The 5 April 2003 Explosion of Stromboli: Timing of Eruption Dynamics using Thermal Data

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Abstract.

Stromboli's 5 April 2003 explosion sent an ash plume to 4 km and blocks to 2 km, representing one of the most powerful events over the last 100 years. A thermal sensor 450 m east of the vent and a helicopter-flown thermal camera captured the event dynamics allowing detailed reconstruction. This review links previous studies providing a complete collation and clarification of the actual event chronology, while showing how relatively inexpensive thermal sensors can be used to provide great insight into processes that cannot be observed from locations outside of the eruption cloud. The eruption progressed through four phases, comprised 29 discrete explosions and lasted 373 s. The opening phase (phase 1) comprised ~30 s of precursory ash emission, with stronger emission beginning after 17 s. This was abruptly terminated by the main blast of phase 2 which comprised emission of a rapidly expanding ash cloud followed, after 0.4 s, by a powerful jet with velocities of up to 320 m/s. A second explosive phase (phase 3) began 38 s later and involved ascent of a phoenix cloud and explosive emission above a lateral vent lasting 75 s. This was followed by a 175-s-long phase of weaker, pulsed emission. The eruption was terminated by a series of three explosions (phase 4) sending ash to ~600 m at velocities of 27-45 m/s and lasting 87 s. Together these results have shown that a low energy opening phase was followed by the highest energy phase. Each phase itself comprised groups of discrete explosions, with energy of the explosions diminishing during the two final phases.

INTRODUCTION

An effusive eruption began on Stromboli (Aeolian Islands, Italy) during 28 December 2002. This continued until July 2003 and was punctuated, on 5 April 2003, by a major explosive event or paroxysm [*Calvari et al.*, 2005; *Rosi et al.*, 2006]. The onset of effusive activity, plus the associated flank instabilities and tsunami hazard [*Bonaccorso et al.*, 2003; *Pino et al.*, 2004; *Tinti et al.*, 2003, 2006], accelerated the deployment of an extensive instrument array. This included a thermo-acoustic-seismic array, of which the infrasonic portion had been installed during autumn 2002 [*Ripepe et al.*, 2004a]. It initially comprised a five-element infrasound array and a four-station broad-band seismometer network [*Ripepe et al.*, 2004a, 2004b]. Three 15° field of view thermal (8 – 14 μm) sensors were added in May 2002 [*Harris et al.*, 2005]. These were initially located at the Pizzo Sopra La Fossa, a position ~250 m SE and ~150 m above of Stromboli's active summit craters, with a second thermal station being added ~450 m east of the summit craters in February 2003 [Figure 1a]. Further geophysical installations following the onset of the eruption included 8 broadband seismometers installed by INGV-Osservatorio Vesuviano [*D'Auria et al.*, 2006], two web-cameras and 3 summit GPS stations deployed by INGV-Catania [*Mattia et al.*, 2004]. In addition, once the eruption was underway, a thermal infrared camera was used to track both the lava flow field and the summit craters during daily monitoring flights [*Calvari et al.*, 2005, 2006; *Harris et al.*, 2005; *Lodato et al.*, 2007].

All permanently installed thermal and infrasonic sensors were operational at the time of the 5 April 2003 paroxysm, except the summit web-cameras, and the helicopter carrying the daily monitoring crew was in the air acquiring thermal images of the summit craters and flow field (Figure 1a). This presence yielded an integrated data set that allowed a detailed event chronology to be put together, with timings accurate to 10^{ths} of a second. While the event chronology drawn from the thermal camera and digital photo data is described in *Calvari et al.* [2006]; that drawn from the thermo-acoustic-seismic array is given in *Ripepe and Harris* [2008]. The latter data were used in combination with a post-eruption examination of the deposits in *Rosi et al.* [2006] to more fully understand the dynamics and mass fluxes involved in the 5 April event. All three studies are complimentary and provide full documentation of the explosion dynamics of the 5 April paroxysm. Here we draw these studies together to provide a full review of the 5 April event chronology.

