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Abstract

The 2007 effusive eruption of Stromboli followed a similar pattern to the previous 2002–2003 episode. In both cases, magma ascent led to breaching of the uppermost part of the conduit forming an eruptive fissure that discharged lava down the Sciara del Fuoco depression. Both eruptions also displayed a ‘paroxysmal’ explosive event during lava flow output. From daily effusion rate measurements retrieved from helicopter- and satellite-based infrared imaging, we deduce that the cumulative volume of lava erupted before each of the two paroxysms was similar. Based on this finding, we propose a conceptual model to explain why both paroxysms occurred after this ‘threshold’ cumulative volume of magma was erupted. The gradual decompression of the deep plumbing system induced by magma withdrawal and eruption, drew deeper volatile-rich magma into the conduit, leading to the paroxysms. The proposed model might provide a basis for forecasting paroxysmal explosions during future effusive eruptions of Stromboli.

Keywords: Stromboli volcano; effusive eruptions; paroxysmal explosions; paroxysm prediction

1. Introduction

Stromboli volcano has been almost continuously active for 1300 yr ([Giberti et al., 1992] and [Rosi et al., 2000]). The steady supply of magma is associated with a bi-flow regime in the conduit, sustained degassing and frequent Strombolian eruptions (sensu strictu), punctuated roughly every 4 to 5 yr by much stronger explosions, commonly referred to as paroxysms (Barberi et al., 1993). These explosions erupt the same highly porphyritic (HP), high-density, crystallised magma associated with typical Strombolian activity and residing within the conduit but mixed with variable amounts ([Lautze and Houghton, 2007] and [Polacci et al., 2009]) of less-porphyritic (LP), low-density, volatile-rich magma ascending directly from an intermediate storage zone (at 6–9 km depth (Fig. 1; [Di Carlo et al., 2006], [Métrich et al., 2005] and [Pichavant et al., 2009]). Once injected into the conduit system, this LP magma rises rapidly enough to inhibit crystallisation and gas separation, resulting in limited mixing with HP magma. Paroxysms produce dense plumes that rise 3–4 km above the crater, and almost all of them have had an impact on the settled area ([Calvari et al., 2006], [Calvari et al., 2010] and [Rittmann, 1931]). On a small island ~ 4 km wide and 1 km high, and populated during summer by as many as 6000 people, such events represent a significant hazard; several people were killed as a result of paroxysms in 1919 and 1930 (Rittmann, 1931). Predicting the occurrence of paroxysms thus assumes considerable importance from a civil protection perspective.

At least two patterns of behaviour have been recognised for Stromboli's historic activity: (i) paroxysms followed by lava effusion, and (ii) lava effusion followed by paroxysms ([Barberi et al., 1993] and [Perret, 1916]). Lava effusions at Stromboli are fairly common — they occur on average every 3.7 yr (Barberi et al., 1993). The last two episodes occurred in 2002–2003 ([Bonaccorso et al., 2003], [Calvari et al., 2005a] and [Calvari et al., 2005b]) and 2007 (Calvari et al., 2010). Both were associated with paroxysms ([Calvari et al., 2006], [Calvari et al., 2010] and [Harris et al., 2008]) that occurred once lava effusion was underway, thus conforming to case (ii) as described above. Depressurisation of deeper regions of the magma supply system, resulting in exsolution (primarily of CO_2) and rapid ascent of a buoyant batch of LP magma, is one of the mechanisms invoked to explain Stromboli's paroxysms (e.g., Aiuppa et al., 2009).

(Alidibirov and Panov, 1998), (Martel et al., 2000) and (Ichihara et al., 2002) support the general idea that decompression rate is one of the key variables influencing eruptive style of eruption, with faster decompression rates inducing fragmentation. However, the two most recent Stromboli paroxysms appear to be associated with slow decompression, because the depressurisation and lava effusion took place over a period of days/weeks. Here, we develop this hypothesis further through an analysis of effusion rate data from the 2002–2003 ([Calvari et al., 2005a], [Calvari et al., 2005b], [Harris et al., 2005] and [Lodato et al., 2007]) and 2007 eruptions (Calvari et al., 2010). We evaluate these observations in the light of studies and laboratory experiments and propose a triggering mechanism for paroxysms that occur during basaltic effusive eruptions. Our hypothesis was developed during the 2007 eruption because its similarity to the 2002–2003 eruption led us to anticipate the 15 March paroxysm. The new model might be the key to understanding how the shallow supply system works, and because it is linked to surface observations of lava effusion, and thus to erupted lava volumes, it could pave the way to forecasting of future paroxysms.

2. Recent paroxysms and effusive eruptions

Table 1 summarises paroxysms that occurred over the last century. Although this provides a valuable longer timeframe over which to consider the coincidence of effusive and paroxysmal events, eruption parameters including magnitude and column height cannot be systematically determined in most of the cases, and sometimes not at all. This is why we focus on the 2002–2003 and 2007 effusive episodes, for which we have reliable geophysical and volcanological data. The following summarises the key events from available accounts ([Bonaccorso et al., 2003], [Burton et al., 2008], [Calvari et al., 2005a], [Calvari et al., 2005b], [Calvari et al., 2006], [Calvari et al., 2010], [Harris et al., 2008], [Lodato et al., 2007], [Neri and Lanzafame, 2009] and [Spampinato et al., 2008]).

