Unusually large magmatic CO_2 gas emissions prior to a basaltic paroxysm

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[1] The low-intensity activity of basaltic volcanoes is occasionally interrupted by short-lived but energetic explosions which, whilst frequently observed, are amongst the most enigmatic volcanic events in Nature. The combination of poorly understood and deep, challenging to measure, source processes make such events currently impossible to forecast. Here we report increases in quiescent degassing CO_2 emissions (>10,000 t/day) prior to a powerful explosive event on Stromboli volcano on 15 March 2007. We interpret such large CO_2 flux as being sourced by passive gas leakage from a deeply (>4 km) stored magma, whose depressurization, possibly caused by the onset of an effusive eruption on 28 February 2007, was the explosion trigger. Our observations suggest that continuous CO_2 flux monitoring may allow anomalously large explosions to be accurately forecast at basaltic volcanoes. **Citation:** Aiuppa, A., M. Burton, T. Caltabiano, G. Giudice, S. Guerrieri, M. Liuzzo, F. Murè, and G. Salerno (2010), Unusually large magmatic CO_2 gas emissions prior to a basaltic paroxysm, *Geophys. Res. Lett.*, *37*, L17303, doi:10.1029/2010GL043837.

1. Introduction

[2] Basaltic volcanoes are normally benign geological features that emit gases, enrich local soils, and provide spectacular demonstrations of Nature's power during effusive and mildly-explosive eruptions. Occasionally, however, highly energetic explosions are observed, which endanger observers, local populations and infrastructure. These "paroxysms" consist of violent cannon-like gas bursts typically lasting seconds to minutes, and producing up to ~km high eruptive columns and fallout of coarse material over relatively large dispersal areas. In contrast to Hawaiian- and Strombolian-style explosions, which have been the subject of extensive theoretical [*Wilson and Head*, 1981; *Jaupart and Vergnoille*, 1989], laboratory [*Jaupart and Vergnoille*, 1989] and field [*Allard et al.*, 2005; *Burton et al.*, 2007a] studies, the processes which can induce basaltic paroxysms are not well constrained [*Allard*, 2010]. These highly impulsive explosions disrupt the quiescent degassing activity of open-vent volcanoes without any evident warning or precursory change in surface activity, possibly because, unlike classic vulcanian explosions [*Self et al.*, 1979], they are produced deep in the volcano's plumbing system [*Métrich et al.*, 2010].

[3] Some of the most frequently observed anomalously energetic basaltic explosions occur on Stromboli volcano, an island in the Aeolian archipelago, Italy (Figure 1). Here, regular explosive activity, consisting of ~5–20 events per hour each producing ~1–20 m^3 of material in jets 100–200 m high, is interspersed ~twice per year by larger 'major' explosions (~100 m^3 of erupted material, plume >200 m high) and, rarer, extreme events termed "paroxysms" [*Barberi et al.*, 1993] of which the 5 April 2003 example produced ~10^5 m^3 of deposits and a column 4 km high [*Rosi et al.*, 2006]. Because of their poorly understood trigger mechanisms and sudden occurrence, these major explosions and paroxysms have no obvious precursor, and pose a significant hazard to the local population and visitors to Stromboli. Such events have in fact, over the past 100 years, resulted in several deaths (most recently in 2001 due to a major explosion [*Barberi and Carapezza*, 2001]), damage to buildings and infrastructure and an evacuation of the island [*Barberi et al.*, 1993].

[4] Two alternative categories of models have been proposed to account for the generation of paroxysms at Stromboli. *Bertagnini et al.* [2003] and *Métrich et al.* [2010], based on the evidence that low porphyritic and highly vesicular pumice fragments are systematically erupted during paroxysmal eruptions, first proposed that such events are triggered by the fast (in a few hours or days) ascent of volatile-rich (~2 wt. % CO_2 and 2.5–3.5 wt. % H_2O) basaltic magma blobs from a 7–10 km deep reservoir. More recently, *Allard* [2010] argued instead that Stromboli paroxysms are caused by the catastrophic release of CO_2-rich gas blobs, deriving from collapse of a previously accumulated bubble foam layer. While these models are divergent in some aspects, they do clearly suggest that the magmatic gas phase is a driving force for these deeply-sourced explosions, and that studying the deepest exsolving volatile species, CO_2, may reveal precursory changes in the magma plumbing system. This hypothesis, however, has never been experimentally verified.

