# Effusive to explosive transition during the 2003 eruption of Stromboli volcano


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## ABSTRACT

**The persistent explosive activity of Stromboli volcano (Italy) ceased in December 2002 and correlated with the onset of a seven-month-long effusive eruption on the volcano flank from new vents that opened just below the summit craters. We intensively monitored this effusive event, collecting and interpreting, in real time, an extensive multiparametric geophysical data set. The resulting data synergy allowed detailed insights into the conduit dynamics that drove the eruption and the transition back to the typical Strombolian activity. We present a direct link between gas flux, magma volume flux, and seismicity, supporting a gas driven model whereby the balance between gas flux and gas overpressure determines whether the system will support effusive or explosive activity. This insight enabled us to monitor the migration of the magma column up the conduit and to explain the onset of explosive activity.**



**Keywords:** Stromboli, volcano monitoring, multiparametric geophysical data set, effusive eruption, conduit dynamics.


## INTRODUCTION

Magmatic conduits represent complex fluid-dynamic systems within which liquid magma interacts with large quantities of gas and solid crystals. Few volcanoes have contributed more to our understanding of these magma-gas interactions during volcanic explosions than Stromboli, Italy. Stromboli has been characterized by persistent moderately explosive (Strombolian) activity for at least 1000 yr (Rosi et al., 2000) with gas, ash, and bombs ejected to heights of 50–300 m in short-lived (<1-min-long) explosive events, typically ~9 times an hour. Because of the reliability of this activity, as well as its geographic position and accessibility of the summit vents, Stromboli can be viewed as an outstanding laboratory volcano where experiments can easily be deployed and hypotheses tested. As a result, many new research directions in volcanology, such as broadband volcano-seismology (Neuberg et al., 1994; Chouet et al., 2003), infrasonic acoustics (Vergniolle and Brandeis, 1994; Buckingham and Garces, 1996), and ground-based thermal radiance (Ripepe et al., 2002; Harris et al., 2005) have been developed at Stromboli.

On 28 December 2002, Stromboli's typical persistent explosive activity was interrupted by an effusive eruption. Lava flowed down the volcano flank for almost seven months, while explosive activity at the summit was virtually absent. Regular explosive activity was re-established only when the effusive phase ceased on 21 July 2003. The interplay between explosive and effusive activity provided us with a unique opportunity to understand the dynamics of an erupting volcanic system.

In response to the eruption, a network of broadband seismometers, infrasonic microphones, and thermal sensors (Ripepe et al., 2004) was deployed during January 2003 (Fig. 1). In addition, thermal radiance recorded by the moderate resolution imaging spectrometer (MODIS) sensor aboard the Terra and Aqua satellites (Wright et al., 2004), and daily measurements of $SO_2$ emission by correlation spectrometer (COSPEC), targeting the summit craters' plume, contributed to daily updates regarding the eruption and system dynamics that drove it. These data allowed us to understand the transition from effusive to explosive activity and to identify the conduit processes that drove this transition.

## EFFUSIVE TO EXPLOSIVE TRANSITION

Thermal infrared thermometers have been introduced as a viable ground-based monitoring tool at a number of volcanoes (Harris et al., 2005). These sensors provide, in an inexpensive but highly efficient manner, a continuous high temporal resolution thermal signal that can be sampled several times per second. These instruments are therefore capable of tracking changes in degassing and explosive activity at volcanoes (e.g., Ripepe et al., 2002).

Infrared thermometers record explosions as temperature pulses when hot gas, ash, and lava fragments pass through the instrument field of view (FOV). Their amplitude is proportional to the temperature and percentage of the FOV covered by hot material and thus may be used as a proxy for the mass of magma and gas ejected during an explosion.