The 2002–2003 eruption began on 28 December, after about seven months of accentuated Strombolian activity at the summit craters during which the frequency of explosions and height of ejecta had both increased. On 28 December, a NE-trending fissure opened at 500 m a.s.l. on the northern flank of the summit crater (Fig. 2a), sourcing lava flows that resulted in complete drainage of the craters and cessation of the typical explosive activity (Fig. 2a). On 5 April, while lava was still erupting, the obstructed summit craters of the volcano were the site of one of the strongest paroxysms recorded at Stromboli since 1930 (Rittmann, 1931). The effusive eruption ended between 21 and 22 July, after the expulsion of an estimated total of ~ 13×10^6 m^3 of vesiculated lava ([Calvari et al., 2005a] and [Calvari et al., 2005b]). A similar amount of 11.5×10^6 m^3 was estimated by using high precision photogrammetry (Baldi et al., 2008), though this figure excludes any lava emplaced below sea level.

The 2007 eruption began on 27 February, after several months of intense explosive activity at the summit craters, with two eruptive fissures propagating on the NE flank of the summit cone (Fig. 2b). Explosive activity ceased as soon as the NE summit cone was breached, and a vent opened at the eastern margin on the Sciara del Fuoco at ~ 400 m a.s.l. (Fig. 2b). More than half of the erupted volume of lava was emplaced during the first 5.5 days, with a peak discharge rate that was one order of magnitude greater than the 2002–2003 eruption. On 15 March 2007, while lava effusion was continuing, a paroxysmal explosion occurred at the summit, with similar features to the 5 April 2003 event. Both events occurred during lava output, when the summit craters were obstructed by debris derived from the crater walls. Lava continued pouring out but at a diminishing rate until 2 April, when the eruption ceased. Estimates of the erupted volume range between ~ $7.1 \pm 3.9 \times 10^6$ m^3 (Calvari et al., 2010) and ~ $8.9 \pm 1.5 \times 10^6$ m^3 (Neri and Lanzafame, 2009). Both these figures were calculated from analysis of thermal imagery, and represent dense rock equivalent volumes (DRE; [Harris et al., 2005] and [Harris et al., 2007]). To compare them with the 2002–2003 bulk volumes requires accounting for the average vesicularity. Vesicularity of the

2002–2003 lavas was found to be between 16 and 32% (Fornaciai et al., 2009). Using these values, the 2002–2003 DRE volume was ~ 9.9 ± 2.0 × 10^6 m^3 based on the estimate of (Calvari et al., 2005a) and (Calvari et al., 2005b), comparable with the 8.7 ± 1.8 × 10^6 m^3 derived by photogrammetry (Baldi et al., 2008). To avoid complications arising from uncertainties in vesicularity, in the following analysis we use the effusion rate data derived from thermal imagery acquired from satellite and airborne platforms ([Calvari et al., 2005a], [Calvari et al., 2005b], [Calvari et al., 2010], [Harris et al., 2005] and [Lodato et al., 2007]). These yield time-series of the cumulative volumes erupted before both 2003 and 2007 paroxysms.

3. Effusion rates and erupted volumes

Effusion rate is a crucial parameter when monitoring effusive eruptions since it controls the extension, morphology and shape of a lava flow field (e.g., [Calvari and Pinkerton, 1998], [Harris et al., 2007], [Kilburn, 1993], [Kilburn and Lopes, 1988], [Lombardo et al., 2009] and [Walker, 1973]). Thus, timely and at least daily effusion rate measurements are essential in support of lava flow monitoring and hazard mitigation. Daily effusion rates measured during ongoing eruptions allow continuous update of the erupted volume, revealing processes occurring in the magma plumbing system. Only for the last two (2002–2003 and 2007) Stromboli effusive eruptions do we have fairly detailed data sets of effusion rates.

Thermal surveys from a helicopter were carried out using a hand-held infrared camera. Using the model of Harris et al. (2005), thermal imagery from both satellite-borne instruments and the helicopter-based survey were used to estimate the minimum and maximum daily effusion rates. Error budgets for the effusion rates are comparable for both the helicopter surveys and satellite imagery (± 40%, [Calvari et al., 2005a] and [Calvari et al., 2005b]).

Figure 3 reports the daily maximum effusion rate data merged together to provide a complete set of daily cumulative maximum volume for the entire durations of the two eruptions. Although the 2002–2003 effusive eruption lasted five months longer than the 2007 event, the latter was characterised by a higher initial effusion rate. Calvari et al., 2005a S. Calvari, L. Spampinato, L. Lodato, A.J.L. Harris, M.R. Patrick, J. Dehn, M.R. Burton and D. Andronico, Chronology and complex volcanic processes during the 2002–2003 flank eruption at Stromboli volcano (Italy) reconstructed from direct observations and surveys with a hand-held thermal camera, *J. Geophys. Res.* **110** (2005), p. B02201 (Calvari et al., 2005a), (Calvari et al., 2005b), (Lodato et al., 2007) and (Calvari et al., 2010) calculated mean effusion rates of 0.5 $m^3\ s^{-1}$ (for a 156 day emplacement time) and 1.5 $m^3\ s^{-1}$ (considering a 34 day emplacement time) for the 2002–2003 and 2007 effusive eruptions, respectively.