THE 5 APRIL PAROXYSM

The 5 April paroxysm had several precursors. Radon anomalies developed about 2 weeks before the event [*Cigolini et al.*, 2005]. In addition, CO_2 anomalies developed in the week prior to the eruption, with peaks in H_2 and He being recorded a few days prior to 5 April [*Carapezza et al.*, 2004]. Anomalously high SO_2/HCl ratios were noted 2-3 days preceding 5 April [*Aiuppa and Federico*, 2004] and deformation was recorded by two GPS stations 30 s prior to the explosion [*Mattia et al.*, 2004]. These precursors have been interpreted as the geochemical signatures from a sulfur-rich magma batch ascending into the shallow system [*Aiuppa and*

Federico, 2004; *Carapezza et al.*, 2004] to cause inflation just prior to the event followed by deflation as the pressure was released during the explosion [*Mattia et al.*, 2004]. The broadband seismometer network recorded an ultra-long-period (>20 s) signal beginning ~4 min before the eruption. This was also interpreted as the effect of radial ground tilt caused by pressurization of the conduit due to vesiculation in the rapidly ascending magma batch [*D'Auria et al.*, 2006; *Ripepe and Harris*, 2008]. The onset of a high frequency (<0.1 s) signal, related to vesiculation of the rising batch, was recorded ~1 min before the explosion with a very-long-period signal at 07:13:35 GMT marking the onset of fragmentation [*D'Auria et al.*, 2006; *Ripepe and Harris*, 2008]. This is consistent with geochemical analysis of erupted samples which indicate that the eruption involved melt that rose through and, interacted with, overlying (slightly more evolved) melt to finally mingle with the shallow crystal-rich magma just before eruption [*Métrich et al.*, 2005]. The same broadband data have also been used to infer slow slip movement along a pre-existing fracture in the minutes prior to the eruption [*Cesca et al.*, 2007]. This may indicate re-opening of the uppermost ~250 m of the conduit, which had previously been blocked [*Calvari et al.*, 2006], to allow a few seconds of ash emission followed by the main blast as the pathway opened up [*Cesca et al.*, 2007].

The ensuing eruption began with a cannon-like detonation accompanied by a shock wave that broke windows at Ginostra, a village ~2 km from the vent [*Calvari et al.*, 2006; *Rosi et al.*, 2006; Figure 1a]. Given the delay time between the infrasonic and thermal signals generated by the initial explosion, the source was extremely shallow; just 80 – 150 m below the crater rim and likely involved a total gas mass of 3 x 10^6 kg [*Ripepe and Harris*, 2008]. The event that followed sent an eruption column to a height of ~4 km and ejected 2-3 m^3 bombs as far as Ginostra where they caused some damage [*Rosi et al.*, 2006]. In all the explosive emission lasted ~8 minutes and involved four distinct phases with the second, most violent, phase lasting 39 s and erupting a total mass of 1.1-1.4 x 10^8 kg [*Rosi et al.*, 2006].

EFFECTS ON THE INSTRUMENT ARRAYS AND THERMAL IMAGE ACQUISITION

Our network of thermal, seismic and infrasonic sensors was subjected to fall-out of hot juvenile and lithic fragments within a few seconds of the event onset. The first damage, however, was inflicted by the pressure wave that spread from the vent at the explosion onset. The damage inflicted on the bunker housing the infrared thermometers was consistent with the pressure wave entering the viewing-slot and exiting through the roof which was partially peeled back by the exiting wave. The following fall-out then covered and partially collapsed the outer-box (Figure 1b). The instrument boxes within the outer-box, however, remained secure and the thermal sensors survived unscathed recording good, unsaturated signal throughout the event (Figure 2) from a location situated on the edge of the column (Figure 1b). The instruments in operation were Omega OS43 thermal infrared thermometers [*Harris et al.*, 2005]. This instrument detects emitted radiation across the 8 – 14 μm range, converting the recorded voltage to temperatures in the –40 to 1200 °C range across a 15 degree field of view (FOV). These were installed in protective, gas-proof cases to view the target through thermally transmissive germanium-arsenide-selenium windows [*Harris et al.*, 2005]. The eastern (ROC, Figure 1) site is ~450 m to the east of the craters, which means the FOV will have a diameter of 120 m (D_{FOV}), and thus will relate to the thermal emission of the plume over the first 120 m of ascent. The Omega OS43 outputs a continuous signal as a voltage, where 1 mV is equivalent to 1 ºC, which we sample at a rate of 54 Hz. A good portion of our seismic network also survived, with three of the four CMG40T broad-band seismometers surviving (see *Marchetti and Ripepe* [2005] for instrument details and capabilities). However, the signal was too intense and all seismic signals were saturated and clipped. The infrasonic microphones used in the 5-element array had sensitivities of 0.54 V/Pa in the infrasonic (1-20 Hz) range [*Ripepe et al.*, 2004b]. However, the entire infrasonic array was destroyed due to bomb impact within a few seconds of the eruption beginning.