Ground-based thermometry is complemen-

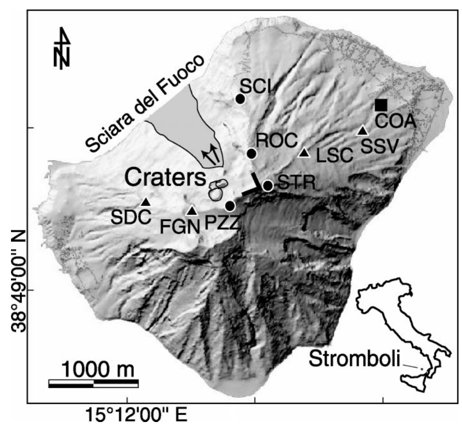


**Figure 1. Multiparameter network (symbols), 2002–2003 lava flow field (gray area), and position of effusive vents (arrows) on Stromboli. Permanent (circles) and temporary (triangles) stations are equipped with broadband CMG40T (30 s period) seismometers and infrasonic (1–10 Hz) microphones. Small-aperture infrasonic array (L-shaped line) operates with five microphones linked with fiber-optic cable. Stations ROC and PZZ are each provided with 15° field of view infrared thermometer. Explosive activity is also recorded from ROC with infrared camera. Signals are digitally transmitted and processed in real time at the operations center (COA) of Department of Civil Defense.**

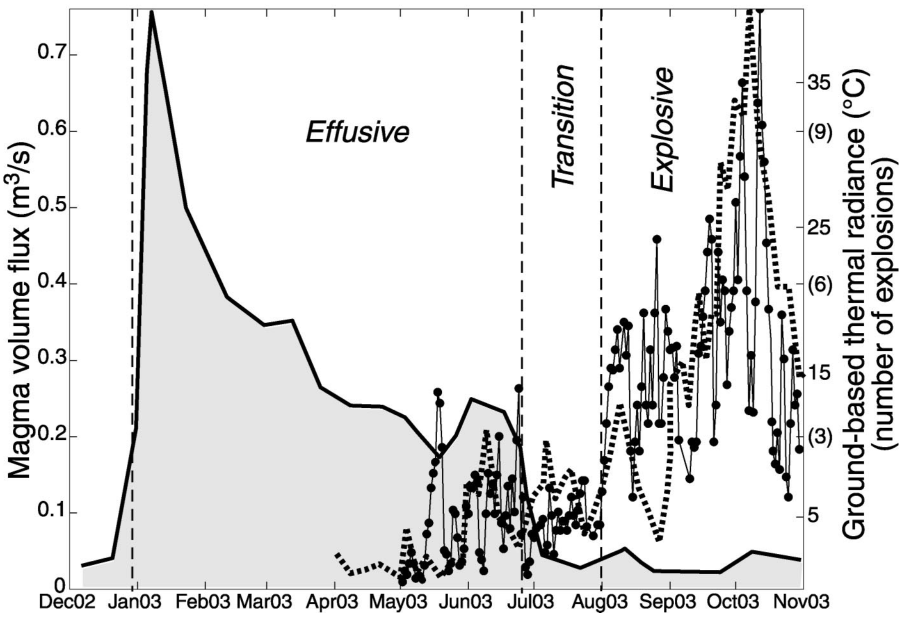


**Figure 2. Transition from effusive to explosive phase detected by ground-based infrared thermometers and moderate resolution imaging spectrometor (MODIS) satellite-borne sensor. No explosions were detected between January and April 2003. Thermal amplitude during explosions (dashed line; right axis labels not in parentheses) and daily average of number of thermal transients per hour (line with dots; right axis labels in parentheses) follow same increasing trend, indicating that size and rate of explosive events are linked. Magma volume flux derived by MODIS (gray area) increased when eruption began on 28 December 2002, and declined sharply at end of June 2003, one month before lava flow activity ceased.**

tary to information obtained from thermal imagery acquired at lower temporal resolutions (1–2 images per day) for the entire lava flow field by satellite-based sensors. Thus while ground-based thermal data can track the thermal contribution due to the explosive activity (e.g., Ripepe et al., 2002), satellite remote sensing allows us to monitor effusive activity across the entire volcano (e.g., Harris et al., 1997).

The combined thermal information gives a quantitative picture of how activity at Stromboli shifted from effusive to explosive during the eruption (Fig. 2). Satellite-derived thermal radiance can be converted into the equivalent magma volume flux necessary to justify the recorded radiance (Harris et al., 1997) . In the first weeks of the eruption we recorded a maximum magma volume flux of 1.5 $m^3$/s. Fluxes decreased almost steadily until June 21, when they dropped sharply below 0.2 $m^3$/s, one month before the end of the effusive activity (Fig. 2). Volume fluxes of 0.1–0.2 $m^3$/s were obtained from the MODIS data during the more typical persistent Strombolian activity following the effusive eruption, and are consistent with volume fluxes measured before the eruption (Harris et al., 1997). Therefore, magma volume fluxes $>$0.2 $m^3$/s are mainly associated with the effusive eruption.