From Figure 3, we derived the DRE cumulative volumes erupted before both paroxysms (Fig. 4). Figure 4 shows the complete time-series of cumulative volume of erupted lava for the two eruptions. It reveals the key result emerging from this analysis that, prior to each paroxysm, similar amounts of lava were erupted (green triangles in Fig. 4), i.e. ~ 4.4 and 4.2 × 10^6 m^3 for the 5 April 2003 and 15 March 2007 paroxysms, respectively. This suggests also that the volume of the drained upper feeder system is comparable. Our hypothesis is that this coincidence reflects a common triggering process for the paroxysms.

4. Decompression and eruptive regime

Models of magma transport in volcanic conduits (e.g., [Jaupart and Vergniolle, 1988] and [Wilson, 1980]) describe the fluid dynamics involved in a wide range of eruptive styles, and offer both conceptual and quantitative insights into the nature of mild explosive basaltic activity, such as Strombolian or Hawaiian. The reasons for the sudden switch from effusive to explosive activity associated with paroxysms, and their association with conduit drainage remain enigmatic. At Stromboli, paroxysms appear to be caused by some processes distinct from those controlling the persistent Strombolian activity. In fact, paroxysms are characterised by eruption of LP magma, and by significantly higher eruption intensity (e.g. [Andronico and Pistolesi, 2010], [Bertagnini et al., 1999] and [Calvari et al., 2006]).

Considering the 2002–2003 and 2007 eruptions, if a similar plumbing system geometry is postulated, then the effusion of a similar amount of magma before paroxysms suggests a comparable decompression of the deep feeding system. In this context, LP magma, slowly ascending and taking the place of the erupted HP magma at shallower levels, reached at some point a critical depth level inducing mass vesiculation. Namiki and Manga (2006) proposed a mechanism that could potentially trigger basaltic explosive behaviour, based on an investigation of the expansion of low viscosity bubbly fluids experiencing decompression at variable rates. They observed experimentally the importance of decompression rate in the expansion behaviour of a bubbly fluid, and compared their observation with velocities of expansion calculated under ‘equilibrium’ conditions (i.e. when the gas expands within the bubbles keeping pace with decompression rate), and in case of non-equilibrium (i.e. when decompression rate exceeds the bubbles' ability to expand). In the latter case, they assume that the enthalpy change due to decompression is transformed into kinetic energy of the expanding bubbly fluid. They compared the two theoretical velocities and integrated the resulting inequality with results from Spieler et al. (2004), who experimentally derived a vesiculation threshold for fragmentation. In this way, they obtained a criterion for the explosive behaviour of basaltic magma: above a critical decompression rate, the non-equilibrium expansion velocity exceeds the equilibrium one, and the regime is predicted to become explosive. The threshold in decompression rate is expressed in terms of vesicularity, initial pressure, total decompression (and thus the total erupted lava volume before paroxysms), and height of the bubbly column:

$$-dP_{Ot} > \left(\frac{2\gamma}{\rho_L \phi_i P_{Gi}(1-\phi_i).(\gamma-1)}\right)^{1/2} \cdot \frac{P_{Ot}^2}{h_{Fi}}$$

where $-dP_{Ot}$ is the decompression rate for the disequilibrium expansion in magmas, ρ_L is the magma density, Φ_i the vesicularity, P_{Gi} the initial pressure of the gas inside the bubbles, P_{Ot} the pressure of the gas outside the bubbles during the expansion, γ the isentropic exponent, and h_{Fi} the height of the bubbly magma column. In the context of Stromboli volcano, we assume that the bubbly magma column is represented by just LP magma, given that the HP magma fills only the upper portion of the feeder conduit (Fig. 5).

A key point is that the threshold in decompression rate is inversely proportional to the height of the bubbly magma column, meaning that a higher column of bubbly magma will experience disequilibrium expansion at lower decompression rates. This result suggests a scenario that could be applicable to the 2003 and 2007 paroxysms at Stromboli. Figure 6 illustrates Eq. 21 in Namiki and Manga (2006) or Eq. (1) here, using parameters appropriate for Stromboli as reported in the caption of Figure 6. As decompression due to lava effusion promotes exsolution over greater depth levels, the column of LP magma would slowly extend in height, potentially leading to a sudden transition from effusive to explosive regimes (Fig. 6).

5. Discussion

Fast decompression is recognised as an important trigger for explosive eruptions (e.g. [Alidibirov and Dingwell, 1996] and [Namiki and Manga, 2006]), thus, examples of gradual/slow decompression leading to violent explosion, such as the several days/weeks in the case of Stromboli, have not been widely reported. They may be more widespread than realised, however. For instance, paroxysms of comparable magnitude to Stromboli's have been observed at Fuego in Guatemala (Lyons et al., 2010) and Vesuvius in 1944 (Hazlett et al., 1991), where paroxysms consistently followed the onset of effusive eruptions.

