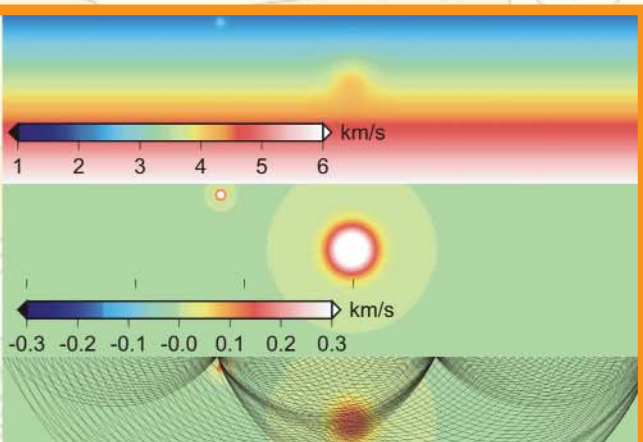
Warner Marzocchi and Aldo Zollo (Editors)

Conception, verification and application of innovative techniques to study active volcanoes

Istituto Nazionale di Geofisica e Vulcanologia

Dipartimento della Protezione Civile



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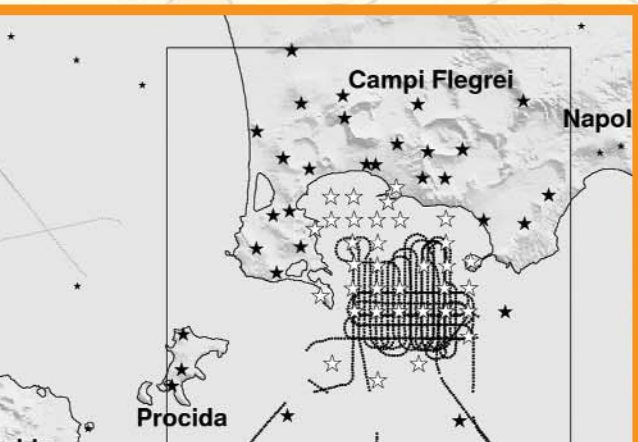

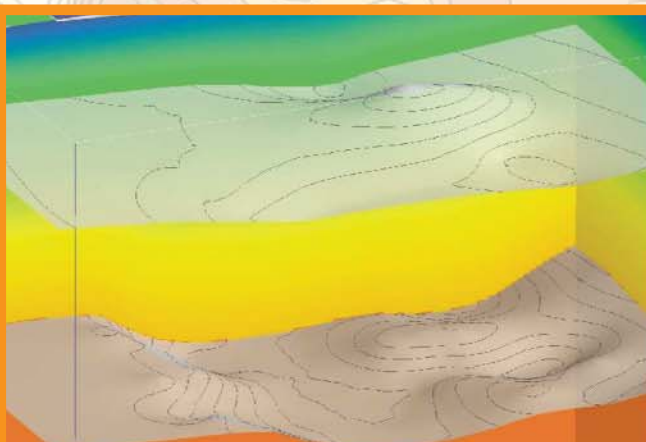

Conception, verification and application of innovative techniques to study active volcanoes

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Task 2

Can flank instability at Stromboli volcano provide insights into precursory patterns of eruptions?

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Abstract: By 30 December, 2002 a flank collapse affected the Sciara del Fuoco on the western slope of Stromboli volcano, Italy. To characterize this landslide-prone area for hazard mitigation purposes, Falsaperla et al. [2006] followed a multidisciplinary approach, merging geo-structural observations with visual images (taken by a video-camera surveillance network and vertical ortho-photos) and seismic data recorded throughout the continuous monitoring of the volcano. The study combined these different data types in a complementary framework to assess how and where the Sciara del Fuoco morphology changed. The time span investigated ranged from 2002 to 2004. We present here the results of that study, which identified the zones affected by sliding episodes and highlighted their changes in time. The evidence of the regression of the upper landslide scarp toward the summit craters over the years leads us to speculate about precursory patterns of eruptive activity linked to the progression of flank instability.

