Volcanic and seismic activity at Stromboli preceding the 2002-03 eruption

Burton M., Calvari S., Spampinato L., Lodato L., Pino N.A., Marchetti E., Murè F.

Abstract

Regular surveys with a PM695 FLIR thermal imaging camera from both the ground and from helicopter were conducted on Stromboli from October 2001. These measurements allow us to (i) examine changes in morphology of the summit craters produced by paroxystic explosions and (ii) track the increasing level of magma within the conduits of Stromboli that preceded and led to the 2002/03 effusive eruption. Two geophysical surveys in May and September/October 2002 demonstrated a clear increasing trend in the amplitude of VLP events, consistent with the presence of a higher magma column above the VLP source region. The observed increase in magma level was probably induced by an increase in the pressure of the magma feeding system at Stromboli, controlled by regional tectonic stress. The increased magma level induced strain on the uppermost part of the crater terrace, allowing an increase in soil permeability and therefore CO_2 and Radon degassing. Eventually this stress caused the northeast flank of the craters to fracture, allowing lava to flood out at high effusion rates on 28th December. Regular surveys with the thermal imaging camera, combined with geophysical monitoring, are an invaluable addition to the armory of volcanologists attempting to follow the evolution of activity on active volcanoes.

1. Introduction

Stromboli volcano is the eastern-most island in the Aeolian archipelago, Italy (figure 1). It has been almost continuously active during the least thirteen centuries (Rosi et al., 2000), producing mild explosive activity interspersed with rarer effusive and major explosive events (Barberi et al., 1993). Typical explosions send small volumes of ejecta 50–100 m above the craters every 15–20 min; this style of activity has become synonymous with Stromboli, and is commonly called strombolian activity when observed at other volcanoes. Explosion products are typically ~50% crystallized, 30-60% vesiculated black scoria sourced from the superficial part of Stromboli's magma plumbing system (Landi et al., 2004; Lautze & Houghton, 2005, 2007; Polacci et al., 2006). Continuous quiescent degassing occurs between explosive events (Burton et al., 2007). Mild strombolian activity is interrupted roughly twice a year by larger, paroxysmal events, explosions that can eject magma fragments hundreds of meters above the craters, producing a hazard for any nearby volcano observers. Paroxysms usually erupt volumes of 10^3-10^5 m^3 (Bertagnini et al., 2003) of crystallized resident magma, which is mixed with "golden pumice", a glassy and gas-rich magma rising straight from the source region (Bertagnini et al., 1999).

Lava effusions are regularly observed on Stromboli with a typical period between eruptions of 5-20 years (Barberi et al., 1993). The most recent effusive eruptions occurred in 1975 (Capaldi et al., 1978), 1985 (De Fino et al., 1988), 2002/03 (Bonaccorso et al., 2003; Calvari et al., 2005) and 2007 (Calvari et al., 2007, submitted to GRL). The 2002-03 event was of particular significance as on the 30th December it produced a minor collapse of the NW flank of the volcano, from the Sciara del Fuoco, inducing a tsunami wave that inundated the coast of Stromboli, and mildly damaged coastlines of other islands in the archipelago as well as the port of Milazzo (Tinti et al., 2004). The landslide was followed by a ~6-month long effusion of lava from the NW flank.

Regular surveys of the summit craters of Stromboli have been conducted using a thermal imaging camera since October 2001. In 2002 two seismic surveys were also carried out close to the summit craters. The objective of this paper is to present and interpret thermal imagery and seismic data collected at Stromboli prior to the 2002-03 eruption, highlighting coupled volcanological and seismic eruption precursors as well as morphological changes in the summit craters associated with paroxysmal explosions.

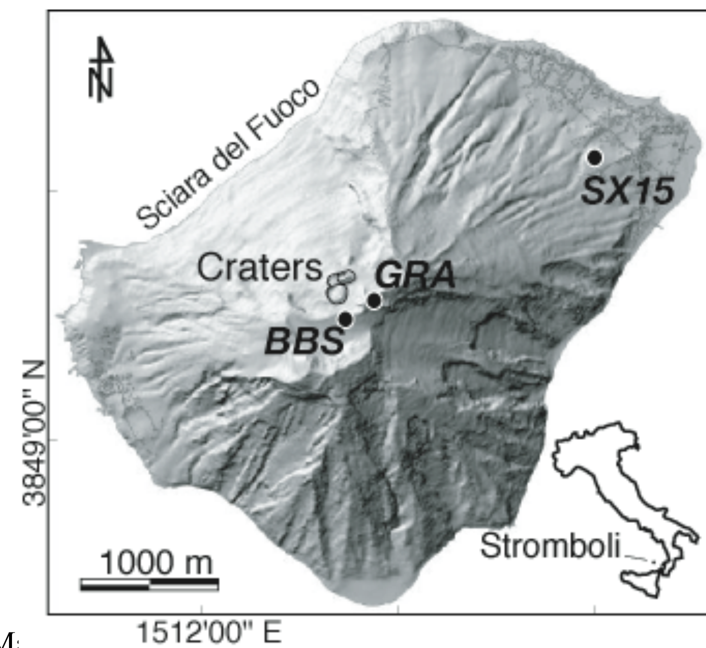

Figure 1: M… nd the position of seismic stations deployed during the temporary experiments before the 2002-2003 eruption of Stromboli volcano.

2. Thermal imaging methodology

The thermal surveys were carried out using a FLIR PM695 thermal camera. The infrared detector within the PM695 is an un-cooled focal plane array of microbolometers with sensitivity between 7.5 and 13 μm. It has a 24° by 18° field of view (FOV) producing an effective 1.3 μrad FOV for each pixel in the 320 by 240 detector array. Images were collected from the ground at Pizzo Sopra la Fossa and from a helicopter provided by the Italian Department of Civil Protection (figure 2). The acquisition rate of the PM695 was limited to 1 image every 1.5 seconds, dictated by the performance of the detector array. This relatively long integration time produced a challenge for data collection from the helicopter as the velocity of the aircraft tended to produce blurred imagery of the summit craters. Fortunately, this problem is easily overcome by collecting imagery whilst hovering, which allows a sufficiently stable platform for the thermal camera.