At the time of the explosion, thermal images and digital photographs were also being collected from a helicopter flying over the summit craters [see Figure 1a for flight path]. A FLIR systems TM 695 thermal (7.5 – 13 μm) camera was being operated, which collects 320 x 240 pixel images of calibrated temperature at one of three gain settings covering the temperature ranges of –40 to 120 °C, 0 to 500 °C and 350 to 1500 °C. In practice, temperatures exceeding these maximum limits can be retrieved; for example, the low gain mode is capable of recording up to 232 °C. Images were collected at a frame rate of 1 image per second initially using the low gain setting, allowing temperatures of up to 232 °C to be recorded [*Calvari et al.*, 2006]. Data collection began at 07:03 (all times are GMT), with 286 images being acquired of the active lava flow field and Sciara del Fuoco (Figure 1a). The over flight began targeting the summit craters ~20 s prior to the paroxysm, so that 16 images of the persistent gas plume were obtained, from a location ~350 m to the south of the summit craters and roughly level with them, in the seconds prior to the event. Five images of the emerging plume and ejecta were then obtained as the helicopter banked rapidly and began evasive action, diving to the south and away from the blast. A further 440 images of the plume and hot deposits lying on the volcano flanks were then acquired from ~2 km to the south beginning around 07:15, by which time the event had been underway for ~2 minutes and the camera gain setting have been changed to the mid-gain mode. Acquisition ended at 07:26, ~13 minutes after the event began. In addition, 101 digital camera photo's were taken from the helicopter using a Canon A40 camera, 29 photo's being acquired in the minutes before the event, and 72 during the event itself.

EVENT CHRONOLOGY

Thermal imagery of the summit craters on 1 April 2003 showed the NE crater to be obstructed and lacking high temperature vents, with talus covering the crater floor [*Calvari et al.*, 2006]. Although the craters remained obstructed just prior to the 5 April explosion, an increase in maximum temperature was noted in the thermal imagery for fumaroles within the NE crater beginning ~3 minutes before the blast [*Calvari et al.*, 2006]. This ties in with the onset of the ultra-long-period seismic signals which began ~4 minutes before the eruption [*D'Auria et al.*, 2006] and may represent the onset of opening/charging of the uppermost section of the conduit.

Examination of the digital photographs show a white, heavily condensed plume, typical of persistent gas emission from Stromboli's active vents immediately prior to the explosion (Figure 3a). The eruption began with a weak emission of red ash from the NE and Central craters. This mixed with the gas plume and drifted SW due to the strong wind, causing a slight reddening of the plume (Figure 3b). After 17 s the emission became more intense and the NE crater became the source of a gray emission (Figure 3c) with a cauliflower shape [*Calvari et al.*, 2006]. The increase in intensity was also apparent from an increase in plume temperature above the crater (Figure 4a-d). This opening phase lasted ~30 s [*Rosi et al.*, 2006], with the NE crater emission being detected as a low amplitude thermal oscillation in the infrared thermometer data beginning at 07:13:24 and lasting 13 s (Figure 5a). This first phase has been interpreted by *Cesca et al.* [2007] as begin due to opening of the blocked upper section of the conduit to feed minor ash emission in the seconds prior to the main blast.