[5] Here, we report on the first observations of CO_2 flux variations before, during, and after a paroxysm which occurred on Stromboli on 15 March 2007. Our dataset provides evidence for large increases in CO_2 plume flux prior to a paroxysm, and allows us to derive new constraints

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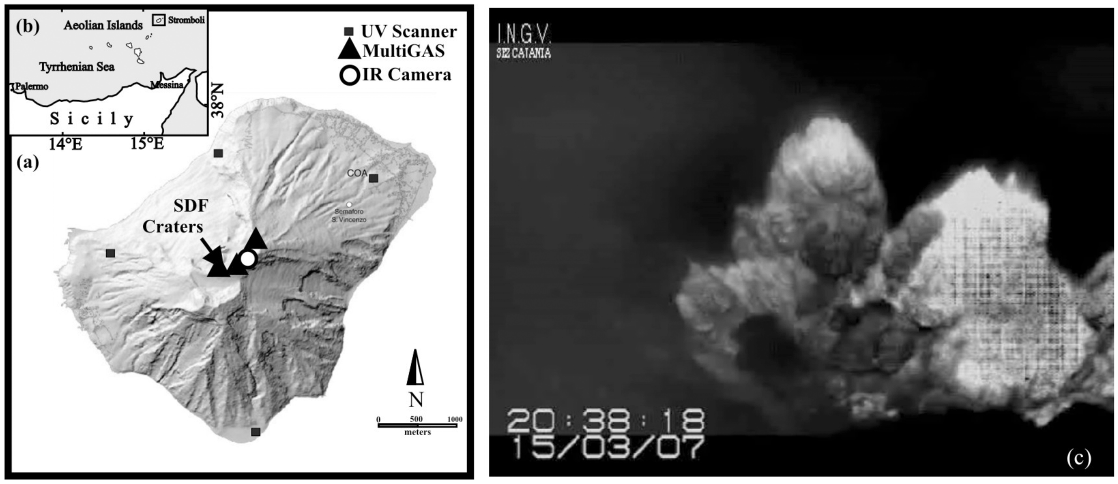

Figure 1. (a) Map of Stromboli with location of MultiGAS and UV scanner stations. (b) Position of Stromboli relative to mainland. (c) A frame from the INGV Catania infrared camera located above the summit craters of Stromboli during the onset of the paroxysmal event.

on the trigger mechanisms of these problematic volcanic manifestations.

2. The 15 March 2007 Paroxysm

[6] This violent explosive event started at 20:37:16 GMT with a cannon-like explosion (gas jet velocity ~100 $m \cdot s^{-1}$) from the Northeast and Central summit craters (Figure 1), producing a ~500 m high eruptive column and an ash plume rising to a maximum height of ~3500 m asl. The initial explosions (~6 minutes) were followed by a ~20 minute-long waning phase, characterised by smaller explosions and degassing. Overall, a shower of ballistic coarse clasts (bombs, blocks) and fallout lapilli affected the SW and NE sectors of the island, down to altitudes as low as 250m asl, close to the inhabited villages. Given its eruptive dynamics and volume (~$3.5 \cdot 10^4$ m^3 of juvenile materials were erupted (M. Rosi, personal communication, 2010)), the 15 March 2007 explosion is ranked among the "intermediate-scale" paroxysms [*Métrich et al.*, 2010], and was typically associated with the eruption of low porphyritic magma fragments ('golden' pumices). This event, similarly to the 5 April 2003 paroxysm, occurred whilst Stromboli was undergoing an effusive eruption from a vent in the upper Sciara del Fuoco depression (Figure 1) which produced ~7 million m^3 of lava by 15 March, and a total of ~11 million m^3 of lava between 28 February to 2 April 2007 in the absence of normal mild strombolian activity [*Marsella et al.*, 2009].