As discussed below a great deal of information on the morphology of the active structures within Stromboli's summit craters can be derived from thermal images, however quantitative determination of the surface temperatures is a challenge for three main reasons: (i) absorption of infrared (IR) radiation from the atmosphere; (ii) absorption of IR radiation by volcanic gases and aerosols; (iii) non-Lambertian emission of radiation from the highly structured emitting surface. Sawyer and Burton (2006) conducted an investigation into the effects of volcanic gases on the absorption of radiation from Stromboli's summit craters, concluding that the presence of a volcanic plume between the observer and the radiation source could produce 10's to 100's of °C underestimation of the true source temperature due to attenuation of radiation principally from SO_2 gas and aerosol absorptions.

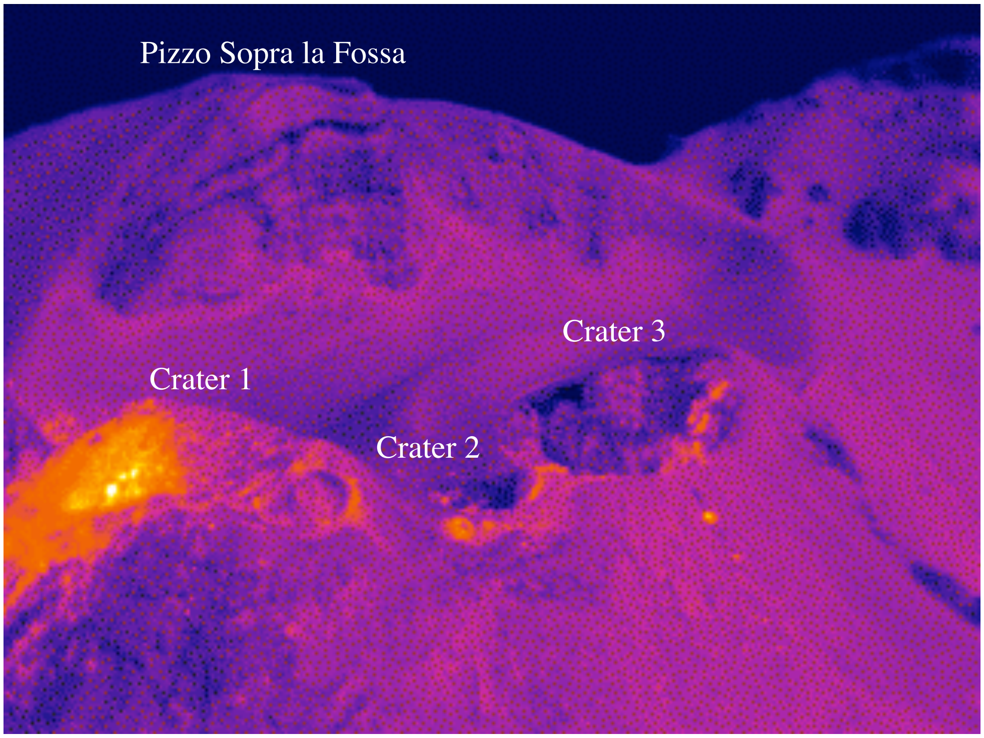

Figure 2. Thermal image of the summit craters of Stromboli and Pizzo Sopra la Fossa (Pizzo) collected on 23rd July 2002 from Civil Protection helicopter. View is from the northwest. All ground-based imagery reported here was collected from Pizzo.

The data presented here has been carefully selected to minimize the effect of plume attenuation, however the fact that the source of degassing is coincident with the volcanic structures that we observe means that it is impossible to completely exclude this effect. All images were collected within a kilometer of the summit craters and minor corrections due to attenuation from atmospheric water vapor were taken into account using the inbuilt correction algorithm of the thermal camera. The effects of non-Lambertian radiation emission have been ignored in this analysis, but given the clarity with which we observed the active structures at the summit craters we believe that this effect is minor compared with plume attenuation. In conclusion, determining errors on the measured temperature of the summit craters of Stromboli is a challenge; we estimate that our quantitative measurements may underestimate the true source temperature by up to ~100°C. Fortunately the order of magnitude of observed temperature variations is significantly larger than this underestimation, and therefore clear trends are detectable.

3. Thermal images on Stromboli after paroxysmal explosive events

Prior to the 2002-03 eruption, field and thermal surveys were carried out immediately after three paroxysmal explosions: on 20 October 2001, 23 January 2002, and 25 July 2002. On 23 January 2002 some morphologic changes at the summit craters were detected by comparison with the previous survey, as well as mapping of the fallout and characterization of the erupted products (Calvari & Pompilio, 2001a; Calvari et al., 2002). Thermal surveys were also carried out on 16 May and 22 June 2002 (Burton & Murè, 2002a, 2002b).

In 2001, three field reports concerning the activity of the volcano observed from Il Pizzo Sopra la Fossa were collected, on 21 August, 20 October and 5 November (Burton & Muré, 2001; Calvari & Pompilio, 2001a, 2001b). The survey on 20 October was the first carried out on Stromboli by INGV researchers where a hand-held thermal camera (FLIR 695) has been used (figure 3).