The similarities between the 2002–2003 and 2007 effusive eruptions at Stromboli volcano, and the occurrence of paroxysmal explosions during lava flow output in each case, suggest similar triggering mechanisms for both paroxysms. In fact, the 15 March 2007 explosive event was foreseen on the basis of the 2002–2003 experience, i.e. that a threshold volume of erupted lava, reflecting a threshold of decompression needed to be discharged from the supply system before LP magma could reach the surface in a paroxysm. If this is true, it is crucial that this threshold volume of erupted magma is discharged at a rate exceeding the LP magma crystallisation rate, thus avoiding LP–HP magma mixing or LP magma transition to HP producing only the typical Strombolian activity ([Burton et al., 2007] and [Schiavi et al., 2010]). Thus, it is striking that both 2003 and 2007 paroxysms ensued on discharge of comparable DRE volumes of magma (~ 4.0×10^6 m^3), implying that paroxysmal events can occur after the start of an apparently gentle effusive eruption. That eruption of such a magma volume could be enough to destabilize the LP magma likely reflects the volume of HP magma stored above the LP source region ([Bertagnini et al., 2003], [Francalanci et al., 2005] and [Métrich et al., 2005]). Applying the model for Stromboli's conduit of (Bonaccorso and Davis, 1999) and (Genco and Ripepe, 2010) estimated a conduit radius of 5 m by modelling of the tilt recorded during the volcano ordinary Strombolian activity. However, considering the model of Burton et al. (2009) for magma circulation and HP magma recycling within the volcano conduit during effusive phases, conduit effective diameter can vary, i.e. increases, due to HP magma removal for drainage through the eruptive vents. The removal has the effect of increasing the diameter of the conduit available to ascending magma, i.e., in our case, the LP magma. Hence, if we consider a LP storage zone at ~ 6–9 km deep ([Bertagnini et al., 2003], [Métrich et al., 2005] and [Pichavant et al., 2009]), and assume a cylindrical enlarged upper conduit (Burton et al., 2009) with an average radius of ~ 10 m, the threshold volume of ~ 4.0×10^6 m^3 represents a significant portion of the magma above the deep LP magma storage zone. After eruption of most of the HP magma stored above the LP storage zone, LP magma ascends to near the surface where it decompresses explosively. This is confirmed by the composition of lavas erupted after the second half of March (Landi et al., 2009), that can be explained by minor mixing between the LP magma rising through the upper magmatic system during the 15 March paroxysm and the relatively degassed residing HP magma.

However, depressurization of the supply system before the paroxysms occurred progressively. Both 2002–2003 and 2007 eruptions started with abrupt draining of a small “plug”, made of HP magma and solid rock as the NE cone was breached (Fig. 4b–c), allowing conduit magma to drain from the eruptive fissures. This breaching lowered the top of the magma column by ~ 200–300 m (Fig. 4c), decompressing both the upper conduit (0.8–2 km depth, Fig. 1) and, as evidenced by ground deformation observations (Bonaccorso et al., 2008), the vertically-extended intermediate storage zone, located between 2 and 4 km depth (Fig. 1). The intermediate reservoir connects the LP magma storage zone (tapped by the paroxysms and extending below 4 km depth; [Bertagnini et al., 2003] and [Métrich et al., 2005]) with the upper conduit (Fig. 1), where expanding gas slugs drive the persistent Strombolian activity (Burton et al., 2007).

In both 2002–2003 and 2007, the conduit breaching corresponds to near instantaneous pressure drop of ~ 4–6 MPa, disturbing the magmastatic equilibrium and promoting lava effusion. Days/weeks after breaching, further drainage of lava occurred via vents that opened along the Sciara del Fuoco, enhancing the depressurization of the shallow plumbing system. The estimated DRE effusion rates of ~ 0.5 and 1.5 $m^3 s^{-1}$ prior to both paroxysms exceeded the characteristic magma supply rate to the conduits (~ 0.23 $m^3 s^{-1}$ DRE from Burton et al., 2007), reflecting a significant perturbation of the plumbing system. This is consistent with a significant increase of the SO_2 flux from the long-term average value of 150–200 Mg day^{-1} to ~ 620 Mg day^{-1} during the 2007 eruption (Burton et al., 2009). Similarly, the CO_2/SO_2 ratio increased from an average of ~ 4.3 for the period January–November 2006 to ~ 21 during the effusive eruption (Aiuppa et al., 2009). This was interpreted as the result of an increased contribution of volatiles from the intermediate-deep storage region (Aiuppa et al., 2009) to the upper conduit. Thus, the shallow storage zone can release more volatiles when it is filled by gas-rich magma from deeper levels, implying lengthening of the LP magma bubbly column.

Pichavant et al. (2009), carried out high-pressure laboratory experiments on Stromboli basalts in presence of fluids and found that even the typical Strombolian explosions must include a component of fluids sourced from 150 to 200 MPa, corresponding to depths of ~ 6–9 km, i.e. to the LP deep storage region (Fig. 1). Thus, it is plausible that this region was increasingly tapped for volatiles during the effusive eruptions of 2002–2003 and 2007. We suggest that magma withdrawal from the intermediate magma storage zone by the effusive eruptions led progressively to decompression of the deep LP storage magma in a manner analogous to that described for Kīlauea, where decompression of the summit magma chamber due to a diking event, resulted in exsolution of volatiles and an increased gas flux observed at the surface (Poland et al., 2009). In the case of Stromboli, this behaviour promoted by the ascent of volatile-rich LP magma, produced lengthening of the magma bubbly column, favouring disequilibrium expansion.