The paroxysm thus began with a low energy opening phase and was followed by three main explosive events. These events were identified and defined by *Rosi et al*. [2006] using the thermal infrared thermometer record and visual documentation (Figure 2). The opening phase (phase 1) was abruptly terminated at 07:13:38 by the first main explosive event (phase 2). The phase 2 thermal onset followed the most powerful VLP seismic signal by ~2.5 s, the VLP being recorded at 07:13:35.5 [*D'Auria et al*., 2006]. The opening events of phase 2 were also captured by the helicopter-borne thermal and digital camera [*Calvari et al*., 2006; *Rosi et al*., 2006]. This showed that phase 2 began with emission of a rapidly expanding, dark-colored cloud that, seconds later, was overtaken by multiple hot (finger) jets of juvenile material from both the NE and SW craters (Figure 3d). The thermal imagery show emission of a rapidly expanding hot cloud behind a leading edge composed of ballistics (Figure 4e-f). Unfortunately, the maximum cloud temperature cannot be determined because it exceeded the upper range of our gain setting, i.e., 232 °C. As described by *Calvari et al*. [2006] and *Rosi et al*. [2006], this first main explosive phase fed a 4-km-high convective column with a well-developed thermal (Figure 1b). Fall out of a large number of blocks and bombs (Figure 1b) reached distances of up to 2 km from the vent [*Rosi et al*., 2006]. The first thermal peak during phase 2 was reached after 0.37 s (Figure 5a; Table 1), making this peak almost synchronous with the 07:13:37 seismically-recorded arrival of the blast wave reported by *D'Auria et al*. [2006]. This is assumed to mark emission of the second plume of multiple jets captured in Figure 3d. This onset time can be used, following the methodology of *Harris and Ripepe* [2007], to give a thermal-data-derived ascent velocity of ~320 m/s for the second finger-jet forming (and blast-wave-associated) plume [*Rosi et al*., 2006]. *Calvari et al*. [2006] obtained a velocity of 80 m/s from the thermal image data. This lower velocity relates to the cloud front of the expanding plume associated with the first emission, showing that velocities for the second jet-like plume were at-least 3 times faster than those of the first. Velocities at Stromboli during normal Strombolian have been measured at up to 101 m/s (mean = 34 m/s) for eruptions dominated by coarse ballistics, with a maximum of 58 m/s (mean = 19 m/s) measured during ash-rich eruptions [*Patrick et al.*, 2007]. Velocities during the opening seconds of phase 2 were thus higher than during normal Strombolian activity.

The thermal signal during phase 2 reached a peak after 10 s, by which time thermal image acquisition had temporarily ceased. This period likely represents a sustained period of jetting [*Rosi et al.*, 2006]. The signal then waned over 28 s to give a total phase 2 duration of 38 s (Figure 5a). Closer examination of the waning thermal signal reveals that it comprised 4 sequential sub-events, each apparent from oscillations in the time series (Table 1). These likely represent a series of shorter explosions [*Rosi et al.*, 2006], which decreased in thermal amplitude as phase 2 proceeded (Figure 5a) and had onsets of between 0.31 and 1.19 seconds. These onsets (δt) give (following *Harris and Ripepe* [2007], $V = D_{FOV}/\delta t$) ascent velocities of 100 to 320 m/s (mean = 230 m/s, standard deviation = 95 m/s). *Rosi et al.* [2006] estimate an erupted mass of 1.1-1.4 x 10^8 kg during phase 2 which (for a 38 s duration) gives a time-averaged discharge rate of 2.8-3.6 x 10^6 kg/s. Assuming that most of the material was emitted in the first 10 s of jetting indicates that the discharge rate probably peaked at 1.0-1.2 x 10^7 kg/s [*Rosi et al.*, 2006]. This is much higher than masses typically erupted during normal Strombolian activity at Stromboli, where a maximum of ~6000 kg is erupted in any single event [*Ripepe et al.*, 1993; *Patrick*, 2005] which, for a mean eruption duration of ~8 seconds [*Ripepe et al.*, this volume], converts to a time-averaged discharge rate 750 kg/s during a single normal event.

The beginning of a second main explosive phase (phase 3) was marked by a reversal of the waning trend in the thermal infrared thermometer data (Figure 2). Phase 3 was coincident with the formation of a scoria flow and the concurrent rise of a phoenix plume [*Rosi et al.*, 2006]. Phase 3 began at 07:14:15 and, like phase 2, comprised a number of sequential thermal events (Figure 5b; Table 1) associated with the phoenix plume that rose from the scoria flow active between the instruments and the vent (Figure 3e). It is possible that the spikes recorded in the thermal data during this phase (Figure 5b) record a series of explosions from a lateral vent. This lateral vent would have been at the head of the dyke extending NE from the summit craters and which was feeding the on-going lava flow [*Rosi et al.*, 2006]. This is consistent with the digital camera data that show plumes from two explosions at this location to feed two plumes of light gray ash which rose in front of the darker plume from the summit craters (Figure 3f). These events occurred at 07:14:51 and 07:15:25; tying in with oscillations recorded by the infrared sensor (L-M1 and M2-M3, Figure 5c; Table 1). The onset times for the 5 thermal oscillations that comprised the main phase of this series of lateral vent explosions (F-J, Figure 5c) give ascent velocities for these explosions of 40 – 85 m/s (calculated for a source that is 225 m from the sensor so that FOV height, D_{FOV}, is 60 m; consistent with emission from the lateral vent). The phase 3 thermal signal began to wane after the 4th event (i.e., at 07:14:27), ending around 07:15:30 (Figure 5b). Given the photographic evidence, the main phase (Figure 5b, Table 1) is likely related to ascent of the phoenix plume, and the waning phase to small explosive emissions of discrete, light-gray plumes (Figure 3f) from the lateral vent. With clearance/dispersal of the phoenix plume following the main phase, a clear line-of-sight into the summit craters was re-established.