Introduction

The 28 December, 2002 marked the beginning of one of the most peculiar eruptive episodes at Stromboli over the last decades [Ripepe et al., 2005]. A flank collapse occurred two days after the onset of the lava emission [Bonaccorso et al., 2003; La Rocca et al., 2004; Calvari et al., 2005; Acocella et al., 2006], and affected both the subaerial and submarine part of the Sciara del Fuoco (hereafter SDF), a deep scar located in the western side of the Stromboli island. The collapse yielded two huge landslides associated with tsunami waves, which ravaged part of the island and swept the coasts of Sicily and Calabria. The landslides involved over 30 X 10^6 m^3 of material, ~2/3 of which below sea level [Bonaccorso et al., 2003; Pino et al., 2004]. Minor sliding episodes continued throughout the lava emission, which lasted 206 days. Landslides, flowing debris, and rockfalls commonly occur in several volcanic areas. A compelling question which rises when similar exogenous phenomena occur is whether they can cause changes that affect the magma feeder. This

question is the subject of intensive studies on andesitic volcanoes, such as for example Soufrière Hills, Montserrat [e.g., Calder et al., 2002]. Nevertheless, even for a basaltic volcano like Stromboli, the potential high risk of large failure events [e.g., Tibaldi, 2001] poses a significant hazard for the local population. SDF is prone to phenomena of flank instability, and therefore the possibility that events similar to or even larger than those of 30 December, 2002 might affect the volcano feeder became one of the major concerns of Italian Civil Defense and volcanologists ever since.
We present here the results of a multidisciplinary study by Falsaperla et al. [2006], which took into account geostructural data, ortho- and video-images, and seismic records at Stromboli volcano. The study provided an overview of the sliding phenomena at SDF between 2002 and 2004. In the light of the results obtained, we outline potential links between flank instability and endogenous changes, which might impinge upon volcanic activity.

Data and analysis

In the multidisciplinary study proposed by Falsaperla et al. [2006], structural field surveys and aerial, digital ortho-photos (courtesy of M. Marsella) allowed reconstructing the morpho-structural evolution of SDF between 2002 and 2004. Figure 1 depicts the changes over these years. The landslide phenomena of 30 December, 2002 deeply eroded the SDF, creating a depression that in some points reached depths of several tens of meters. Afterwards, a reshape process began through other minor erosive episodes and the deposition of lavas. The latter were erupted within a part of the collapsed/eroded zone, until the end of the eruption on 21 July, 2003. The lava effusion contributed to fill the depression, stabilizing a wide portion (more than 50 percent) of it and approaching a new gravitational equilibrium. Conversely, erosive phenomena continued in the zone of the landslides not reached by the lavas, as evident from the progressive regression of the erosive rim, which approached the crater zone (Figure 2). These phenomena yielded several rockfalls and flowing debris, which involved a rock volume estimated at ~ 5 X 10^5 m^3 [Falsaperla et al., 2006]. A comparative analysis of these sliding processes was based on seismic signals and video images covering the time span from March to October, 2004. The seismic signals were recorded at three seismic stations (Table 1) in continuous acquisition mode. The stations belonged to the permanent seismic network of *Istituto Nazionale di Geofisica e Vulcanologia* (INGV), and were located between a few hundreds meters and 1.8 km from SDF (ISTR, STR3 and STR8 in Figure 1). The images came from two live-cams, which recorded in the visible and IR band. The live-cams were set up in October, 2003 at 374 m a.s.l., and at a distance of 1042 m from SDF (LC in Figure 1). For the thermal live-cam, vertical and horizontal viewing was 18° and 24°, respectively. Video signals were digitalized to 640 X 480 pixels, and a GPS time-code added date

and time to each frame. Both seismic and live-cam equipment was run by INGV, and continuously monitored the volcano in the framework of surveillance activities to reduce volcanic hazard.