Considering that in 2003 and 2007 the paroxysms at Stromboli occurred after eruption of ~ 4×10^6 m^3 of magma, we propose that this cumulative volume might be the threshold corresponding to the critical decompression of the supply system allowing magma fragmentation. Withdrawal of this threshold magma volume tapped a small batch of LP magma which then ascended the conduit. The timescale of its transport to the surface could only have been from hours to days ([Calvari et al., 2006], [Calvari et al., 2010], [Harris et al., 2008] and [Polacci et al., 2009]). The volumes involved in the paroxysms, i.e. « 10^6 m^3 (Bertagnini et al., 1999), reflect the critical balance between magma storage, crystallisation, degassing, and pressure evolution. Furthermore, the fact that the threshold erupted volume required to trigger paroxysms in both 2003 and 2007 was similar suggests that the geometry and capacity of the upper conduit and intermediate storage system varied little over this period.

The 2002–2003 and 2007 cases show that the incubation time for a paroxysm depends on the effusion rate. In 2003, a mean eruption rate of 0.5 $m^3 s^{-1}$

([Calvari et al., 2005a], [Calvari et al., 2005b] and [Lodato et al., 2007]) resulted in a paroxysm after ~ 3 months of lava effusion, whereas a mean eruption rate of 1.5 $m^3 s^{-1}$ in 2007 (Calvari et al., 2010) produced a paroxysm after only two weeks. So long as the volcano maintains its present subsurface storage configuration, we infer that it will be possible to use the same threshold volume to forecast future explosive paroxysmal events.

6. Concluding remarks

Analysis of the 2002–2003 and 2007 eruptive episodes on Stromboli suggests that paroxysms can be triggered as a result of the progressive decompression of the conduit system. That a similar quantity of dense lava – approximately 4×10^6 m^3 – was erupted prior to paroxysm in each case hints at the operation of a threshold mechanism. We have argued here that the lava effusion slowly decompresses the magma supply system, acting to extend the depth of the bubbly magma column in the conduit. This promotes fragmentation of the LP magma that has been tapped by the conduit system from its storage zone at 6–9 km depth. Provided the magmatic system is relatively stable in terms of geometry, magma composition, and supply rate (and Stromboli has demonstrated a high degree of stability over two millennia; Rosi et al., 2000), the timing of paroxysms may be estimated on the basis of daily effusion rate measurements. The use of this threshold during future effusive eruptions at Stromboli could represent a significant step forward in predicting paroxysmal events and prove decisive for civil protection purposes. The slow decompression mechanism and similar threshold criteria may also be relevant to other volcanoes that experience episodes of Strombolian eruption, lava effusion and paroxysms.

