to collect a huge amount of data; all colleagues of INGV-Catania Section who helped during our monitoring effort, and E. Boschi who strongly encouraged this work. We thank K. Cashman and P. M. Davis for the reviews that led to improvements in the manuscript. We also thank E. Del Pezzo and G. Saccorotti who provided the broad-band seismograms recorded at Panarea.

References

- Barberi, F., F. Innocenti, G. Ferrara, J. Keller, and L. Villari, Evolution of Eolian arc volcanism, *Earth Planet. Sci. Lett.*, 21, 269–276, 1974.
- Barberi, F., M. Rosi, and A. Sodi, Volcanic hazard assessment at Stromboli based on review of historical data, *Acta Vulcanologica*, 3, 173–187, 1993.
- Bonaccorso, A., Evidence of a dyke-sheet intrusion at Stromboli volcano inferred through continuous tilt, *Geophys. Res. Lett.*, 25, 4225–4228, 1998.
- Chouet, B., G. Saccorotti, M. Martini, P. Dawson, G. De Luca, G. Milana, and R. Scarpa, Source and path effects in the wave fields of tremor and explosions at Stromboli volcano Italy, *J. Geophys. Res.*, 102, 12,915–12,950, 1997.
- Chouet, B., P. Dawson, T. Ohminato, M. Martini, G. Saccorotti, F. Giudicepietro, G. De Luca, G. Milana, and R. Scarpa, Source mechanisms of explosions at Stromboli determined from moment tensor inversions of very-long-period data, *J. Geophys. Res.*, in print, 2003.
- De Fino, M., L. La Volpe, S. Falsaperla, G. Frazzetta, G. Neri, L. Francalanci, M. Rosi, and A. Sbrana, The Stromboli eruption of December 6, 1985–April 25, 1986: Volcanological, petrological and seismological data, *Rendiconti della Società Italiana di Mineralogia e Petrologia*, 43, 1021–1038, 1988.
- Falsaperla, S., G. Lanzafame, V. Longo, and S. Spampinato, Regional stress field in the area of Stromboli (Italy): Insights into structural data and tectonic earthquakes, *J. Volcanol. Geotherm. Res.*, 88, 147–166, 1999.
- Falsaperla, S., and S. Spampinato, Tectonic seismicity at Stromboli volcano (Italy) from historical data and seismic records, *Earth Planet. Sci. Lett.*, 173, 425–437, 1999.
- Pasquaré, G., L. Francalanci, V. H. Garduño, and A. Tibaldi, Structure and geologic evolution of the Stromboli volcano, Aeolian Islands, Italy, *Acta Vulcanologica*, 3, 79–89, 1993.
- Romagnoli, C., P. Kokelaar, P. L. Rossi, and A. Sodi, The submarine extension of Sciara del Fuoco feature (Stromboli island): Morphologic characterization, *Acta Vulcanologica*, 3, 91–98, 1993.
- Saccorotti, G., and E. Del Pezzo, A probabilistic approach to the inversion of data from a seismic array and its application to volcanic signals, *Geophysical J. International*, 143, 249–261, 2000.
- Tibaldi, A., Multiple sector collapses at Stromboli volcano, Italy: How they work, *Bull. Volcanol.*, 63, 112–125, 2001.
- Tinti, S., G. Pagnoni, F. Zaniboni, and E. Bortolucci, Tsunami generation in Stromboli island and impact on the south-east Tyrrhenian coasts, *Nat. Hazards Earth Sys. Sci.*, 3, 1–11, 2003a.
- Tinti, S., G. Pagnoni, F. Zaniboni, and A. Armigliato, Simulations of the 30 December 2002 Stromboli tsunami, Italy. EGS-AGU-EUG Joint Assembly, 06–11 April 2003, Nice, France, 2003b.