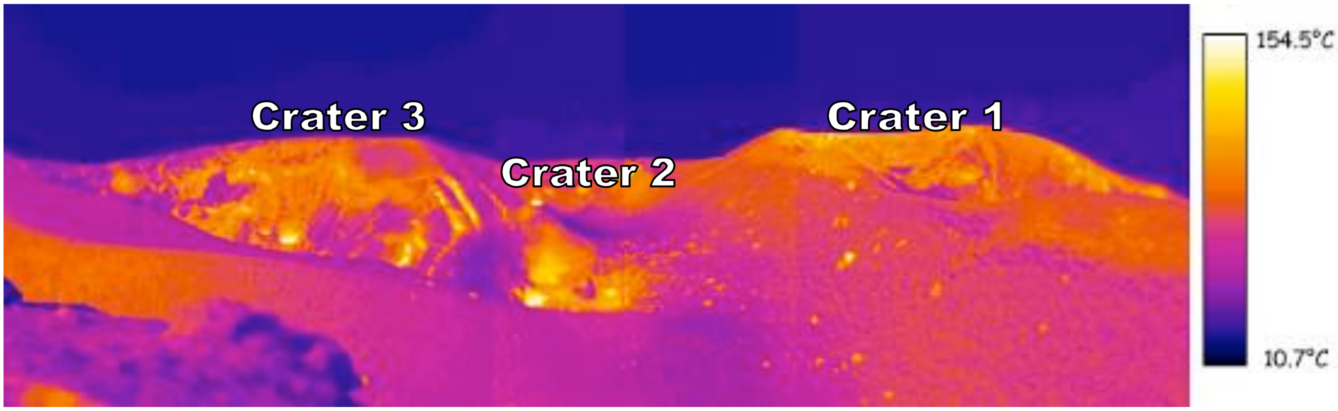

Figure 3: Composite thermal image of the summit craters of Stromboli on 20 October 2001, as seen from Il Pizzo Sopra la Fossa, SE of the craters. Crater 1 is also known as the northeast crater (NEC) and Crater 3 as the southwest crater (SWC). Note the hotspots are the still-hot debris from a paroxystic explosion that occurred on 20 October 2001 at 00:32 GMT.

In August, during 3 hours of field observation from Pizzo (Burton & Muré, 2001), crater 3 was the most active (Fig. 3), with maximum height of ejecta up to 400 m above the crater, with more typical explosions throwing clasts up 75-200 m. A total of 20 explosions were recorded during the measurement period. Two vents were inferred at crater 1, distributed along the main axis of the summit craters. A total of nine explosions were observed at crater 1 during the 3 hour survey, with maximum height of ejecta up to 50m above the crater rim. Crater 1 also occasionally demonstrated vigorous gas venting, with little or no ejecta reaching the crater rim.

On 20 October a field survey was carried out on the summit in response to a paroxysmal event that had occurred at 00:32 GMT that morning, causing injuries to two tourists sleeping at the summit, one of whom later died of their injuries. The web camera at Pizzo showed that the explosive event occurred at crater 2, as shown by the image where it is surrounded by hot ejecta (figure 4).

Figure 4 – Frame recorded by the web camera located at Il Pizzo on 20 October 2001 showing a number of incandescent blocks surrounding crater 2. Time (0:36:41) in GMT (Calvari & Pompilio, 2001)

Thermal imagery collected during a field survey carried out a few hours after the explosion showed a wide dispersion of the still-hot blocks (max 100°C between 13:00 and 14:00 GMT, 20 October 2001, Fig. 2). The central part of the crater terrace between crater 1 and crater 3 cinder cones contained three closely spaced vents in the middle portion, and three hornitos oriented approximately NE-SW to the northern margin. The eruptive activity observed during the field survey was taking place from a single vent located on the northern margin of crater 3, and from two vents within crater 2.

During ~1 hour of observation, ~10 explosions were recorded from crater 1, throwing jets of lava ~100 m above the crater rim (Fig. 5a). Crater 3 instead exhibited high-pressure gas venting, with rare strombolian explosions producing jets 20-30 m in height (Fig. 5b).

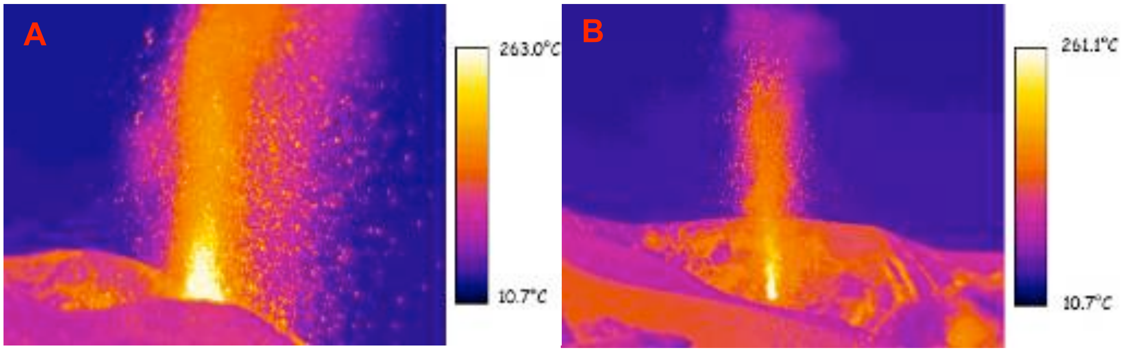

Figure 5 – Thermal images recorded on 20 October 2001 from Il Pizzo Sopra la Fossa, showing explosive activity at crater 1 and crater 3 (Calvari & Pompilio, 2001). The temperature scale does not show the peak values, which reached over 500°C.

On 23 January 2002 at 20:54 (local time) another paroxysm occurred at Stromboli. The noise from the explosion was audible from the villages at the base of the island, and was accompanied by ash fallout that lasted several minutes. In the morning of 24 January INGV researchers (Calvari et al., 2002) surveyed the summit area of the volcano to verify the dispersal of the erupted products and their nature. The area around the summit craters was covered with ash and blocks. Most of the fallout comprised lithic material up to 60 cm in size, with minor amounts of spatter up to 1.7 m in length. No low-porphyritic products were found, which usually characterize the most energetic events (Bertagnini et al., 1999). The greatest density of lithic deposits was observed in a belt about 200 m wide between the craters and Pizzo. Spatter was more heavily deposited northeast of Pizzo. Fine-grained material covered the crater zone and the NE flank of the volcano up to the village of Stromboli. Fallout material formed an almost continuous carpet at Pizzo, in the areas where usually many tourists observe the eruptive activity. During the 2.5 hours of field survey (Calvari et al., 2002), only 5 weak explosions from crater 1 were recorded, and none at all from craters 2 and 3. This activity was much weaker compared with that observed after the major explosion of 20 October 2001 (figure 5). Our survey also revealed profound morphological changes at crater 2, which had significantly widened compared with observations made during our previous survey of 20 October 2001 (figure 6).