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Figures

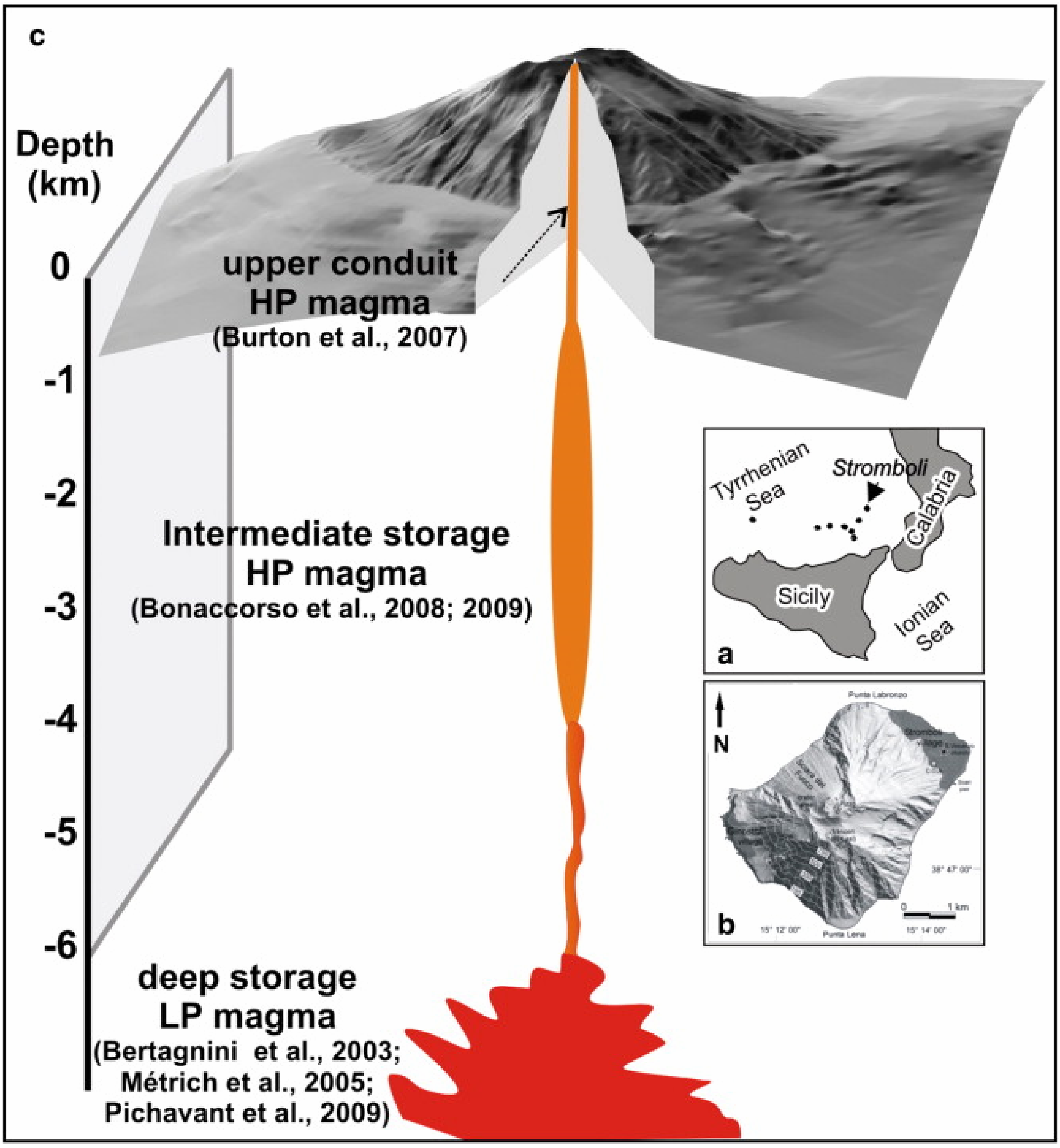

Fig. 1. : (a) Aeolian Islands and position of Stromboli in the southern Tyrrhenian Sea. (b) Map of Stromboli island. (c) Simplified section of Stromboli feeding system, showing the upper conduit extending from the magma surface (750 m a.s.l. corresponding to the elevation of the summit craters) to ~ 2 km b.s.l. (Burton et al., 2007), and the intermediate storage system (2–4 km depth; [Bonaccorso et al., 2008] and [Bonaccorso et al., 2009]). These both contain HP magma, whereas the deep magma storage zone, below 6 km depth, contains LP magma (e.g., [Bertagnini et al., 2003], [Métrich et al., 2005] and [Pichavant et al., 2009]).

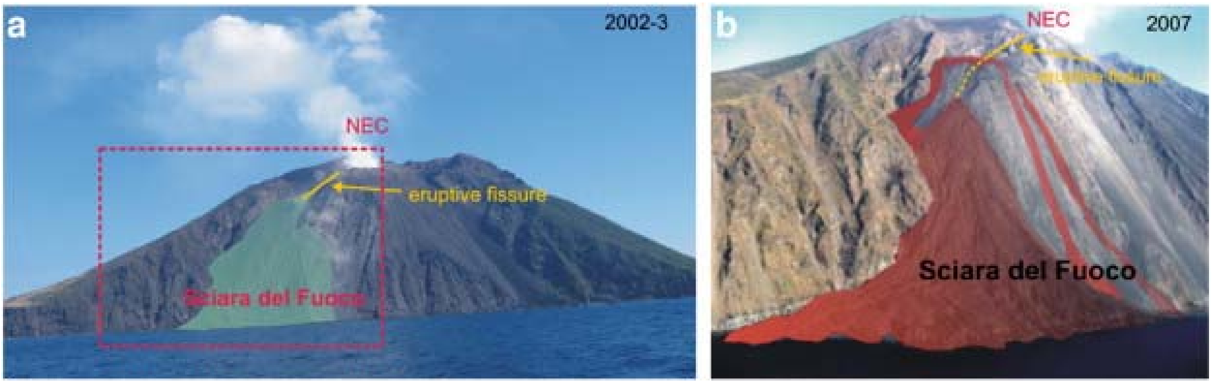

Fig. 2. : (a) Photograph of Stromboli island taken from the north on 8 April 2003, showing the Sciara del Fuoco, the north-east summit crater (NEC), the 2002–2003 eruptive fissure (in yellow) and lava flow field (in green). The red dotted square indicates the area shown in b. (b) Photograph of the Sciara del Fuoco taken from the north on 16 July 2007, showing the NEC, the 2007 eruptive fissure (in yellow) and lava flow field (in red).

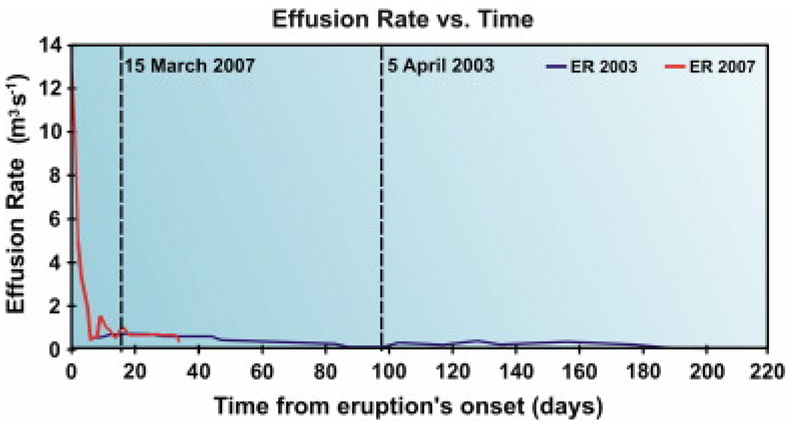

Fig. 3. Comparison of the effusion rates ($m^3 s^{-1}$) measured during the 2002–2003 ([Calvari et al., 2005a], [Calvari et al., 2005b] and [Lodato et al., 2007]) and the 2007 (Calvari et al., 2010) eruptions vs. time (days) from eruption's onset. Note that for both eruptions effusion rate values are here reported as 7-day-moving averages.