There followed a 174 second long hiatus. Throughout the hiatus the thermal signal remained elevated (Figure 2). Examination of the thermal signal revealed that low intensity emissions continued to give 9 low amplitude thermal oscillations (Table 1; n1-n9, Figure 5c).

Thermal imagery for this phase shows high temperature (up to 400 °C) fall out mantling the upper flanks and extending down some gullies, with isolated hot spots at lower altitudes locating bombs from phase 2 (Figure 4g-l). The thermal imagery and digital photos show a persistent, low intensity, pulsing emission from the SW crater (Figures 3g and 4g-l), explaining the oscillating thermal signal during the hiatus in terms of continued, but lower intensity, pulsed emission. The digital photos also show a persistent steam cloud rising above hot deposits emplaced on proximal section of the active flow field [*Calvari et al.,* 2006; *Rosi et al.*, 2006; Figure 3h]. Emission of the steam plume begins only after the two lateral vent explosive bursts (Figure 3e-g). At the location of the thermal infrared thermometer, however, the steam plume was below the line of sight (Figure 3g), so that the instrument had an unimpeded view of activity within the summit craters.

At 07:18:24 the final major explosive phase began (phase 4, Figure 2). This comprised three discrete explosions at the SW crater, each apparent from oscillations in the thermal signal (Figure 5c), and lasted 1 minute 27 seconds [*Rosi et al.*, 2006]. The digital photos show a billowing red-brown emission from the SW crater overtaking the lighter color emission of the hiatus (Figure 3h). This fed a plume front that, by 07:19:23 (~1 minute after phase 4 began), had reached a height of ~600 m above the SW crater (Figure 3h). Likewise, the thermal imagery revealed the persistent low intensity plume of the hiatus being replaced by a stronger (higher temperature) plume from the SW crater (c.f. Figures 4l and 4m). The thermal amplitude of the hiatus oscillations also appeared to pick up just before phase 4 (events n6-n9; Figure 5c), with the final oscillation (n9) being interrupted by the first explosion of phase 4 (Figure 5c). This is also consistent with the thermal imagery, which shows emission of a more intense ash plume just before phase 4 (c.f. Figures 4j-k and 4l).

The thermal images captured during phase 4 show that the three explosions fed emissions that began, following the terminology of *Turner* [1969], with emission of a starting plume rooted to the vent which then developed into buoyantly rising thermals (Figure 4m-r). The plume emitted by the second explosion developed into three thermals (Figure 4p-r), and likely explains why the thermal signal associated with this event (P, Figure 5c) has a broad peak which itself contains three oscillations. The three explosions of phase 4 had thermally-infrared-thermometer-derived velocities of 25, 30-40 and 45 m/s, respectively. This compares well with thermal-image-derived velocities. The thermal image data places the plume front from the first explosion at ~190 m above the vent after 7 s (Figure 5m), that of the second explosion at ~250 m after 7 s (Figure 5n) and that of the third at ~180 m after 4 s. These give velocities of 27, 36 and 45 m/s for three pulses, respectively. The paroxysm was effectively over by 07:19:51, with the main explosive emission having lasted 6 minutes and 13 seconds, and comprising 3 main phases (Figure 2) and 29 discrete explosions (Table 1).

TIMING ERRORS AND UNCERTAINTIES

Recovery of the analog signal from the German transmitted time code [DCF; http://www.hopf-time.com/en/dcf-info.htm] allowed *Ripepe and Harris* [2008] to better synchronize the thermal events, with timings given in *Rosi et al.* [2006] and *Harris and Ripepe* [2007] being offset by 17 s. Although this does not affect the event chronology or durations, all absolute times given in these earlier studies will be 17 s too early. Correct absolute times are given in *Ripepe and Harris* [2008] and here (Table 1).