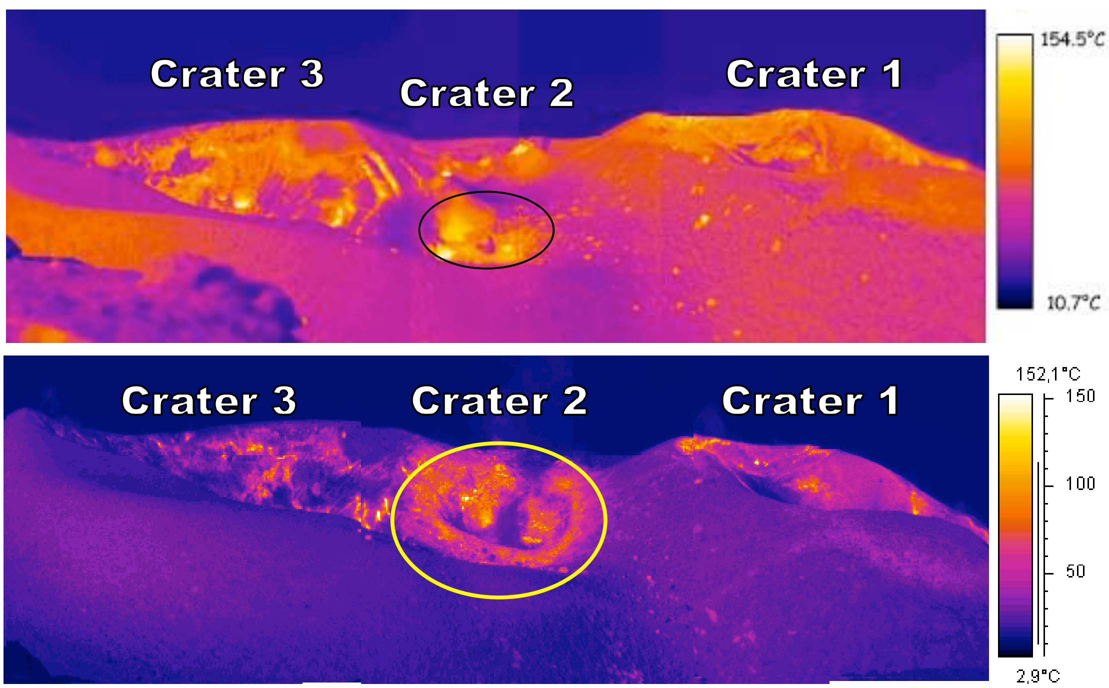

Figure 6: Two thermal images collected from Pizzo on 20 October 2001 (upper image) and 24 January 2001 (lower image) collected ~10 hours after a paroxysmal explosion that occurred on 23 January. The three yellow spots above Crater 2 in the upper image are hornitos. The yellow spots on the flanks of Crater 1 are spatter from the explosive event. The black circle around Crater 2 in the upper plot indicates the portion blown up during the paroxysm of 23 January 2002.The yellow circle in the lower plot highlights the new morphology of crater 2 after the explosion.

Thermal imagery recorded on 20 October 2001 showed three hot spots with maximum temperatures of 205°C in crater 2. On the contrary, the maximum apparent temperature recorded at this crater after the 23 January paroxysm was 320°C averaged over a pixel area of 40 cm. The high temperature of the inner walls of crater 2 was due to spatter coating, following the explosive event. Measurements taken with laser range-finding binoculars demonstrated that crater 2 had enlarged to a diameter of 26 m, compared with a pre-paroxysmal crater size on October 2001 of ~10 m. From the nature of erupted products, their distribution, and the morphology changes observed at the craters, Calvari et al. (2002) concluded that the eruptive event of 23 January 2002 could have been caused by an the obstruction of crater 2, leading to an over-pressurization and explosion. This idea is supported by the high abundance of lithic material and absence of low-porphyritic products, consistent with a superficial source for the explosion. After this major explosion, some concern arose regarding the lack of explosive activity at CR3, suggesting a potential obstruction of this crater, which might be followed by a new violent episode similar to that of 23 January 2002. A further paroxystic explosion occurred on 24th July 2002, but poor weather inhibited detailed examination of the crater area in the immediate aftermath of the explosion.

4. Thermal surveys after April 2002

A total of 9 field surveys were conducted with the PM695 thermal imaging camera on Stromboli from April 2002 until the eruption onset on 28th December 2002 (see figure 7). Below we highlight some of the main observations recorded during these surveys.