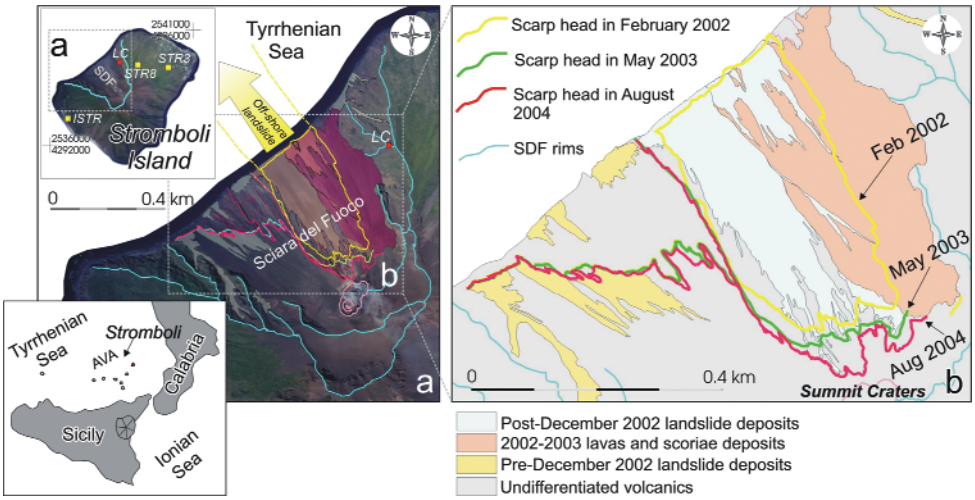

Fig. 1. Morpho-structural evolution of SDF between 2002 and 2004 (modified from Falsaperla et al., 2006). **(a)** Location of the studied area and ortho-photo in August 2004, with projection of the landslide margins, main displaced materials, lava flows, and SDF rim. AVA = Aeolian volcanic arc; LC = Thermal and visual live-cameras; ISTR, STR3, STR8 = seismic stations. **(b)** Morphological details of the landslide area.

Tab. 1. Instrumental characteristics of the seismic stations.

Station	Seismometer	Sampling frequency	Latitude	Longitude	Altitude (m)
ISTR	Geothech S-13	100 Hz	38N47.04	15E11.58	70
STR3	Guralp CMG40T	50 Hz	38N47.57	15E13.50	236
STR8	Guralp CMG40T	50 Hz	38N47.58	15E13.07	569

The data set consisted of 49 episodes, which were taken in daytime (Table 2). In so doing, the comparative analysis of video images and seismic records provided the opportunity to detect the sliding episodes in space and time. The search of each episode was fixed from the beginning of the digital readings on the seismic records.

Landslides, rockfalls, and flowing debris have a typical seismic signature [e.g., McNutt, 2000], which allowed a simple identifications of these signals from events of other origin, such as earthquakes and explosion quakes (Figure 3a). Their frequency content was characteristic as well (Figure 3b), and ranged bet-