Assigning onset and termination points for specific events involves manual picking of onsets, many of which are not step-like, but instead turn around gradually over up to 1 s. This means that errors of 1 s may be applied to most times, so that timings given here may differ by ~1 s from those given in *Rosi et al.* [2006]. Assigning a termination time to phase 3 was particularly problematic; it being characterized by a waning thermal signal which is not abruptly terminated by a new explosive event, as at the end of phase 2 (Figure 2). *Rosi et al.* [2006] assigned a duration of 25 s; a consideration which includes the 4 main high amplitude thermal events that comprise this explosion cluster, plus the first event of the waning phase (events F-J, Figure 5b). However, this excludes two moderate amplitude events (K-L, Figure 5b) which, if included, places the termination of this event at 07:14:57, to give a duration of 42 s [*Harris and Ripepe*, 2007]. If the termination is set at the point at which the waning tail flattens out, and the final three low amplitude thermal events of the waning tail (M1-M3, Figure 5b) are included, the duration increases to 75 s. This also means that the hiatus period may be between 175 s (Table 1) and 225 s [*Rosi et al.*, 2006] in duration, depending on choice for phase 3 termination. Given that the low amplitude events M1-M3 can be linked to emissions from the lateral vent activity, we ascribe these two the lateral vent eruption phase therefore preferring 75 s for the duration of phase 3 (lateral vent) activity. Finally, two extremely low thermal amplitude thermal oscillations occurred after phase 4 (r1-r2, Figure 5c). These began at 7:20:17 and ended at 07:21:19 (Table 1); beginning 26 s after phase 4 ended. Including these two events (as well as the opening phase: phase 1) as part of the emission associated with the paroxysm increases the duration to ~8 minutes [*Rosi et al.*, 2006].

CONCLUSIONS

Integration of thermal, seismic and acoustic data collected during explosive eruptions is becoming an increasingly useful tool in tracking event dynamics (see *Harris and Ripepe* [2007] for review). Simultaneous collection of seismic and infrasonic data has been relatively widely reported in the literature, where studies at Stromboli include those of *Braun and Ripepe* [1993], *Ripepe and Braun* [1994], *Chouet et al.* [1997] and *Ripepe et al.* [2001]. Addition of a thermal infrared sensor to the array allows further constraint of the shallow system dynamics, including explosion source depth and ascent velocity [*Harris and Ripepe*, 2007]; the first experiment integrating a calibrated thermal infrared sensor occurring on Stromboli in 1999 [*Ripepe et al.*, 2002]. Recently, the advent of light-weight, portable thermal cameras capable of collecting images of calibrated temperature at frame rates of up to 30 Hz, has added to this capability; allowing improved analysis of the plume ascent dynamics following emission [*Patrick et al.*, 2007; *Patrick*, 2007]. The use of both permanently deployed thermal infrared sensors and helicopter flown thermal imagers during Stromboli's 5 April explosion greatly enhanced our ability to produce a detailed chronology of this explosive event [*Calvari et al.*, 2006; *Rosi et al.*, 2006; *Ripepe and Harris*, 2008; Table 1], with the addition of seismic and infrasonic data allowing a full consideration of the event dynamics [*Ripepe and Harris*, 2008]. For comparison, the dynamics of normal Strombolian events at Stromboli, obtained through an identical integration of thermal, seismic and acoustic data, are reviewed by *Ripepe et al.* (this volume).

The extreme detail provided by the thermal record reveals important new insights into the dynamics of an explosive paroxysm. Possibly the most profound is that even a short explosive event is not necessarily composed of a single, simple event, as already observed during previous major explosions at this volcano [*Bertagnini et al.,* 1999]. Instead, it is a complex emission comprising numerous individual pulses. As a result, the eruption comprises a pulsing emission, with explosions grouping together to define individual explosive phases. Even the most apparently simple explosive event is thus a complex phenomena comprising, itself, of a series of explosive events. These complex dynamics can be clearly tracked using a suitably placed and protected thermal instruments, revealing processes invisible to the more distant observer. For such observers, after the initial emission, the dynamics at the core of the plume are hidden from view by the optically thick ash at the plume edge. Placement of sensors within the plume reveals these invisible dynamics, yielding new insights into the rapidly evolving and complex behavior of an explosive volcanic eruption.

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Table 1. Thermal-infrared-thermometer-derived event chronology.