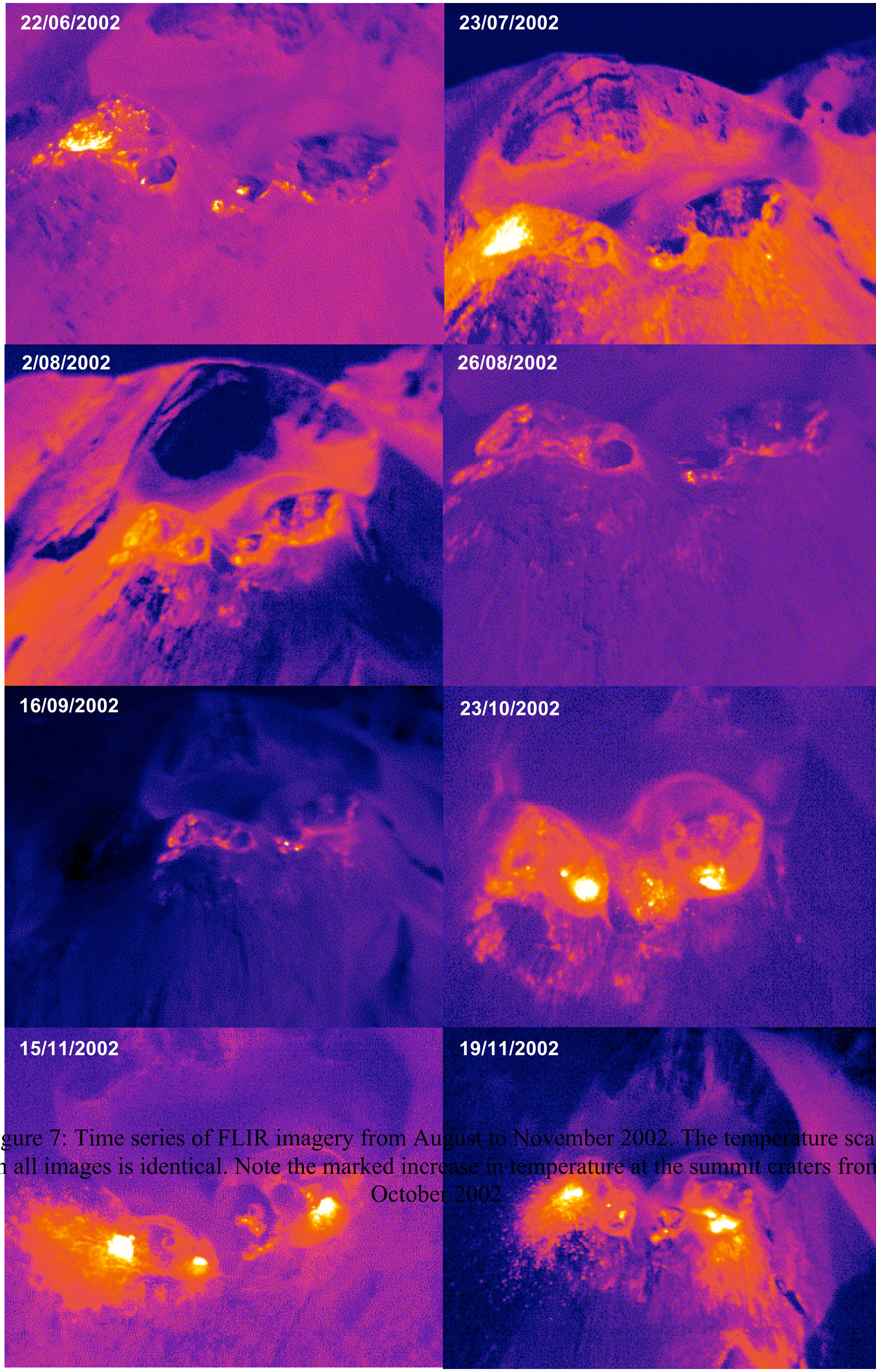

Figure 7: Time series of FLIR imagery from August to November 2002. The temperature scale in all images is identical. Note the marked increase in temperature at the summit craters from October 2002

May 16th 2002: FLIR measurements were made continuously from Pizzo, starting at 10.14 GMT and concluding at 12.35 GMT. Activity at the summit was primarily located at crater 1 and consisted of relatively weak explosions, containing smaller amounts of pyroclasts than had been seen in the preceding months.

June 22nd 2002: FLIR measurements were made from Pizzo, observing all three craters in sequence, starting from 09.42 GMT and concluding at 11.50 GMT. Activity at the summit was primarily located at crater 1 and consisted of explosions that propelled scoriae to a maximum height of approximately 250 m above the craters. Occasional ash emissions were observed from crater 1 and crater 3. The activity was of significantly greater intensity compared with that observed in May.

July 23rd 2002: Measurements with a thermal imaging camera were carried out at Pizzo on the summit of Stromboli, with the assistance of a Civil Protection helicopter. During the period of observation (10.12 – 13.57 GMT) activity was characterized by 50-300m high explosions of incandescent material from crater 1 that fell primarily on the north flank of the crater. Jets of ash and scoria from crater 3 powered convecting clouds of ash to maximum heights of approx 500m above the summit craters. The thermal signature of the deposits of explosive activity from crater 1 is clearly shown in figure 2. Explosions occurred approximately every 10 minutes from CR1a and every 20 minutes from CR3. Gas emissions were observed at the other craters in the absence of explosive activity. The presence of large (1-2 meter), incandescent scoria ejected from crater 1 suggests that magma was present at a superficial level in this crater. On the contrary, high-pressure jets of ash from crater 3 suggest that this conduit was less fully open, with a deeper magma level during the observations. The level of volcanic activity was significantly higher compared with that observed in the preceding surveys.

25th July 2002: In response to a paroxystic event that occurred on 24th July an over flight of the summit craters of Stromboli was conducted on 25th July. Low cloud prevented landing at the summit, but thermal images and digital photographs were collected from the helicopter (figure 8). No obvious morphological changes had taken place within the summit craters, however a clear NE-trending thermal anomaly was visible within the craters and on the north flank of crater 1.

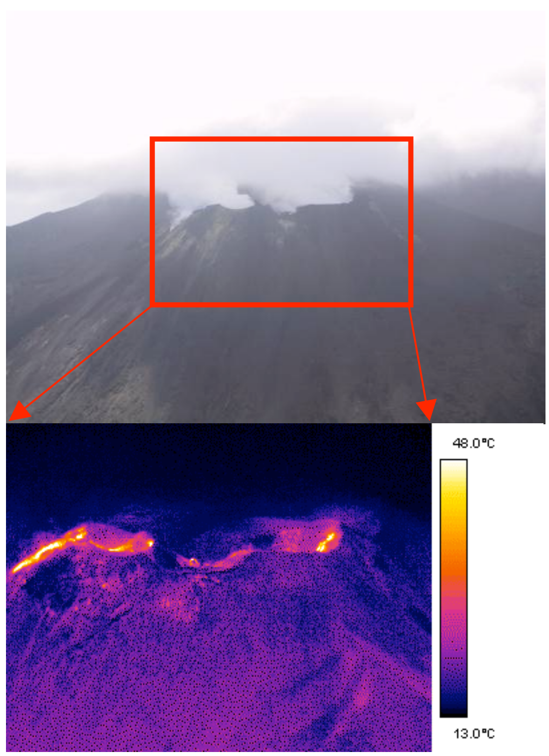

Figure 8. Upper image, aerial photograph of the summit craters of Stromboli, 25th July 2002, from NW. Red box indicates approximate field of view shown in the thermal image, below.