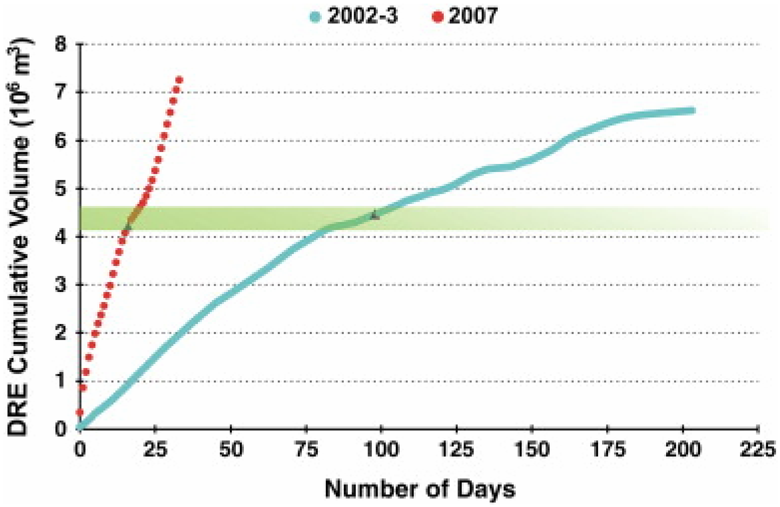

Fig. 4. Graph of the cumulative DRE volumes of erupted lava for both the 2002–2003 (blue line) and 2007 (red dots) *vs*. time since the eruption onset. In both time-series, the green triangles indicate the cumulative volumes of lava emitted by 5 April 2003 (4.4×10^6 m^3) and 15 March 2007 (4.2×10^6 m^3), i.e., the dates of paroxysms. The green band highlights the similarity of the two cumulative volumes. Data recalculated after [Calvari et al., 2005a], [Calvari et al., 2005b], [Calvari et al., 2010], [Harris et al., 2005] and [Lodato et al., 2007].

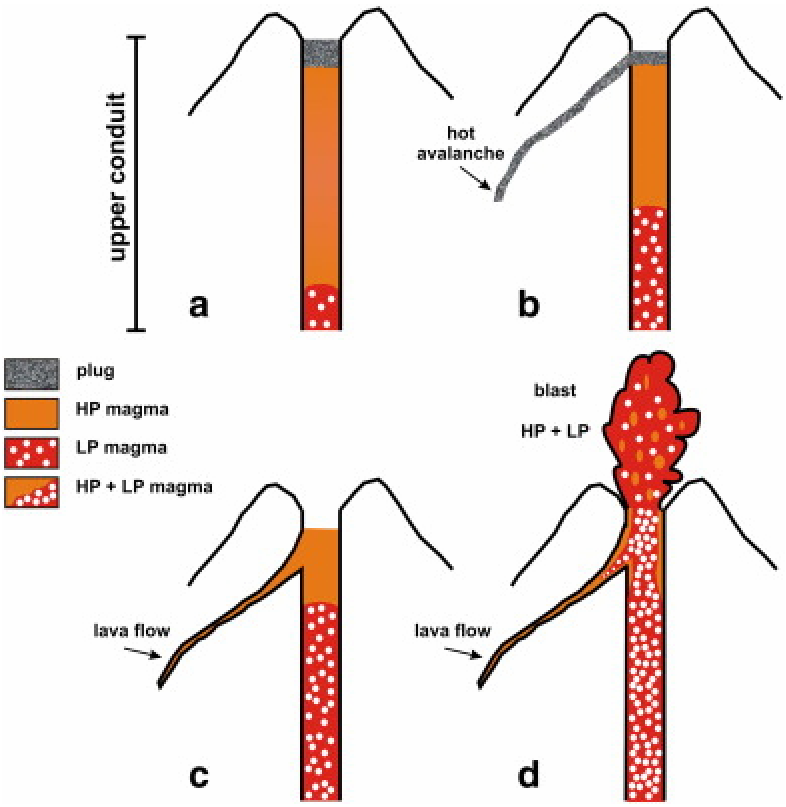

Fig. 5. Sketch showing the upper conduit of Stromboli, with phases of less-porphyritic (LP) magma rising, and its relationships with the high-porphyricity (HP) magma. (a) The upper conduit before the onset of an effusive eruption. (b) The plug removed during the initial phases of an effusive eruption (crater breaching and hot avalanche spreading). (c) Effusive vent opening and lava flow draining the upper, HP magma column. (d) LP magma erupting explosively (paroxysm) and being drained through the effusive vent, mixing with the HP magma.