3. Results

[7] Before and after the 15 March paroxysm, we routinely measured the gas emission from Stromboli's craters using an integrated network of automatic devices allowing, for the first time on an active volcano, the simultaneous measurement of CO_2/SO_2 plume ratios (by three fully-automated Multi-GAS instruments [*Aiuppa et al.*, 2009]) and SO_2 fluxes (by four UV scanning spectrometers [*Burton et al.*, 2009]) (Figure 1). Combining results from these systems provides us with an unprecedented time series of daily magmatic CO_2 flux measurements. Typical errors for SO_2 fluxes are dominated by uncertainties in wind speed which at Stromboli are ~30%. Errors in the CO_2/SO_2 ratio are ~25%. The geometric combination produces a typical error of 39%.

[8] CO_2 fluxes are reported in Figure 2. In May–November 2006, the CO_2 flux was relatively low at 400 t/day. In December 2006, a brief but significant increase was

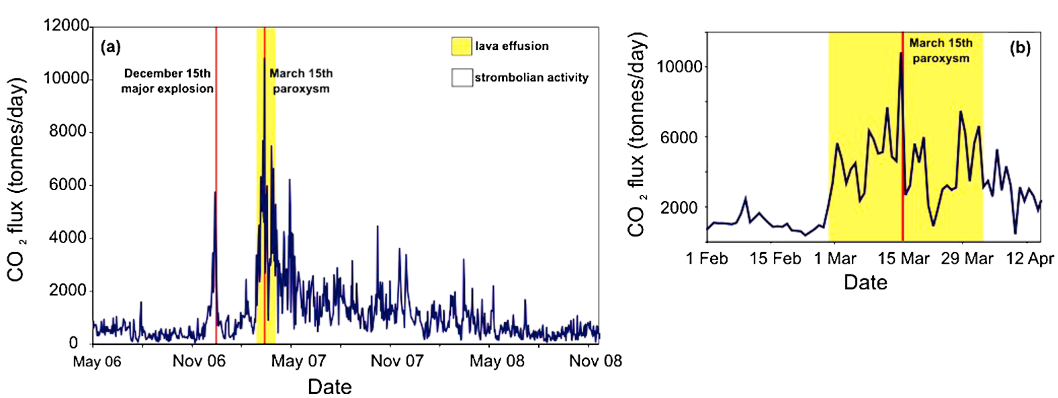

Figure 2. (a) Daily averages of CO_2 fluxes (in tonnes per day) from Stromboli's summit crater plume, from May 2006 to November 2008. (b) A detail of the 1 February to 15 April period. Typical errors for CO_2 fluxes are ~39%.

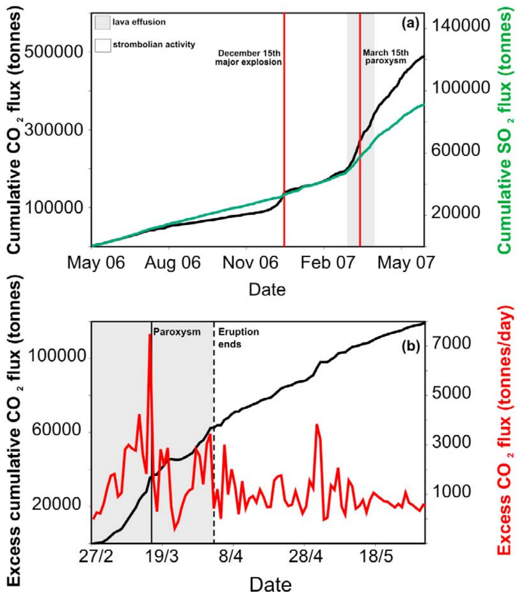

Figure 3. (a) Cumulative CO_2 and SO_2 fluxes (in tonnes) May 2006–July 2007. Distinct changes in the gradient of cumulative CO_2 flux are observed prior to 15 December and 15 March explosions. The cumulative CO_2 flux decelerated relative to SO_2 flux prior to 15 December, suggesting an episode of gas retention at depth prior to this major explosion. Note that the CO_2 scale (left) is 4 times greater than the SO_2 scale reflecting the time-averaged mass ratio of Stromboli's emissions [*Allard*, 2010]. (b) Excess CO_2 degassing from eruption onset until June 2007 was calculated as the difference between observed CO_2 fluxes and those expected using the time-averaged CO_2/SO_2 ratio and SO_2 flux measurements. Note the peak in excess CO_2 on 15 March prior to the paroxysm.