1st and 2nd August 2002: Sequences of thermal imagery were collected on both 1st and 2nd August from Pizzo and on 2nd August from helicopter. A low level of explosive activity was observed on both days, leaving few hot deposits on the crater floor.

26th August 2002: Observations from Pizzo showed a higher frequency of explosions from crater 1 and crater 3 compared with that observed on 2nd August. The northernmost sector of crater 1 showed almost continuous mild strombolian activity during 5 minutes of a one hour observation. Helicopter-borne measurements showed modest temperatures at the base of the summit craters.

16th September: Explosions were of greater intensity from both craters 1 and 3, with scoria landing outside the crater rim. Crater 2 showed an intermittent, passively released, high temperature gas emission.

23rd October 2002: Observations were conducted from helicopter, and showed higher temperatures than those previously seen for all three craters. Craters 1 and 3 had large thermal anomalies at their base associated with recently deposited pyroclasts from explosive activity. One vent in crater 2 demonstrated continuous high pressure gas venting, at an inclined angle relative to vertical. In general, the observations of this day showed a notable increase in thermal energy release compared with the previous observations in 2001 and 2002.

15 and 19 November 2002: A thermal survey carried out on 15 November demonstrated exceptionally high temperatures (see figure 9) and the presence of two small lava flows sourced from overflowing magma from vents within craters 1 and 2. Intense explosive activity and increasingly shallow magma level had filled the summit craters with scoria. Superficial magma is clearly visible in the digital photograph.

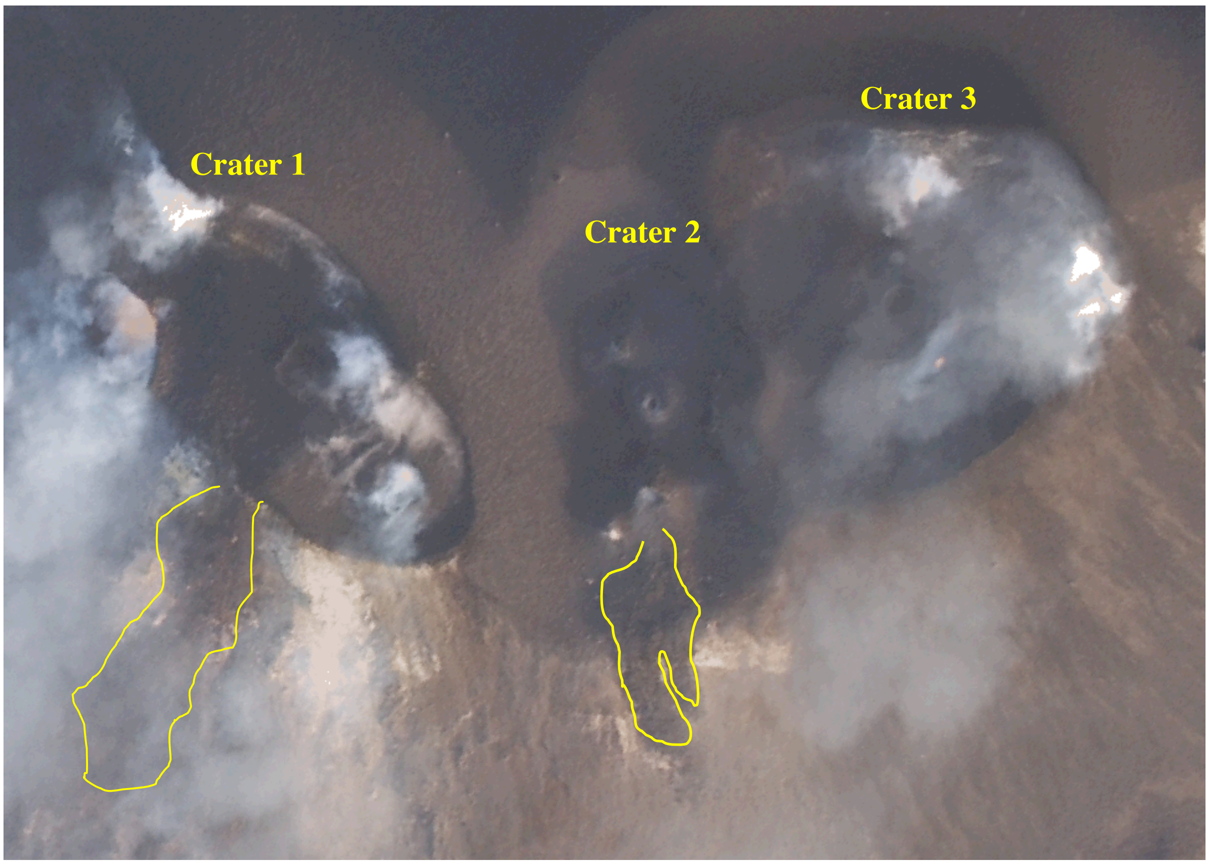

Figure 9: Visible image of the summit craters of Stromboli on 15th November. Lava overflows from craters 1 and 2 are highlighted with a yellow line. Note the presence of superficial magma in the northern sector of crater 1. The craters are filled with pyroclastic deposits, compare with figure 2.

5. Quantitative analysis of thermal imagery

Thermal images collected on Stromboli allow us to track variations in the temperatures of each crater since surveys began in 2001; a plot showing these time series is shown in figure 10. As discussed in Methods, thermal images are attenuated by water vapor, volcanic aerosol and SO_2, leading to a potential underestimation in temperature of tens of °C. However, the variations in temperature shown in figure 10 cannot be explained simply due to this attenuation, as the temperatures vary by a much larger magnitude during the measurement period.