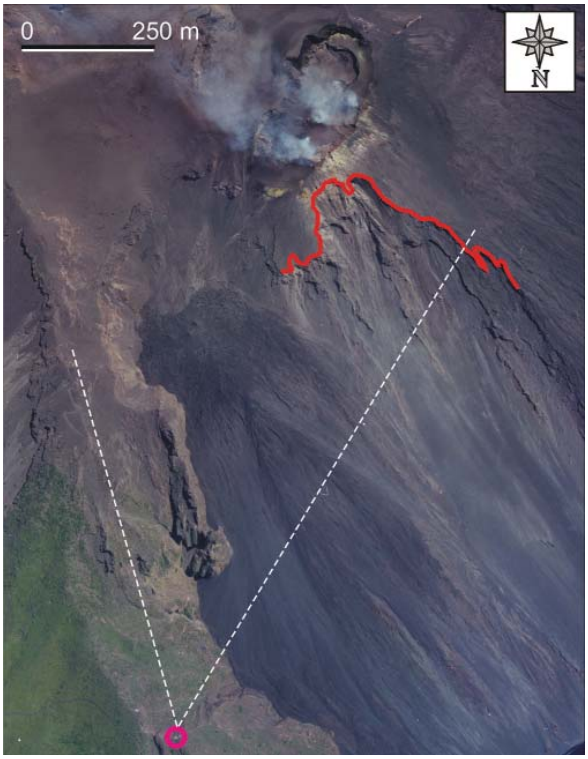

Fig. 2. Close-up view of an aerial snapshot taken on 4 August, 2004, showing the zone of SDF affected by 23 sliding episodes documented by visual images. The red circle and white dashed lines mark the position and visual field of the INGV live-cams. The red line marks the upper landslide scarp close to the summit craters. Image credit: M. Marsella, University of Rome 1.

ween 1 Hz and 20 Hz with small differences from station to station. Amplitude and duration of the episodes analyzed on the seismic records had no linear relationship. Consequently, no estimate of the source volume involved in the sliding process could be done from seismograms.

Overall, 23 out of 49 episodes had a documented visual record (Table 2). The remnant 26 episodes were not distinguishable as: i) they occurred during cloudy and/or bad weather conditions which might have hindered their occurrence (22 cases); ii) the weather conditions were fine, but there was no trace of them (4 cases). It is likely that the four unseen episodes stemmed from a zone outside the visual field of the video cameras, which covered only the upper-medium slope of SDF. The comparison between seismic records and timing of the images for the 23 documented episodes highlighted that the start of the visual phenomenon was almost concurrent with the beginning of the seismic record (Figure 4). The delay was of the order of a couple of seconds, i.e., within the scale of the resolution on the frames.

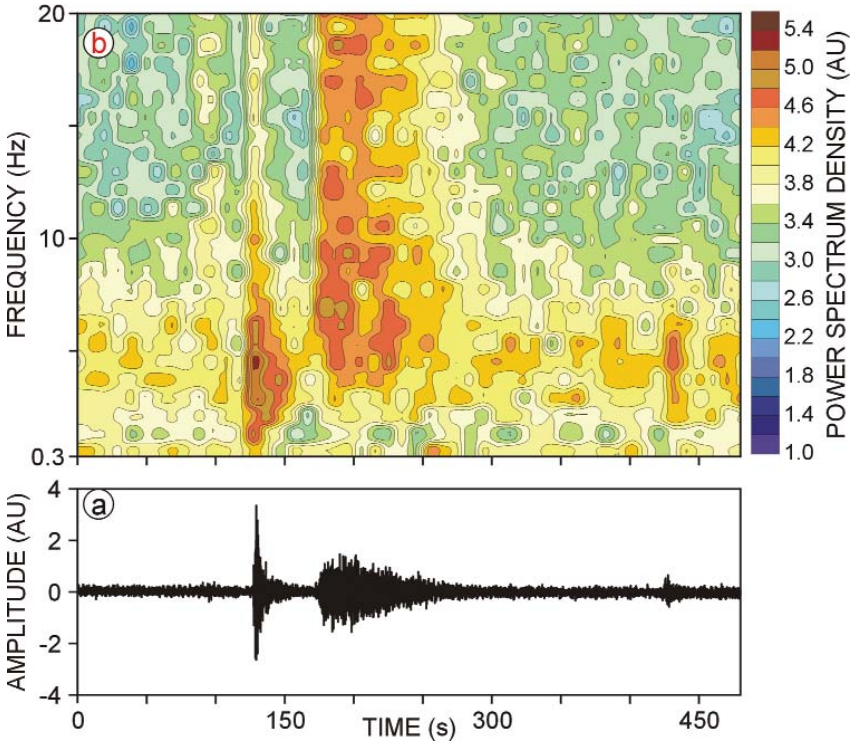

Fig. 3. Seismogram (a) and relative spectrogram (b) of a time series recorded at the vertical component of STR8 on 27 August, 2004. An explosion quake shortly precedes a rockfall episode. The spectrogram is calculated applying the Fast Fourier Transform to successive time series of 2.56 s with an overlap of 50%, and depicting the results as consecutive spectra. The frequency content of the rockfall is outstandingly higher than that of the explosion quake.