observed, leading to a major explosion on 15 December. After this event, the magma column within Stromboli's upper conduits began to rise, evidenced by greater explosive activity at the summit craters and increase in seismic tremor amplitude [*Ripepe et al.*, 2009], a trend that was also accompanied by an increase in the plume flux. During the two weeks prior to the 2007 eruption, the average SO_2 and CO_2 fluxes were 210 and 820 t/day respectively, maintaining the same average CO_2/SO_2 mass ratio (~4) of the period May 2006–January 2007. After the onset of lava effusion on 28 February, the CO_2 flux rapidly increased, reaching ~6000 t/day on 8 March. The elevated CO_2 flux was sustained for 7 days until 15 March, when the largest ever measured CO_2 flux (~11,000 t/day) at Stromboli preceded the paroxystic explosion by a few hours (Figure 2b). After the explosion, the CO_2 flux declined irregularly, with brief increases before the cessation of effusive activity on 2 April, and in May 2007. By September 2007, the CO_2 flux had declined to its pre-eruptive level of ~500 t/day.

4. Discussion and Conclusions

[9] The tenfold increase in gas fluxes prior to 15 March represents an unusually clear and large anomaly prior to a paroxysm, and suggests that increased gas fluxes are involved in triggering paroxysms and could be potentially useful indicators of elevated risk in the future. Our observations thus provide empirical evidence supporting the hypothesis [*Allard*, 2010] that real-time continuous gas monitoring may allow detection of precursory signals to such dangerous explosions.

[10] During the course of the Stromboli 2007 crisis, daily updates on the CO_2 flux were provided to the DPC (Dipartimento di Protezione Civile) risk management team, providing an exceptional new constraint on the state of the volcano, and ultimately contributed to the decision to limit access to the volcano's summit, which mitigated against the potentially harmful effects of the 15 March explosion [*Barberi et al.*, 2009].

[11] Accepting that a link must have existed between the prodigious CO_2 emissions prior to 15 March and the paroxysm itself, our observations offer new hints on the trigger mechanisms of such events. Firstly, we infer from our data that the source of the anomalous CO_2 degassing phase must have been deep in the plumbing system, consistently with the hypothesised deep source area of the 15 March paroxysm [*Métrich et al.*, 2010]. The cumulative trends of Figure 3a clearly indicate that prior to the onset of the effusive eruption a clear increase in degassing took place, which then accelerated after the eruption began, with CO_2 flux increasing faster than SO_2 flux. Average SO_2 and CO_2 fluxes during the eruption were 610 and 4200 t/day, respectively ~3 and 5 times their pre-eruptive values. The increase in SO_2 flux is explained by augmented magma supply to the conduit system of Stromboli [*Burton et al.*, 2009], but such a process, if acting in isolation, should produce a similar increase in CO_2 degassing, not the relatively larger CO_2 flux we observed. We conclude that a further process, favouring excess CO_2 gas transfer from depth, must have played a decisive role.

[12] Since SO_2 is extensively degassed from Stromboli magmas at pressures lower than ~100–150 MPa [*Métrich et al.*, 2010], the observation of disproportionately high CO_2 fluxes (relative to SO_2 flux) requires a degassing magma feeding the pre-paroxysmal gas emissions located at equivalent magmastatic depths greater than ~4 km. Using the time-averaged CO_2/SO_2 mass ratio of ~4 of Stromboli gas emissions [*Allard*, 2010] (we observed a very similar ratio in May–November 2006, prior to the effusive eruption), we may quantify the excess CO_2 flux, as shown in Figure 3b. This shows the rapid increase in cumulative excess CO_2 immediately prior to the paroxysm, reaching 36,000 tonnes on 15 March.

