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First experimental evidence for the CO_2-driven origin of Stromboli's major explosions

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Abstract

We report on the first detection of CO_2 flux precursors of the till now unforecastable larger than normal ("major") explosions that intermittently occur at Stromboli volcano (Italy). Automated survey of the crater plume emissions in the period 2006–2010, during which 12 such explosions happened, demonstrate that these events are systematically preceded by a brief phase of increasing CO_2/SO_2 weight ratio (up to >40) and CO_2 flux (>1300 t/d) with respect to the time-averaged values of 3.7 and ~500 t/d typical for standard Stromboli's activity. These signals are best explained by the accumulation of CO_2-rich gas at a discontinuity of the plumbing system (decreasing CO_2 emission at the surface), followed by increasing gas leakage prior to the explosion. Our observations thus support the recent model of Allard (2010) for a CO_2-rich gas trigger of recurrent major explosions at Stromboli, and demonstrate the possibility to forecast these events in advance from geochemical precursors. These observations and conclusions have clear implications for monitoring strategies at other open-vent basaltic volcanoes worldwide.

1 Introduction

Steady or/and mildly explosive eruptive activity at many open-vent basaltic volcanoes is occasionally interrupted by sudden large-scale explosions that constitute a major hazard. These currently unforecastable discrete events thus raise dramatic issues to volcano hazard managers and pose still unanswered questions to volcanologists: what are the trigger mechanisms for such events? Could they be preceded, and hence forecasted, by signals detectable from monitoring networks?

Stromboli volcano (Fig. 1), in Southern Italy, is an archetype for this explosive pattern at open-vents basaltic volcanoes. Its regular activity consists of ~5–20 "Strombolian"-type mild explosions per hour, characterized by 50–200 m high jets of gas and lava clots that produce only ~1 m^3 of scoriae and ash (e.g. Chouet et al., 1974; Ripepe et al., 2008). Intermittently, however, this standard activity is interrupted by more energetic explosive events, which range in magnitude from (i) major explosions (~2–4 per year, jets >200 m high, ~100 m^3 of erupted material) to (ii) more powerful but rarer "paroxysmal explosions" (~1 every 5 years, km-sized columns, and ~10^4–10^6 m^3 of deposits) (Barberi et al., 1993; Bertagnini et al., 1999, 2003, 2008; Rosi et al., 2006). These latter explosions are very sudden and eject much coarser (including ballistic blocks) and more widely dispersed tephra than regular activity. They thus represent a great hazard to the thousands of visitors per year attracted by the spectacular activity of Stromboli and even, occasionally, to the inhabitants of the island. This high volcanic risk has motivated enhanced interest in the scientific community for a better understanding of both major explosions and paroxysmal events, focused on their dynamics (Rosi et al., 2006; Ripepe and Harris, 2008; Andronico and Pistolesi, 2010), triggering mechanisms (Métrich et al., 2005, 2010; Allard, 2010) and possible precursors (Falsaperla and Spampinato, 2003; Aiuppa and Federico, 200~~5~~).

The recent occurrence of two violent paroxysmal explosions, on 5 April 2003 and 15 March 2007, has deeply improved our state of knowledge for such events. In particular, detailed investigations of melt inclusions entrapped in olivine crystals of the erupted products have led to the conclusion that these paroxysmal explosions were produced by the rapid ascent and decompression of small batches of gas-rich, low porphyric (LP) basaltic magma (Métrich et al., 2005, 2010) – erupted at the surface as highly vesiculated "blond" pumice – from a 7–10 km deep magma storage zone (all depths being referred to as below summit vents, bsv). In contrast, the source mechanism of the "major" explosions is not yet understood, even though these are far more frequent and, therefore, potentially even more hazardous than paroxysmal events. Recently, Allard (2010) argued for a CO_2-rich gas trigger of most of these major explosions: periodic accumulation of deeply-derived CO_2-rich gas bubbles in the sub-volcano plumbing system would lead to the growth of bubble foams which, upon collapse, can trigger the fast ascent of large CO_2-rich gas slugs driving the explosions (Jaupart and Vergniolle, 1989; Woods and Cardoso, 1997; Menand and Phillips, 2007). According to Allard

(2010), major explosions should be heralded by increasing leakage of CO_2-rich gas as the bubble foam approaches instability (Jaupart and Vergniolle, 1989), and the magnitude of each explosion should be proportional to its source depth or/and the stored gas amount.