The 23 episodes documented by images shed some light on trigger mechanisms of seismic shaking. In spite of the absence of earthquakes preceding the sliding processes, the comparative analysis allowed documenting explosion quakes and Strombolian explosions conducive to shaking instability. There were 14 out of 49 episodes preceded by an explosion quake in a time span around two minutes before the onset on seismogram. An example is given in Figure 5, which includes a thermal image of the live-cam in IR band. The thermal image shows a typical Strombolian explosion at the summit craters – with ejection of ash, lapilli, and hot gas – followed by a rockfall episode. It is worth noting that the inspection of the thermal images excluded the presence of hot components within the material involved in the rockfalls.

Flowing debris and rockfalls yielded no evident distinction on the seismic record. On the other hand, since the video footage was limited, the mechanism of motion could not be wholly traced by the images. The boost of the

Tab. 2.

Date and time (yyyymmdd hh.mm.ss)	Visual observations and index (I) of resolution from 1 (poor) to 5 (good)	Time onset of: visible explosion	Time onset of: explosion quake
20040329 09.39.38	Cloudy, hard to distinguish anything		
20040329 12.27.52	Cloudy, hard to distinguish anything		12.26.55
20040401 12.08.38	Cloudy, hard to distinguish anything		
20040403 17.41.36	Fine weather, no event		
20040410 05.33.16	I2		
20040413 15.56.35	Strong wind and ash, hard to distinguish anything		15.55.04
20040413 17.03.40	Strong wind and ash, hard to distinguish anything		17.03.19
20040414 07.35.06	Foggy, hard to distinguish anything		
20040414 08.32.49	Strong wind and ash, hard to distinguish anything		
20040414 12.20.14	Foggy, hard to distinguish anything		
20040415 07.43.55	I3		07.43.39
20040415 10.07.58	I4		
20040415 15.48.19	Foggy, hard to distinguish anything		
20040417 06.38.07	Strong wind and ash, hard to distinguish anything		
20040610 14.05.31	Strong wind and ash, hard to distinguish anything		14.05.12
20040628 09.44.56	Strong wind and ash, hard to distinguish anything		
20040630 13.09.55	Strong wind and ash, hard to distinguish anything		
20040722 17.35.29	Fine weather, no event		
20040723 16.02.31	Strong wind and ash, hard to distinguish anything		
20040723 16.21.33	Strong wind and ash, hard to distinguish anything		
20040723 16.29.34	Strong wind and ash, hard to distinguish anything		16.28.37
20040724 17.22.26	Strong wind and ash, hard to distinguish anything		17.21.22
20040725 09.26.14	I3		09.24.28
20040725 09.37.38	I2		
20040725 13.58.33	Cloudy, hard to distinguish anything		
20040727 13.44.02	I2		
20040727 14.47.20	Foggy, hard to distinguish anything		
20040802 07.24.31	I1		
20040802 17.19.27	I4-5	17.17.49	17.17.23
20040806 17.04.59	Fair visibility, no event		
20040807 06.37.58	Fair visibility, no event		06.37.26
20040810 18.12.28	I2		
20040811 07.38.57	I2		
20040813 16.18.29	I4		16.17.29
20040813 17.44.41	I5		
20040816 09.20.23	I5		
20040816 09.42.49	I5		
20040827 16.30.50	I4	16.30.08	16.30.06
20040827 16.48.01	I3		
20040830 08.55.03	I3		
20040830 13.45.49	I2		13.43.40
20040830 14.55.07	I2		
20040830 15.12.47	Cloudy, hard to distinguish anything		
20040830 15.31.42	I3		
20040905 07.57.41	I3	07.56.34	07.56.04
20040906 11.43.31	I3		
20040906 11.57.49	I3		
20041010 09.04.49	Cloudy, hard to distinguish anything		
20041013 11.02.49	Cloudy, hard to distinguish anything		