[13] We note that while aspects of both a gas-trigger [*Allard*, 2010] and a magma-trigger [*Bertagnini et al.*, 2003; *Métrich et al.*, 2010] model are in agreement with our observations, ultimately neither model is perfectly consistent with the degassing measurements prior to the paroxysm. Examination of the foam accumulation model proposed by *Allard* [2010] shows that our pre−15 March excess CO_2 fluxes might be viewed as hints of gradual foam leakage before the explosion. Such quiescent gas leakage from a growing foam has indeed been observed in laboratory experiments of basaltic explosions [*Jaupart and Vergnoille*, 1989], and is consistent with predictions of physical models [*Jaupart and Vergnoille*, 1989; *Woods and Cardoso*, 1997; *Phillips and Woods*, 2001]. *Allard* [2010] discusses several mechanisms through which such foams may gradually develop at Stromboli by retention (at some discontinuity in

the deep plumbing system) of a relatively minor fraction of the volcano's long-term gas supply. We note however that while the 15 December 2006 explosion is perfectly consistent with CO_2 flux retention, when the CO_2 flux clearly decelerated relative to SO_2 flux (see Figure 3a), no clear evidence for this retention exist prior to 15 March. On the contrary, an increasing gas release in the absence of a period of gas retention seems to prevail.

[14] In *Métrich et al.* [2010] model deep, rapid magma ascent is the main trigger for the paroxysm, which could create the observed excess CO_2 degassing upon decompression of the rising volatile-rich magma. However, the sustained high CO_2 fluxes observe since 8 March (Figure 2b) would require that the crystal-poor magma started its ascent from its ~8 km deep reservoir [*Métrich et al.*, 2010] at least one week before the paroxysm, thus rising at an average speed of 0.013 $m \cdot s^{-1}$. This estimated ascent rate would be significantly slower than previously estimated (0.05–0.55 $m \cdot s^{-1}$ [*Bertagnini et al.*, 2003]) based on the size of olivines crystallizing from the decompressing magma and would be inconsistent with the textural features of pumices (nearly aphyric nature, lack of large and coalescing vesicles), all pointing to very short (hours) magma travel time from reservoir to surface [*Polacci et al.*, 2009]. In addition, to become the source of our CO_2 flux increases, the decompressing magma would necessarily have ascended in open system conditions, contrary to melt inclusion and textural evidence of closed-system ascent [*Métrich et al.*, 2010].

[15] We conclude that neither the foam accumulation [*Allard*, 2010] or fast magma ascent [*Métrich et al.*, 2010] model is consistent with all the observed degassing behaviour prior to the 15 March paroxysm. We instead highlight that the increasing trend in gas flux started concurrently with the onset of lava effusion (Figure 2). We thus propose that the lava effusion produced a general de-pressurization of the deep plumbing system, and was the causal factor of both excess CO_2 degassing, and ultimately the paroxysm.

[16] We identify two main sources of depressurization. First, the rapid emptying (on 28 February) of ~2 million m^3 of vesiculated lava [*Marsella et al.*, 2009] from the upper conduits produced a rapid drop in the magmatic column within the conduit, from ~650 m asl to ~400 m asl (the height of the effusive vent). This 250 m drop in the magma column was associated with the cessation of explosive activity and decrease in seismic tremor amplitude [*Ripepe et al.*, 2009]. The pressure decrease associated with the removal of a 250 m magmatic column is 3.4 MPa, assuming a 50% vesiculated magma with density 2700 kgm^{-3}. Secondly, the effusion of degassed magma from 28 February perturbed the normal magma circulation observed at Stromboli, in which magma ascends, degasses and then descends back down the conduit [*Stevenson and Blake*, 1998]. The consequent absence of a degassed magma source produced an increase in the effective conduit diameter occupied by ascending magma, and reduced the average density of magma in the conduit [*Burton et al.*, 2009]. This density reduction progressively extended down the conduit as resident dense (~2700 kgm^{-3}) degassed magma, sinking within the conduit prior to the eruption, continued its descent and was replaced by vesiculated magma (density ~1350 kgm^{-3}) destined to erupt. The daily dense degassed magma removal rate at Stromboli is normally 0.2 $m^3 s^{-1}$ or 17280 m^3/day [*Burton et al.*, 2007b]. Fluid dynamical calculations suggest that sinking degassed magma would descend with velocity of ~0.05 ms^{-1} [*Burton et al.*, 2007b], implying a daily length substitution of 4320m and effectively complete removal 1–2 days after eruption onset, in coincidence with the start of excess CO_2 degassing.