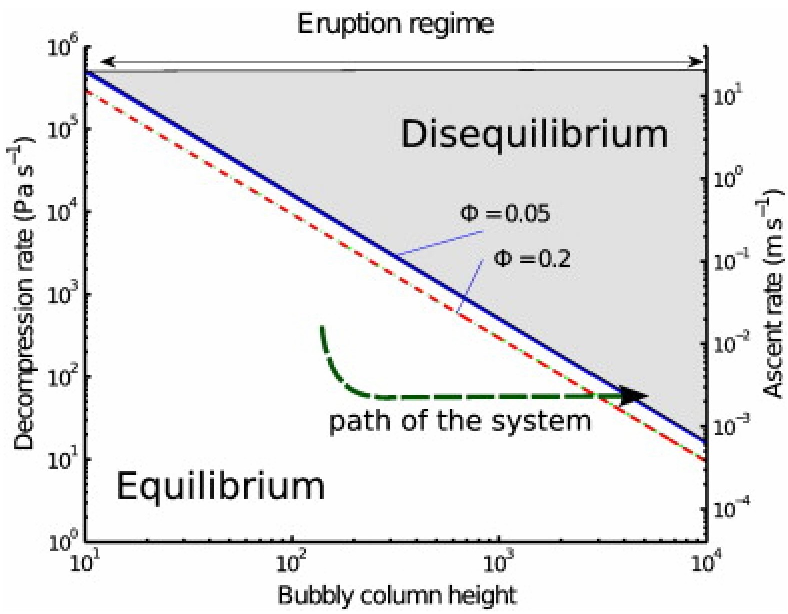

Fig. 6. Eruption regime as a function of decompression rate and height of the bubbly magma column. The solid and the dashed lines correspond to vesicularity of $\Phi = 0.05$, and $\Phi = 0.2$, respectively. The grey area represents the space of parameters where disequilibrium expansion, and possibly fragmentation, is favoured. After a fast initial eruptive phase, the rate of lava emission in 2003 and 2007 stabilises around 1 $m^3\ s^{-1}$, meaning that more volatile-rich LP magma volumes from the deeper storage system ascend with velocity of about 3 mm s^{-1}, equivalent to a decompression rate of ~ 90 Pa s^{-1} (a conduit radius of 10 m and magma density $\rho = 2500$ kg m^{-3} are assumed in this calculation). If this decompressed magma vesiculates, then the height of the bubbly magma column increases until a threshold is overcome (green arrow) and the system experiences disequilibrium expansion. After Namiki and Manga (2006), (see equation 1 in our text), using the pressure of the gas outside the bubbles during the expansion at $P_{Ot} = 10^5$ Pa (atmospheric pressure), and the initial pressure of the gas inside the bubbles $P_{Gi} = \rho gh(1 - \Phi)$.

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Table 1. Catalogue of paroxysms at Stromboli over the last century, based on Barberi et al. (1993). Several occurred in association with effusive eruptions, including the 2002–2003 and 2007 eruptions.

Date of paroxysms	Effects	Notes	Total erupted lava volume (m^3)	References
11–16 July 1906	Hot avalanche, vegetation ignited			Barberi et al., 1993
27 April 1907	Ash fall up to Messina, acid rain, houses damaged by air shock			Barberi et al., 1993
13 November 1915	Fallout of ash, bombs and light scoriae (pumice?), vegetation ignited, avalanche	Paroxysm during lava flow output	Unknown	Perret, 1916
4 July 1916	Fallout of ash, bombs and scoriae, vegetation ignited			Barberi et al., 1993
22 May 1919	1000 kg bombs fell on the village of Stromboli; 4 deaths; 20 injured			Barberi et al., 1993
11 September 1930	Hot avalanche and bombs fell on Ginostra, blocks and light scoriae (pumice?), 150 kg blocks fell on the village of Stromboli, tsunami and lava flows, 6 deaths, 22 injured		Unknown	Rittmann, 1931
22 October 1930	Lava fountains, vegetation ignited	Paroxysm during lava		Barberi et al., 1993

Date of paroxysms	Effects	Notes	Total erupted lava volume (m³)	References
		flow output		
2 February 1934	Blocks fell near Stromboli village, ash fall caused damage to houses			Barberi et al., 1993
31 January 1936	Block and ash fallout, air shock, secondary lava flows, vegetation ignited, a several houses damaged	Paroxysm during lava flow output	Unknown	Barberi et al., 1993
26–27 October 1936	Formation of 3 plumes, ash fallout			Barberi et al., 1993
22 August 1941	Blocks fell near villages, lava fountains 1 km high, vegetation ignited, air shock caused some damage to houses			Barberi et al., 1993
3 December 1943	Block and ash fallout, vegetation ignited, houses damaged	Paroxysm during lava flow output		Barberi et al., 1993
20 August 1944	Plume 2 km high, hot avalanche at Forgia Vecchia, tsunami			Barberi et al., 1993
20–23 October 1950	Block and ash fallout, vegetation ignited			Barberi et al., 1993
1 February 1954	Ash fallout, hot avalanche, tsunami	Paroxysm during lava		Barberi et al., 1993

Date of paroxysms	Effects	Notes	Total erupted lava volume (m^3)	References
		flow output		
5 April 2003	Plume 2 km high, pyroclastic flows, houses damaged at Ginostra	Paroxysm during lava flow output	~ 13×10^6	[Calvari et al., 2005a], [Calvari et al., 2005b] and [Calvari et al., 2006]
15 March 2007	Plume ~ 2.5 km high, pyroclastic flows, fire fountaining	Paroxysm during lava flow output	~ 7.1×10^6 ~ 8.9×10^6	Calvari et al., 2010 Neri and Lanzafame, 2009