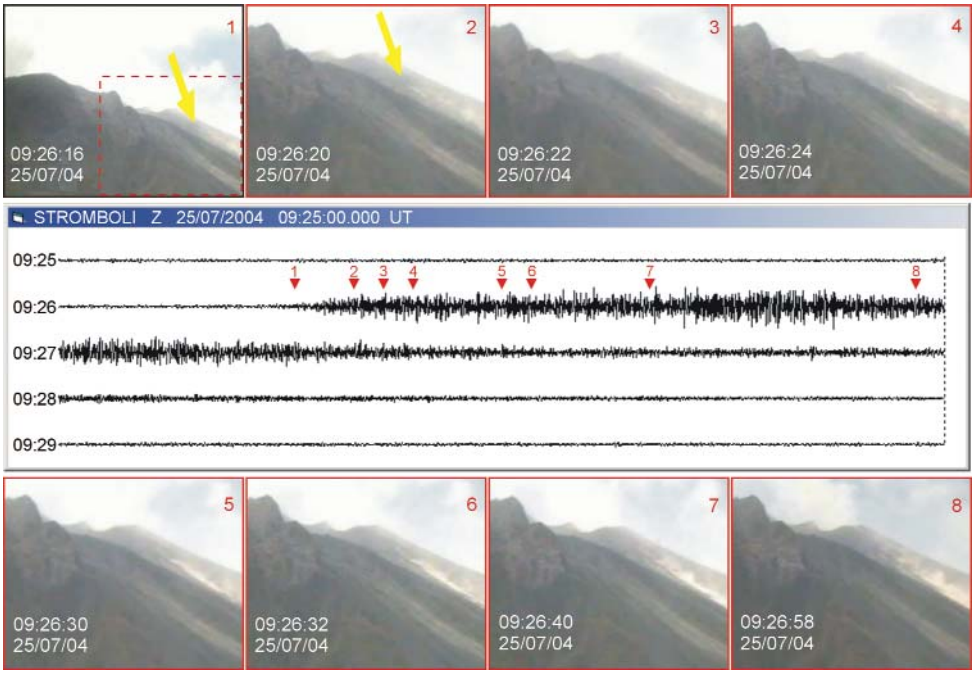

Fig. 4. Seismogram of a rockfall episode at the Sciara del Fuoco and concurrent snapshots (1-8) at the INGV live-cam in the visible band. The yellow arrow marks the beginning of the rockfall in the snapshots. The numbered red triangles from 1 to 8 on the seismogram match the sequence of video frames, which are a close-up view of the red dashed rectangle in frame 1.

live-cam network – in the wake of a renewal of effusive activity in spring 2007 – might shed more light on the variety of the mechanisms of motion and the zone from which they stem.

Discussion and conclusions

Apart from the two huge landslides and concurrent tsunami on 30 December, 2002 – two days after the renewal of effusive activity – the island of Stromboli was not affected by as large sliding episodes ever since. However, whilst the lava flows emplaced along the slope of SDF had a stabilizing effect, numerous flowing debris and rockfalls continued in the zones which were not covered by lavas during and well after the end of the lava effusion in July, 2003. This evidence supported the hypothesis that the flank collapse of 30 December enhanced the latent instability of SDF [Falsaperla et al., 2006]. The observation that 14 out of 49 sliding episodes shortly (about 120 s) occurred after moderate explosion quakes / Strombolian explosions (Figure 5) further corroborated this hypothesis.