[17] The combination of a density decrease and magma column drop produced a significant depressurization, for which there is geodetic evidence [*Bonaccorso et al.*, 2008], and promoted further degassing into the pre-existing 2–20% by volume [*Allard*, 2010] gas phase present within the deeply stored magma. The consequent jump in vesicularity increased the permeability of the upper low porphyritic magma, allowing quiescent, open-system, CO_2-rich degassing for 2 weeks prior to the 15 March paroxysm. This voluminous, quiescent degassing process produced a destabilization of the crystal-poor magma reservoir, leading to the paroxysm.

[18] This process is quite distinct from that which produced the major explosion of 15 December 2006. In that event retention and then rapid release of CO_2-rich gas preceded the explosion, consistent with the foam accumulation model proposed by *Allard* [2010]. In the 15 March paroxysm depressurization due to lava effusion produced a quiescent, open degassing system that promoted CO_2 gas loss and destabilised the low porphyritic magma reservoir, producing the rapid ascent of magma from depth that caused the paroxysm.

[19] In both cases large increases in CO_2 emissions were observed prior to the explosion, suggesting that this could be a general indicator for imminent powerful explosive activity at basaltic volcanoes. The combination of relatively cheap instruments for the measurement of both SO_2 flux and CO_2/SO_2 ratios now allow the possibility of this measurement technique to be widely applied for monitoring and risk mitigation.

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References

Aiuppa, A., C. Federico, G. Giudice, G. Giuffrida, R. Guida, S. Gurrieri, M. Liuzzo, R. Moretti, and P. Papale (2009), The 2007 eruption of Stromboli volcano: Insights from real-time measurements of the volcanic gas plume CO_2/SO_2 ratio, *J. Volcanol. Geotherm. Res.*, *182*, 221–230, doi:10.1016/j.jvolgeores.2008.09.013.

Allard, P. (2010), A CO_2-rich gas trigger of explosive paroxysms at Stromboli volcano, Italy, *J. Volcanol. Geotherm. Res.*, *189*, 363–374, doi:10.1016/j.jvolgeores.2009.11.018.

Allard, P., M. Burton, and F. Murè (2005), Spectroscopic evidence for a lava fountain driven by previously accumulated magmatic gases, *Nature*, *433*, 407–410, doi:10.1038/nature03246.

Barberi, F., and M. L. Carapezza (2001), Major explosion at Stromboli kills a tourist on 20 October 2001, *Bull. Global Volcanism Network*, *26*, 2–3.

Barberi, F., M. Rosi, and A. Sodi (1993), Volcanic hazard assessment at Stromboli based on review of historical data, *Acta Vulcanol.*, *3*, 173–187.

Barberi, F., L. Civetta, M. Rosi, and R. Scandone (2009), Chronology of the 2007 eruption of Stromboli and the activity of the Scientific Synthesis Group, *J. Volcanol. Geotherm. Res.*, *182*, 123–130, doi:10.1016/j.jvolgeores.2008.09.019.

Bertagnini, A., N. Métrich, P. Landi, and M. Rosi (2003), Stromboli volcano (Aeolian Archipelago, Italy): An open window on the deep-feeding system of a steady state basaltic volcano, *J. Geophys. Res.*, *108*(B7), 2336, doi:10.1029/2002JB002146.