Phase	Event (Fig. 5)	Start Time (GMT)	Finish Time (GMT)	Duration (mm:ss)	Notes
(A) Three Phase Eruption Sequence (modified from *Rosi et al.* [2006])					
1		7:13:24	7:13:37	00:13	Eruption onset (vent opening phase)
2		7:13:38	7:14:15	00:37	Climactic explosion
3		7:14:15	7:15:30	01:15	Pyroclastic flow and smaller explosions
Hiatus		7:15:30	7:18:24	02:54	Persistent, low intensity, pulsed emission
4		7:18:24	7:19:51	01:27	Terminating ash emission from SW crater
Post-4		7:20:17	7:21:19	01:02	Final bursts
(B) Detail from thermal infrared thermometer log					
(i) Phase 1: Eruption Onset (vent opening phase)					
1	A	7:13:24	7:13:37	00:12.6	Opening phase of NE crater (NEC)
(ii) Phase 2: Climactic Explosion					
2	B	7:13:37	7:13:37	00:00.7	Initial explosion (NEC explosion 1) to feed expanding plume
2	C	7:13:37	7:13:54	00:17.1	Main pulse (NEC explosion 2) to feed sustained jetting
2	D	7:13:54	7:14:03	00:08.8	Third pulse (NEC explosion 3)
2	E	7:14:03	7:14:08	00:04.3	Fourth pulse (NEC Explosion 4)
2	E1	7:14:08	7:14:10	00:02.7	Fifth pulse (NEC explosion 5)
2	E2	7:14:11	7:14:14	00:02.9	Sixth pulse (NEC explosion 6)
(iii) Phase 3: Pyroclastic flow and smaller explosions (from lateral vent?)					
3	F	7:14:15	7:14:16	00:01.3	Initial pulse (Lateral vent explosion 1)
3	G	7:14:16	7:14:19	00:02.7	Main pulse 1 (Lateral vent explosion 2)
3	H	7:14:19	7:14:24	00:05.3	Main pulse 2 (Lateral vent explosion 3)
3	I	7:14:24	7:14:27	00:02.4	Main pulse 3 (Lateral vent explosion 4)
3		7:14:27	7:14:32	00:04.9	Inter-pulse
3	J	7:14:32	7:14:37	00:05.5	Waning pulse 1 (Lateral vent explosion 5)
3		7:14:37	7:14:42	00:04.8	Inter-pulse
3	K	7:14:42	7:14:51	00:08.8	Waning pulse 2 (Lateral vent explosion 6)
3	L	7:14:51	7:14:57	00:05.8	Waning pulse 3 (Lateral vent explosion 7)
3	M1	7:14:57	7:15:16	00:19.8	Waning pulse 4 (Lateral vent explosion 8)
3	M2	7:15:16	7:15:22	00:05.9	Waning pulse 5 (Lateral vent explosion 9)
3	M3	7:15:22	7:15:30	00:07.3	Waning pulse 6 (Lateral vent explosion 10)
(iii) Hiatus (H): Persistent, low intensity, pulsed emission from SW crater (SWC)					
H	N1	7:15:56	7:16:02	00:06.1	Hiatus pulse #1 (SWC burst)
H	N2	7:16:09	7:16:23	00:14.4	Hiatus pulse #2 (SWC burst)
H	N3	7:16:34	7:16:55	00:20.3	Hiatus pulse #3 (SWC burst)
H	N4	7:16:57	7:17:07	00:10.7	Hiatus pulse #4 (SWC burst)
H	N5	7:17:20	7:17:31	00:10.6	Hiatus pulse #5 (SWC burst)
H	N6	7:17:42	7:17:53	00:10.6	Hiatus pulse #6 (SWC burst)
H	N7	7:17:53	7:18:06	00:13.4	Hiatus pulse #7 (SWC burst)
H	N8	7:18:06	7:18:17	00:10.3	Hiatus pulse #8 (SWC burst)
H	N9	7:18:17	7:18:24	00:07.2	Hiatus pulse #9; interrupted by explosive onset of phase 4
(iv) Phase 4: Terminating ash emission from SW crater					
4	O	7:18:24	7:18:39	00:15.1	First explosion
4	P	7:18:39	7:19:19	00:39.7	Second explosion
4	Q	7:19:19	7:19:51	00:32.1	Third explosion
(v) Final bursts					
	R1	7:20:17	7:20:37	00:19.7	Minor (low thermal amplitude) emission #1
	R2	7:20:54	7:21:19	00:25.3	Minor (low thermal amplitude) emission #2

Figure Captions

Figure 1 (a) Stromboli showing locations of the SW, Central and NE craters (SW, CC and NE). The two thermal sensor sites to the southeast (P) and east (ROC) of the summit craters and the Civil Protection Operations Center (COA) are given, as is the 5 April helicopter flight path (red line; from *Calvari et al.* [2006]), on which approximate times for the helicopter location at each point are marked. Note sharp turn to the SE (marked with a star) just after 07:13 forced by the paroxysm onset. (b) The 5 April 2003 paroxysmal eruption viewed from the east at 07:14:15 showing the main column of phase 2 and location of ROC thermal station within the column. Black curtains of ballistic fall-out are apparent at the plume margins, as is a small cloud rising above the phase 3 pyroclastic flow. The plume front has the form of a well-developed thermal. Insets are photographs of the thermal sensor bunker upon installation in May 2002 at the Pizzo (top) and immediately following the 5 April event (below) (from *Harris et al.* [2005]).