It is noteworthy that Aiuppa et al. (2010a) already detected large increases in Stromboli's CO_2 plume flux (>10 times larger than normal) during the 1–2 weeks preceding the 15 March 2007 paroxysmal explosion (Fig. 2a). These unusually large CO_2 emissions were interpreted as reflecting passive gas leakage from decompressing LP magma emplaced at >4 km depth, just prior to its eruption during the paroxysm (Métrich et al., 2010). In this paper, we report on CO_2 flux variations measured on top of Stromboli in the period 2006–2010, during which 12 major explosions occurred. We find that each of these explosions actually happened after a brief period (days to weeks) of increasing CO_2 flux at the crater, following a previous phase of reduced CO_2 emission. We show that this pattern is consistent with periodic accumulation and release of deeply-derived CO_2-rich bubbles in the plumbing system. Our observations thus demonstrate a key role of CO_2-rich gas in triggering these events, and provide the first experimental evidence in support to the model of Allard (2010). We finally discuss their implications for the forecasting of major explosions in the future.

2 Recorded explosive activity and methods

In a previous work (Aiuppa et al., 2010a), we have reported on results for the May 2006 to November 2008 period, focusing on observations made during the 2007 effusive eruption (27 February to 2 April) during which the 15 March 2007 paroxysmal explosion occurred. Here, we extend our observations to the following 3 years of Stromboli's activity, from July 2007 to July 2010, during which 12 major explosions took place (Fig. 2). All these events were highly impulsive, generally consisted of a sequence of cannon-like blasts from one vent or several vents simultaneously (Andronico and Pistolesi, 2010), and had durations of a few tens of seconds to a few minutes at most.

They showered the volcano slopes with coarse lithic blocks, lava bombs and pumice lapilli up to 1–2 km distance from the summit (Andronico and Pistolesi, 2010; Fig. 1), but without making casualties nor damages to human settlements. Pumiceous LP basaltic magma was erupted only during the strongest five explosions, on 3 May 2009, 8 and 24 November 2009, and 25 and 30 June 2010. These events were actually the largest in terms of pyroclastic tephra dispersal, erupted volumes, and recorded amplitude of syn-eruptive seismic and infrasonic signals (web reports from INGV-Catania and Università di Firenze). Figure 2 shows that, apart from isolated events (e.g., the 3 May 2009 explosion), most of the major explosions succeeded within relatively short intervals: 6–17 December 2008 (2 events), 8 November 2009 to 21 January 2010 (4 events), and 25–30 December 2010 (2 events). Such a clustering in their occurrence suggests a common source process or instability in the plumbing system.

Our daily record of the CO_2 plume flux from Stromboli summit crater (Fig. 2) has been obtained following the procedure previously described by Aiuppa et al. (2010a). The CO_2 plume flux is given by simultaneous measurement of the CO_2/SO_2 plume ratio (semi-continuous survey with three fully automated Multi-GAS instruments; Aiuppa et al., 2009) and the SO_2 mass flux, determined by a remotely-controlled network (Fig. 1) of four UV scanning DOAS spectrometers (Burton et al., 2009). CO_2 and SO_2 concentrations in the volcanic plume are measured and recorded every six hours, for 30 min and at a frequency of 9 seconds, during four sequential intervals per day (01:00–01:30, 07:00–07:30, 13:00–13:30 and 19:00–19:30). The typical error associated with our calculated CO_2 fluxes is ~40%.

3 Data analysis

Figure 2a shows the results for >4 years of daily survey of the CO_2 plume flux from Stromboli, which constitutes one of the most complete and systematic CO_2 flux record ever acquired on an active volcano. The most prominent feature of the dataset is the exceptional CO_2 degassing rate that characterized the February–April 2007 effusive eruption: the high (>6000 t/d) CO_2 fluxes during this period were attributed to a large supply of CO_2-rich gas bubbles from the deep LP magma reservoir (Aiuppa et al., 2010a, b), as a consequence of its likely depressurisation following copious lava drainage since 27 February 2007 (Bonaccorso et al., 2008). This depressurization-induced CO_2 degassing event was thus precursory to fast ascent and eruption of the LP magma during the 15 March 2007 paroxysm (Aiuppa et al., 2010a; Métrich et al., 2010). Figure 2a also shows that, as the 2007 effusive eruption ended on 2 April 2007, CO_2 fluxes progressively but slowly slowed down, recovering their pre-2007 eruption levels only by late summer 2008.