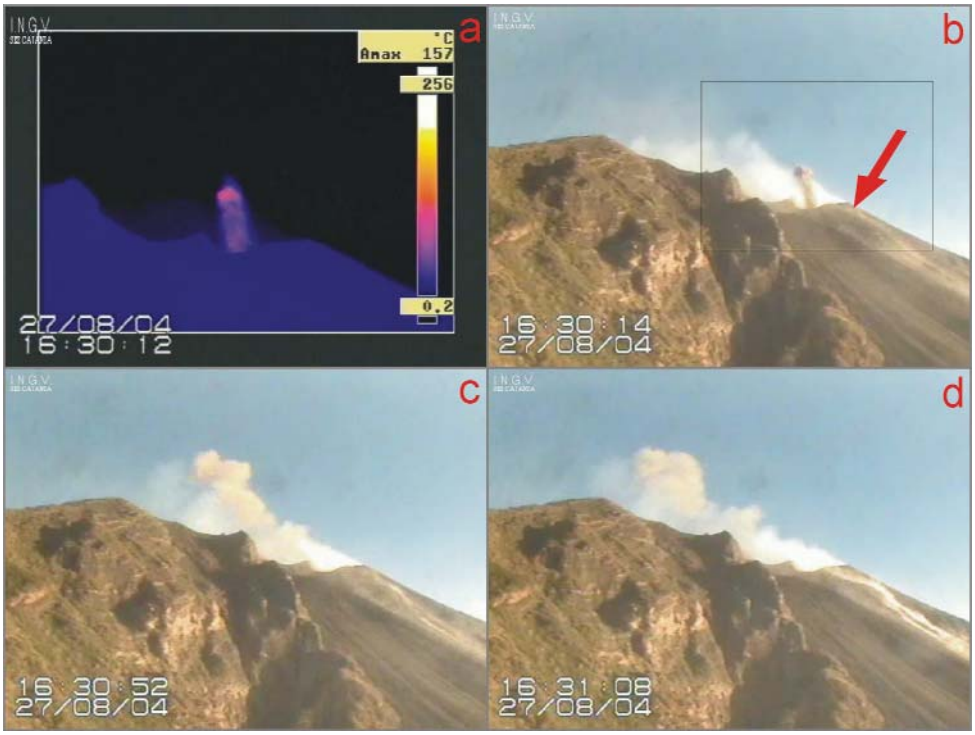

Fig. 5. Thermal image (a) and snapshots (b-d) taken from the INGV video cameras for a rockfall episode of our data set, which was shortly preceded by a Strombolian explosion. The red arrow marks the beginning of the rockfall in the snapshots. The frame in (a) is a close-up view of the black rectangle in (b).

Falsaperla et al. [2006] identified the zones affected by the sliding episodes between 2002 and 2004 (Figure 1). The most active zone was located in the upper part of the SDF, close to the niche of detachment of the landslides of 30 December, 2002 (Figure 2). In August, 2004 this niche was only 125 m distant from the summit craters, showing to be still active. Reporting this finding, Falsaperla et al. [2006] concluded that if progressive degradation continued toward the craters, then a change in eruptive behavior cannot be excluded due to a possible sudden depressurization of the volcano feeder. In this light, even neglecting the hypothesis of large failure events, unrelenting sliding episodes close to the craters might represent a potential hazard due to the consequences on the impinging eruptive activity. On the other hand, there is a mutable remodeling process of the SDF slopes, which is the result of contra posed actions between the welding effect of new lava flows and erosive phenomena. For example, the renewal of lava effusions in spring 2007 once again changed the morpho-structural characteristics of the SDF, leading the balance of the two actions in favor of the stabilizing effect. In that occasion, an effusive frac-

ture propagated downslope in the SDF, reaching a minimum elevation of about 400 m asl. During the propagation of the dike, the highest portion of the fracture system collapsed, forming a graben (Neri et al., 2007). But the major morpho-structural changes happened in the summit area: the internal walls of the central conduit collapsed, causing the enlargement of the summit crater area and the partial obstruction of the conduit which triggered some explosive events due to the overpressure inside the system.
Therefore, only a continuous multidisciplinary monitoring of the volcano can provide valuable information to evaluate the on-going assessment and contribute in reducing the hazard of this landslide-prone area.

Acknowledgments

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