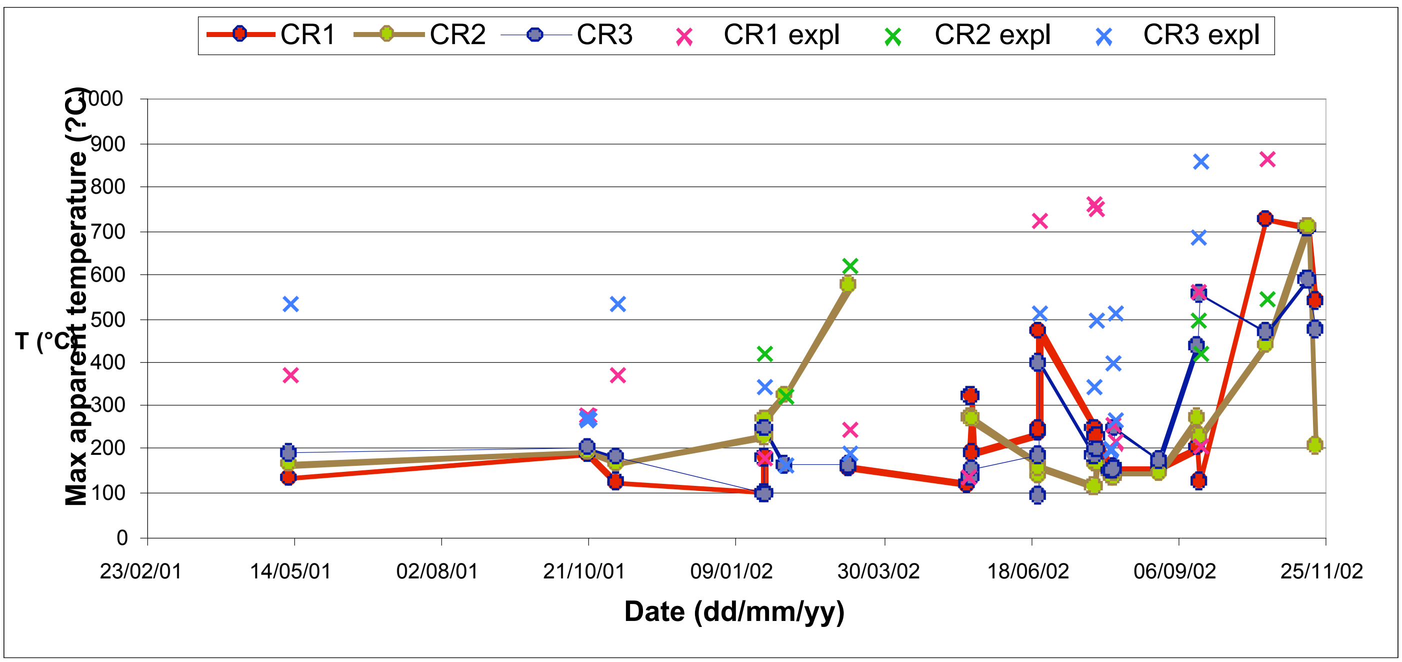

Figure 10: Time series of temperatures observed at the summit craters of Stromboli from mid-2001 until November 2002. Circles show the peak temperatures at each crater during persistent degassing, crosses show the peak temperatures at each crater during explosions.

Whilst the detailed variations of temperature in each crater are complex, a clear overall trend is observable, that of steadily increasing temperatures of both degassing and explosions after September 2002. A significant but smaller peak is also seen in June 2002. The increased thermal emission from September followed by minor lava overflows from craters 1 and 2 in November, followed by the eruption itself on 28th December suggests that a significant increase in the magma level within the conduit occurred during this period.

6. Seismic investigations on Stromboli during 2002

Explosive activity at Stromboli volcano has been investigated and monitored for the last 30 years with permanent geophysical instruments and temporary experiments [see Harris and Ripepe 2007 for a review] and contributed largely to the understanding of the dynamics driving explosive activity at open conduit basaltic volcanoes. A description of seismic activity at Stromboli before the 2002-2003 eruption is based here on data provided by a temporary seismic station (SX15), equipped with a 3-components Lennartz seismometer with eigenperiod of 5 s and sensitivity of 400 V/m/s, installed for the project SAPTEX (Southern Apennines Tomography EXperiment project, P.I.G.B., Cimini) since May 2002 in the village of Stromboli (Figure 1) [Pino et al., 2004], and data collected during 2 temporary seismic broadband-acoustic-thermal experiment (Figure 1) in May 14-27, and September 29 – October 2, 2002 on the summit area of the volcano [Marchetti and Ripepe, 2005]. Given the broader frequency content of the instrument deployed and the shorter source–to-receiver distance, we focus on data collected during the 2 temporary summit experiments, as they best describe the VLP seismic activity recorded during the typical explosive activity at Stromboli volcano.

During May 2002 two seismic-acoustic stations (BBS, GRA) were deployed on the summit of Stromboli volcano at distances of 250-300 meters from the summit craters (Figure 1). Four months later, between September 29 and October 2, 2002, a seismo-acoustic station was deployed again at one of the two sites investigated during the previous experiment (GRA). For both experiments, each station consisted into a 5 channel 16 bits A/D converter and was equipped with a Guralp CMG-40T broadband seismometer, with sensitivity of 800 V/m/s and 30 seconds eigenperiod, and a Monacor pre-amplified electred microphones with sensitivity of 46 mV/Pa. Time syncronization was achieved with DCF radiocode receiver. Despite the short deployment of the seismic-acoustic stations the two temporary experiment are of particular interest, as they represent the only geophysical observations at close distance from the active craters within 7 months before the eruption onset.

At the time of the May 2002 experiment the level of explosive activity was low, with rare and mild explosions recorded from the crater 1 and 3, and a sustained intermittent degassing process from the Central crater. On September 2002 the explosive activity was higher with frequent explosive emissions of bombs and lithics both from the crater 1 and 3. Moreover, the explosive activity changed during the 4-day-long investigation period, with increased energy of explosions from crater 3 starting September 30, 2002, when bombs and fragments were ejected up to heights of ~300 m above the summit vents.