We thus consider the post-September 2008 period (Fig. 2b) as representative of the regular degassing regime of Stromboli. From the measured daily CO_2/SO_2 ratios and SO_2 fluxes we compute a cumulative degassing of ∼0.36 Mtons of CO_2 and ∼0.098 Mtons of SO_2 between September 2008 and July 2010. Over this period the CO_2/SO_2 mass ratio thus averaged ∼3.7 and the CO_2 emission rate ∼550 t/d (a factor ∼2 lower than the time-averaged value estimated by Allard (2010)). However, one also observes (Fig. 2b) that the CO_2 flux displayed wide temporal fluctuations (from 60 t/d to 7000 t/d) and, in particular, increased noticeably (>1300 t/d) during 4 main phases (I to IV in Fig. 2b) in which virtually all the major explosions have occurred.

In order to examine in detail the relationship between these phases of high CO_2 degassing and the occurrence of major explosions, we focus in Fig. 3 on the period from 22 January to 22 July 2010, during which 3 such events took place. This time interval starts just after a major explosion on 21 January that marked the end of the phase III (Fig. 2b). Figure 3 shows that over the entire period the SO_2 flux remained relatively steady and low (mean: 105 ± 46 t/d). In contrast, the CO_2 flux varied significantly in function of the explosive activity. After the 21 January explosion it dropped to a low level for about one month then moderately increased until a small-scale major explosion that occurred on 12 March (among the smallest scale events in the dataset; Ripepe, perso~~an~~l communication). Afterwards, it tended to decrease again and preserved a moderate level until early June 2010. Then, it began to sharply increase (phase IV) by a factor ≥3, keeping high values for ~2 weeks until 25 June when a strong major explosion happened (Fig. 3c). After this event, the CO_2 flux slowly decayed, but 5 days later a second major explosion succeeded on 30 June. The phase IV ended with an ultimate CO_2 flux peak increase, but without any consequent explosive event.

Since the SO_2 flux remained quite steady during the 6-months considered period, the CO_2 flux increases registered before and, especially, during that phase IV essentially reflect net increases of the CO_2/SO_2 ratio (from ~5 to >20) in Stromboli's bulk plume emissions, as shown in Fig. 3b. This is also verified by the composition of the gas phase driving the recurrent Strombolian-type explosions in the same period (Fig. 3a). As previously shown (Burton et al., 2007a), the gas phase driving the Strombolian explosions is richer in CO_2 than the non-explosive passive gas emission, with the latter contributing most of the bulk gas output and hence determining the bulk plume composition (Allard et al., 1994, Mori and Burton 2009). Our systematic determinations in January–July 2010 (using the technique detailed in Aiuppa et al., 2010b) actually demonstrate an increasing CO_2/SO_2 ratio (>40) also during single Strombolian outbursts prior to the strong 25 June major explosion (Fig. 3a). Therefore, we evidence that an anomalous CO_2-rich gas phase, recorded in both quiescent (~bulk) and explosive standard emissions, was reaching the surface days to weeks before this event. We emphasize that similar observations apply to the most significant major explosions in the period 2008–2010 (phases I to III; Fig. 3b), evidencing a systematic process. Owing to both our sequential analysis of the volcanic plume each day and the brief duration of major explosions, we did not get the chance to measure the CO_2/SO_2 gas ratio right during any of these event.