At the same time, the number and amplitude of thermal pulses related to explosions increased (Fig. 2). This relationship points toward a threshold magma supply rate above which the volume flux cannot be contained within Stromboli's shallow conduit geometry; pressurization then causes brittle mechanical failure of the conduit so that fractures open to tap the central conduit and feed lava flows over the flanks. If the flux drops below this level, fractures can seal. The magma volume flux at which we observe the transition back to explosive activity is consistent with the average magma input rate of $\sim$0.3 $m^3$/s typically associated with Stromboli's stable explosive activity (Allard at al., 1994). Thus we suggest that this value approximates a threshold below which the system is able to accommodate the magma supply rate, and above which the system becomes overwhelmed.

## VOLCANO SEISMICITY AND RATE OF GAS COALESCENCE

Seismicity at Stromboli is characterized by a very long period (VLP) component ($>$3 s) and is generally associated with the explosive process (Neuberg et al., 1994; Ripepe et al., 2001; Chouet et al., 2003). Although the seven-month-long effusive period was characterized by an absence of visible explosions at the summit craters, volcano seismicity was intense ($>$20 VLP events per hour). However, the location of VLP seismicity remained stable before, during, and after the effusive eruption; confined to a zone $\sim$250 m below the summit craters (Ripepe et al., 2004), a location consistent with previous estimates (Chouet et al., 2003) and at the same elevation as the effusive vents.

VLP seismicity is common at several volcanoes that exhibit Strombolian activity (Chouet, 1996) and that are most likely produced by the rapid expansion of large gas slugs within the magma column, as suggested by laboratory experiments (Ripepe et al., 2001; James et al., 2004) and seismic moment tensor inversion (Chouet et al., 2003). Therefore, the rate of occurrence of VLP events is here considered synonymous with rates of gas coalescence and expansion in the magma column. This rate remained at almost twice (1.7 times) the normal rate during the effusive activity, until July 21, when it finally declined to a more typical rate of $\sim$9 events/h. This indicated that, during the effusive phase, the gas coalescence process continued, but at an elevated rate.

## $SO_2$ EMISSION RATE AND SEISMICITY

An increase in the gas supply can accelerate the coalescence process; at higher gas fluxes the rate at which gas slugs develop increases as a consequence of foam generation and collapse (Jaupart and Vergniolle, 1989). Therefore, an increase in gas flux should increase the number of VLP events. There is strong evidence for this link in that the $SO_2$ emission rate measured for the plume emitted by the summit vents by COSPEC showed an increase during the effusive eruption. Occurrence of VLP events and $SO_2$ emission rates show the same trend where, during the effusive phase, the number of seismic VLP events per hour was high ($\sim$17 events/h) and $SO_2$ emission was also high (450 t/d). Both, however, declined when the effusive phase ceased (Fig. 3). This reduction was accompanied by an increase in the explosive activity, where the number of explosions detected as thermal transients by the infrared thermometer increased after July 21 (Fig. 3). The style of explosive activity progressively changed from ash-rich explosions (in May and June) to spatter-rich explosions (after July 21). This change correlated with both the increase in the number of thermal transients and the increase in the amplitude of the infrasonic waves produced by the explosions (Fig. 3). The amplitude of the infrasonic waves is directly linked to the overpressure inside the bursting gas (Vergniolle and Brandeis, 1994), and indicates that while gas flux was decreasing, gas overpressure was increasing.