The change in explosive level observed during the May and September 2002 experiment is reflected by the amplitude of VLP events (Figure 11) recorded at the summit of Stromboli volcano. Here amplitude of VLP events appeared quite stable during May 2002, with a mean value of $5x10^{-6}$ m, and was higher ($\sim 10^{-5}$ m) during the September/October temporary experiment (Figure 11). In particular the amplitude of VLP events reflects the observed change in explosive activity during the 4-day-long experiment, with a rapid increase of VLP amplitude in September 30, 2002, with values rising from $6x10^{-6}$ to $1.5x10^{-5}$ m.

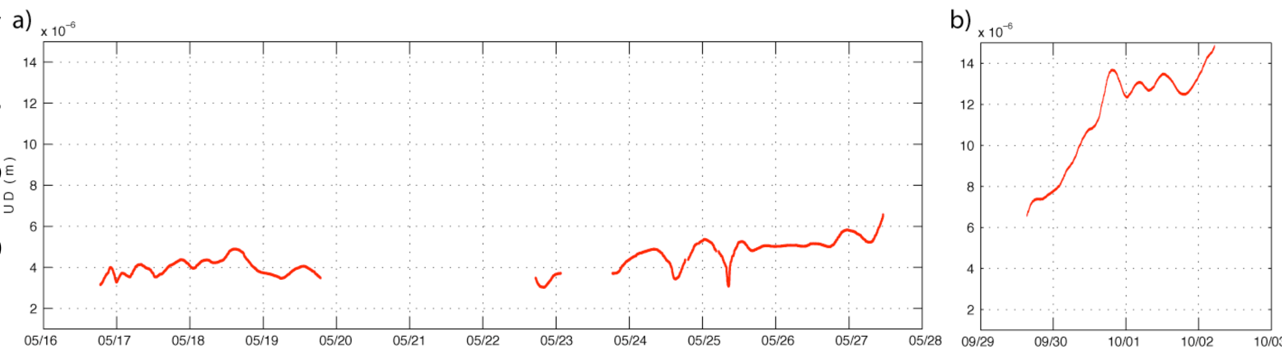

Figure 11: Amplitude of VLP seismic transients recorded at station GRA deployed on the summit of Stromboli volcano during temporary experiments carried on in May (a) and September 2002 (b).

7. Discussion

Laboratory experiments [Ripepe et al., 2001; James et al., 2004] and moment tensor inversion of seismic records [Chouet et al., 2003] suggest that VLP seismic transients may be produced by the rapid transfer and expansion of gas volumes within the conduit, and therefore their frequency should reflect the rate of formation of gas slugs within the magma column. The amplitude of VLP events is instead controlled by both the volume and gas overpressure within the gas slugs. Accordingly, the VLP seismicity is a direct expression of both gas dynamics and magma level at Stromboli, and the increased amplitude recorded in October 2002 might result from an increased gas overpressure due to the heightened magma free surface, as evidenced by the thermal monitoring data. The magma level within Stromboli's conduits exercises a fundamental control on the nature of eruptive activity at this volcano. The fact that mild explosive activity has been maintained almost continuously for hundreds of years at Stromboli (Rosi et al., 2000) suggests that the magma level must have varied relatively little over that timescale; a drop of only a few tens of meters in the magma level is sufficient to inhibit observable explosive activity at the surface. On the contrary, a magma level at the surface will result in overflows, which are observed every 5-20 years (Barberi et al., 1993). The majority of the activity is instead consistent with a remarkably stable magma level; the observation of a clear perturbation to this steady-state behavior allows a deeper insight into the plumbing system feeding the volcano.

The main control on the level of magma in the conduit of Stromboli is the pressure exerted at the feeding reservoir balanced by the weight of magma filling the conduit, and therefore the density of magma. There are therefore two main ways in which the magma level may be perturbed: a change in the density of magma or a change in the pressure of the source. Whilst there is little evidence for a change in magma density from September 2002, there is ample evidence for a heightened magnitude of regional tectonic stress in late 2002. A large magnitude earthquake occurred off the coast of Palermo in September 2002 (Cigolini et al., 2007), causing fractures to open in the countryside near the north coast of Sicily. In October 2002 a major dike-driven eruption began on Mt. Etna (Andronico et al., 2005). Cigolini et al., 2007 hypothesized that the increased levels of

Radon degassing at Stromboli observed leading up to the 2002-03 eruption may have been induced by the regional tectonic stress. Our observations support the hypothesis that such a stress could have induced increases in magma level that led to (i) Increase in the thermal energy released at the surface; (ii) higher overpressure in VLP events; (iii) eventual rupturing of the north flank of crater 1, producing an effusive eruption. Increased magma levels could also induce changes in permeability of gas flow through the structure of the summit area, as the stress exerted by the high magma level produces strain in the surrounding superficial rocks. Such strain could produce the observed increases in CO_2 (Carapezza et al., 2002) and radon (Cigolini et al., 2007) degassing measured prior to the 2002-03 eruption.

8. Conclusions

Regular surveys with a thermal imaging camera from both the ground and from helicopter allowed us to (i) examine changes in morphology of the summit craters produced by paroxystic explosions and (ii) track the increasing level of magma within the conduits of Stromboli that preceded and led to the 2002-03 effusive eruption. Combining these observations with seismic surveys carried out in 2002 allows us to gain a clearer picture of the effects of an increasing magma level within the conduit system of Stromboli prior to the 2002/03 eruption. The increase in magma level was probably produced by an increase in the pressure of the magma feeding system at Stromboli, controlled by regional tectonic stress. The increased magma level induced strain on the uppermost part of the crater terrace, allowing an increase in ground permeability and therefore CO_2 and Radon degassing. Eventually this stress caused the northeast flank of the craters to fracture, allowing lava to flood out at high effusion rates on 28th December. Regular surveys with the thermal imaging camera combined with geophysical measurements are an invaluable addition to the armory of volcanologists attempting to follow the evolution of activity on active volcanoes.

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