Figure 2. Overview of the thermal signal obtained for the 5 April paroxysm. The opening phase (phase 1) and three main explosive phases (2 to 3) defined using these thermal data by *Rosi et al.* [2006] are marked.

Figure 3. Digital photo sequence of the 5 April paroxysm. Timings are set by correcting the digital camera time using the difference between the thermal-infrared thermometer-derived onset for phase 2 (07:13:38 GMT) and the camera time of the same event. This time is also used as time zero. (a) View from the west of Stromboli's summit craters ~2 minutes prior to phase 2, showing a normal condensed plume emitted from the NE, central and SW craters as well as the proximal section of the active lava flow field (p). (b) View from the south showing slight

reddening of the plume due to emission from the central and NE craters, followed by (c) slightly more intense emission from NE crater to form a darker, billowing cloud in the seconds before the main phase 2 blast. (d) The expanding cloud and finger jet components of the phase 2 emission imaged ~2 seconds after the blast onset. (e) View from the east showing the eruption plume ~20 s after the onset of phase 3, showing well-developed phoenix cloud from the scoria flow and thermal from the phase 2 emission. (f) View from the NE showing (i) thermal generated by the phase 3 phenix cloud, and (ii) two pulses of light gray ash most likely (given their source location) from the lateral vent. (g) View from the NE showing (i) pulsing plume characteristic of the hiatus, (ii) steam rising from hot, wet deposits emplaced on the active flow field, and (iii) location of the east ridge thermal sensor (black dot). (h) Phase 4 plume ~1 minute 15 s after initial emission showing the plumes from each of the three pulses (O, P and Q, Table 1) that comprised this three explosion phase, as well as the steam plume (s) generated by hot deposits over the lateral vent / shield.

Figure 4. Thermal camera time series for (a-f) phases 1-2, (g-l) the hiatus, and (m-r) phase 4. Timings are set by correcting the digital camera time using the difference between the thermal-infrared thermometer-derived onset for phase 2 (07:13:38 GMT) and the camera time of the same event. This time is also used as time zero. Figures (a-d) show increasing emission from NE and SW craters during the opening phase (phase 1), interrupted (e-f) by emission of the phase 2 plume. This initially comprised an expanding cloud of high temperature ash (ec) behind a leading edge of ballistics (bl). Figures (g-i) show the pulsing plume of the hiatus, revealing the SW crater as its source (Figure j-l). Also apparent is hot fall out from phase 2 mantling the upper sections of the outer flank, and extending down valley (Figure g-l). Approximate outer

flank altitude range covered by images in g-i and j-l is given, as is the approximate scale for the image position of the SW crater plume. The location of the east ridge infrared thermometer (open circle), Pizzo Sopra La Fossa (p, 918 m. a.s.l.) and NE crater (ne) are given. NE crater flank is mantled by a near continuous cover of high temperature (200 – 400 °C) fall out (Figure j-l). Figures m-r record emission of the phase 4 plume, showing the starting plumes and thermals associated with the 3 explosion events (1-3). The plume from the second explosion forms 3 discrete thermals (2a, 2b and 2c). Where given, vertical (white) scale line is 150 m. Images given in (a-f) are obtained over a viewing distance of ~450 m and thus cover a ~150 x 200 m field of view at the plume location.

Figure 5. Detail of the thermal infrared thermometer signal obtained during (a) phases 1-2, (b) phase 3, and (c) phase 4. Time is in seconds since 07:13:18 GMT. Each of the main pulses that comprise each phase and hiatus are lettered (see Table 1). The four main eruption phases defined by *Rosi et al.* [2006] using these data are also marked. Arrows labeled V and B in mark the seismically-recorded arrivals of the most powerful VLP and blast wave, respectively. In (b) numbered arrows indicate the minimum [*Rosi et al.*, 2006], median [*Harris and Ripepe*, 2007] and maximum likely duration of phase 3.