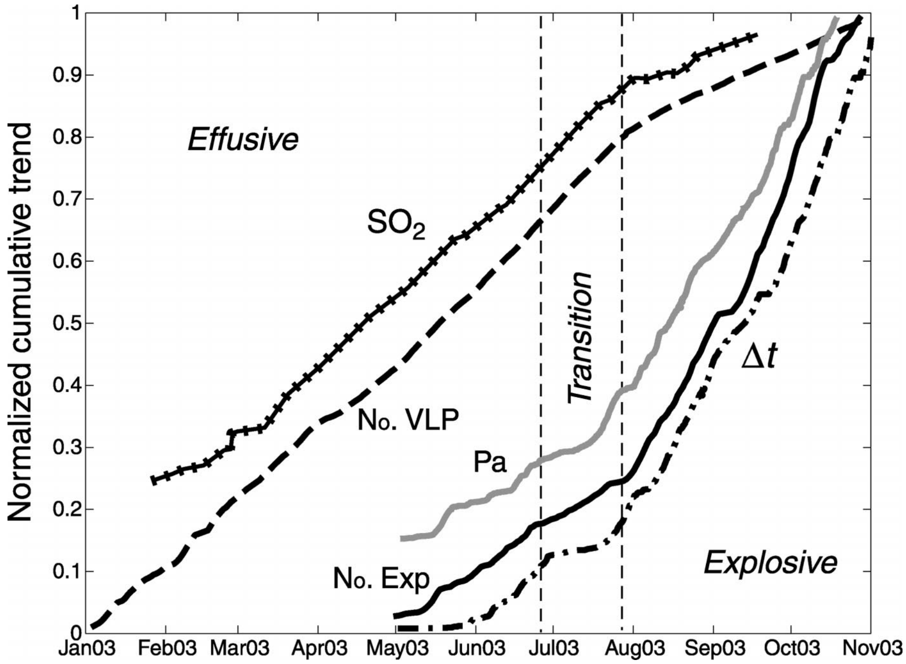


**Figure 3. Data set represented as cumulative functions, allowing trends in data to be most easily visualized. Daily average of very long period (VLP) events per hour (dashed line) and $SO_2$ emission rate (stippled line) follow same trend with change in slope after July 21, when lava effusion ceased. During effusion 18 VLP events per hour and 450 t/day of $SO_2$ were recorded. After July 21, VLP event rates and $SO_2$ flux decreased by half (to 9 events/h and 220 t/d, respectively). Common trend in VLP event rates and $SO_2$ flux underlines gas flux control on coalescence rates. Reduction in gas flux was followed by increase in rate of explosions, represented by frequency of thermal transients (bold line), and in amplitude of infrasonic pressure recorded during explosions (Pa, gray line), pointing to increase in gas overpressure. Explosive activity increased at end of effusive phase and was followed by strong reduction in thermo-acoustic time delays ($\Delta t$, dash-dot line), implying increase in magma level and/or gas-fragment velocity. Trends in explosion count, acoustic pressure, and time delay data indicate that increase in gas overpressure was associated with steady upward migration of magma column.**

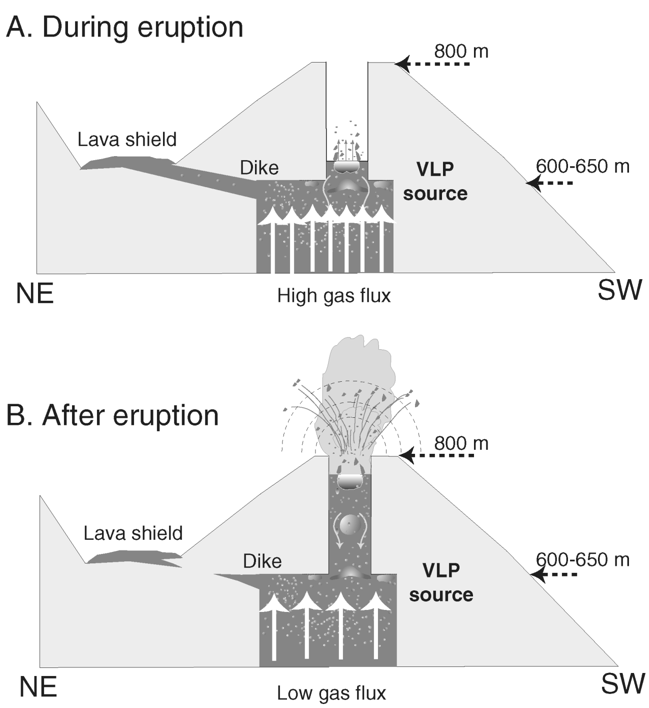


**Figure 4. A: After 28 December 2002, lava erupted from vents located just below summit craters at elevations of ~600 m. During lava effusion no explosions were observed at summit, but very long period (VLP) seismicity and $SO_2$ emission were high. B: Reduction in magma volume flux at end of June caused effusive fractures to progressively shut down. This induced magma to steadily rise up conduit, increasing gas overpressure and explosive activity. Upward magma migration was monitored by progressive reduction in thermo-acoustic time delays, and by amplitude increase of infrasonic waves.**