Bonaccorso, A., S. Gambino, F. Guglielmino, M. Mattia, G. Puglisi, and E. Boschi (2008), Stromboli 2007 eruption: Deflation modelling to infer shallow-intermediate plumbing system, *Geophys. Res. Lett.*, *35*, L06311, doi:10.1029/2007GL032921.

Burton, M., P. Allard, F. Muré, and A. La Spina (2007a), Magmatic gas composition reveals the source depth of slug-driven Strombolian explosive activity, *Science*, *317*, 227–230, doi:10.1126/science.1141900.

Burton, M., H. Mader, and M. Polacci (2007b), The role of gas percolation in quiescent degassing of persistently active basaltic volcanoes, *Earth Planet. Sci. Lett.*, *264*, 46–60, doi:10.1016/j.epsl.2007.08.028.

Burton, M., T. Caltabiano, F. Murè, G. Salerno, and D. Randazzo (2009), SO_2 flux from Stromboli during the 2007 eruption: Results from the FLAME network and traverse measurements, *J. Volcanol. Geotherm. Res.*, *182*, 214–220, doi:10.1016/j.jvolgeores.2008.11.025.

Jaupart, C., and S. Vergnoille (1989), The generation and collapse of a foam layer at the roof of a basaltic magma chamber, *J. Fluid Mech.*, *203*, 347–380, doi:10.1017/S0022112089001497.

Marsella, M., C. Proietti, A. Sonnessa, M. Coltelli, P. Tommasi, and E. Bernardo (2009), The evolution of the Sciara del Fuoco subaerial slope during the 2007 Stromboli eruption: Relation between deformation processes and effusive activity. *J. Volcanol. Geotherm. Res.*, *182*, 201–213, doi:10.1016/j.jvolgeores.2009.02.002.

Métrich, N., A. Bertagnini, and A. Di Muro (2010), Conditions of magma storage, degassing and ascent at Stromboli: New insights into the volcano plumbing system with interferences on the eruptive dynamics, *J. Petrol.*, *51*, 603–626, doi:10.1093/petrology/egp083.

Phillips, J. C., and A. W. Woods (2001), Bubble plumes generated during recharge of basaltic magma reservoirs, *Earth Planet. Sci. Lett.*, *186*, 297–309, doi:10.1016/S0012-821X(01)00221-7.

Polacci, M., D. R. Baker, L. Mancini, S. Favretto, and R. H. Hill (2009), Vesiculation in magmas from Stromboli and implications for normal strombolian activity and paroxysmal explosions in basaltic systems, *J. Geophys. Res.*, *114*, B01206, doi:10.1029/2008JB005672.

Ripepe, M., M. Delle Donne, G. La Canna, E. Marchetti, and G. Ulivieri (2009), The onset of the effusive eruption by an integrated geophysical network, *J. Volcanol. Geotherm. Res.*, *182*, 131–136, doi:10.1016/j.jvolgeores.2009.02.011.

Rosi, M., A. Bertagnini, A. J. L. Harris, L. Pioli, M. Pistolesi, and M. Ripepe (2006), A case history of paroxysmal explosion at Stromboli: Timing and dynamics of the April 5, 2003 event, *Earth Planet. Sci. Lett.*, *243*, 594–606, doi:10.1016/j.epsl.2006.01.035.

Self, S., L. Wilson, and I. A. Nairn (1979), Vulcanian eruption mechanisms, *Nature*, *277*, 440–443, doi:10.1038/277440a0.

Stevenson, D. S., and S. Blake (1998), Modelling the dynamics and thermodynamics of volcanic degassing, *Bull. Volcanol.*, *60*, 307–317, doi:10.1007/s004450050234.

Wilson, L., and J. W. Head (1981), Ascent and eruption of basaltic magma on the Earth and Moon, *J. Geophys. Res.*, *86*, 2971–3001, doi:10.1029/JB086iB04p02971.

Woods, A. W., and S. S. S. Cardoso (1997), Triggering basaltic volcanic eruptions by bubble-melt separation, *Nature*, *385*, 518–520, doi:10.1038/385518a0.

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