## MIGRATION OF THE MAGMA COLUMN

Thermal and infrasonic waves share the same source-to-receiver travel distance: first in the conduit and then in the atmosphere (Ripepe et al., 2002). Outside the conduit, the thermal signal propagates at light speed, much faster than infrasonic waves, which travel at the speed of sound in air (~340 m/s). However, within the conduit the thermal signal travels with the velocity ($U$) of the expansion of the gas-fragment cloud between the fragmentation level ($z$) and the vent. This gas expansion velocity $U$ is slower ($10 < U < 150$ m/s) than the sound speed ($340 < c < 800$ m/s) in the conduit (Weill et al., 1992) and depends on gas overpressure (Blackburn et al., 1976). As a result, time delays between thermal and infrasonic onsets inside the conduit ($\Delta t = z[(c - U)/cU]$) will approach 0 when the position of the fragmentation level approaches the surface ($z = 0$) or when the velocities of the gas-fragment cloud and the sound velocity in the conduit are equivalent ($c = U$).

Measuring the time delay thus provides a good proxy for the position of the fragmentation level and/or velocity of the gas expansion. Time delays were longer (>20 s) during the effusive phase, suggesting a deep position of fragmentation and/or a slow gas decompression velocity. Time delays became smaller following the sharp increase in the explosion frequency and amplitude of acoustic pressure (Fig. 3). This result is consistent with an upward migration of the magma column to the surface, and/or an increase in the gas decompression velocity.

The transition from the effusive to the explosive phase thus appears to have been controlled by two factors: (1) the progressive reduction in the magma volume flux to a level below a threshold value (0.3 $m^3$/s), and (2) the increase of the magma level within the conduit. The reduction in the magma volume flux may have promoted closure of the effusive fractures, leading to a steady reduction in the tapping of the central conduit to cause magma levels to recover during the one-month-long transition phase. As a result, gas overpressure and explosive activity also steadily increased.

## CONCLUSIONS

At the onset of the eruption, gas flux was high. This would have been induced by an increase in the magma supply such that it exceeded the typical rate of ~0.3 $m^3$/s. This increased rate generated the opening of effusive fractures to cause the tapping of the central conduit by a lateral fissure so that the height of the magma column declined (Fig. 4A). Although higher gas fluxes meant that gas coalescence rates increased, the reduction in column height led to a decrease in gas overpressure and hence a decrease in explosive activity at the summit. As the eruption progressed, volume fluxes declined and the eruptive fractures steadily sealed. The reduced tapping allowed magma levels in the conduit, and hence gas overpressure and explosive activity, to steadily recover (Fig. 4B). This was not a sudden refilling of the conduit. The system was instead fluctuating between effusive and explosive behavior over a one-month-long transition. Thus, gas flux and magma migration in the central column played significant roles in determining whether the system supported explosive activity. Seismic VLP events, infrasonic waves, ground-based thermal data, $SO_2$ emissions, and satellite-derived heat flux data collected during the eruption all support this conclusion.

The synergy of different volcano monitoring methods is a powerful means by which we can track, monitor, and understand volcanic processes. Data collected at Stromboli as part of routine monitoring during and after the 2002–2003 effusive eruption indicate that explosive activity at persistently active volcanic systems results from a balance between overpressure (a function of the magma column level in relation to the explosion source) and gas flux rate. These control the position of the fragmentation level above a quasi-steady level of gas coalescence and expansion in the feeding system.

The complexity of the magma-gas interactions requires sophisticated monitoring procedures that are now within our capability. This realization moves us a significant step closer to the ultimate aim of volcanology: to confidently predict the behavior of an ongoing volcanic eruption.


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# CORRECTION

**Dauphiné twinning as evidence for an impact origin of preferred orientation in quartzite: An example from Vredefort, South Africa: Correction**

Wenk et al.


*Geology,* v. 33, no. 4, p. 273–276 (April 2004)


An error appeared in the second paragraph of the Introduction. The fifth sentence should have read: ''In terms of elastic properties, the pole to the negative rhomb is close to the stiffest direction of quartz, and that of the positive rhomb is close to the softest direction.'' The terms positive and negative were inadvertently switched in the printed version.