4 Discussion

Our observations, detailed in Figs. 2 and 3, provide experimental support to the proposed model by Allard (2010) that major explosions at Stromboli would be systematically anticipated by a phase of increasing CO_2 degassing, and that the magnitude of this enhanced degassing should scale to the size of the forthcoming explosion. Our dataset shows indeed that CO_2 flux increase prior to the 15 March 2007, by far the largest-scale event during the overall 2006–2010 period, was a factor ~10 greater than the increases recorded prior to any of the major explosions in 2008–2010 (Fig. 2). It therefore follows that smaller (but still hazardous) explosive events will be preceded by smaller and less obvious precursors. Although additional measurements are required to strengthen our conclusions, our present results already emphasise that major explosions at Stromboli (the strongest ones at least) are preceded by a CO_2 flux increase, and tend to cluster in periods when CO_2 is being degassed at rates exceeding a critical level, which we tentatively set at ~1300 t/d (Fig. 2b). This opens new promising perspectives for the forecasting of such events in future.

The association between major explosions and high CO_2 degassing phases also brings novel lines of evidence to constrain the source mechanisms of these events. Allard (2010) argued that CO_2 is heavily implicated in triggering these explosions. He pointed out that, due to their very high original CO_2 content (~2 wt %), Stromboli's magma batches likely coexist with a large fraction of CO_2-rich gas bubbles at crustal conditions. Combined with the low viscosity of Stromboli HK-basalt (~20 Pa s at 10 km depth; Allard, 2010), such a high CO_2 content should favour the segregation and hence separate ascent of deeply-derived CO_2-rich gas bubbles through the magma column. Differential bubbly gas flow across the magma column (quiescent degassing) is actually responsible for most the volcano gas discharge (Allard et al., 1994, 2008). However, bubble coalescence at depth is required to generate the large gas pockets or slugs whose fast upraise then bursting drive the periodic Strombolian-type explosions (Burton et al., 2007a) and probably the intermittent major explosions as well (Allard, 2010). One common mechanism able to generate large gas slugs through bubble coalescence is bubble accumulation at the roof of a magma ponding zone or at a feeder discontinuity (Jaupart and Vergniolle, 1989; Menand and Phillips, 2007). Beneath Stromboli, olivine-hosted melt inclusions indicate the presence of such discontinuities, potentially acting as "gas traps", at 7–10 km depth ~~below the summit vents (~~bsv~~)~~, where a main magma storage zone likely occurs, and at about the volcano-crust interface (2–4 km depth bsv), where magma may pond and CO_2-rich gas bubbles may accumulate to contents >5 wt % (Allard et al., 2008; Métrich et al., 2010). This shallow magma-gas ponding zone is the probable source area for the gas slugs producing the regular explosive activity (Burton et al., 2007a). If "gas trapping" regularly occurs at those discontinuities, the accumulation of CO_2-rich bubbles will lead to the growth of bubble-melt foam layers (Jaupart and Vergniolle, 1989; Woods and Cardoso, 1997; Menand and Phillips, 2007). When approaching a critical thickness such foams increasingly leak in a connected conduit, first passively, then catastrophically as they collapse and coalesce, generating large gas slugs that rapidly rise to the surface (Jaupart and Vergniolle, 1989). Allard (2010) proposed that Stromboli's major explosions may typically result from that process, however no field validation had yet been obtained to date.

We show below that our CO_2 flux dataset actually supports a process of gas bubble retention, foam leakage and slug-driven explosion. Figure 4a reports the cumulative masses of degassed SO_2 and CO_2 in the months preceding the 25 and 30 June major explosions. Note that the CO_2 scale (left axis) was fitted to be 3.5 times greater than the SO_2 scale (right), in order to clearly reflect the time-averaged CO_2/SO_2 weight ratio typical for the whole period from January to July 2010 (3.7; see above).

The mass of degassed SO_2 is a proxy for magma degassing and convective transport in the shallow (<3–4 km bsv) conduit system (Allard et al., 1994), because sulphur exsolves only in this shallow system (Métrich et al., 2010; Allard, 2010). Figure 4a shows a relatively flat cumulative trend for the SO_2 flux and, in particular, no appreciable change in its gradient prior to the 25–30 June explosions. This is fully consistent with the idea (Bertagnini et al., 1999; Allard, 2010) that the shallow magmatic system is not or very marginally involved in the generation of major explosions, as indicated by the lack of forerunners in surface volcanic activity and seismicity, and by the soon return to standard activity after each major explosion. We then conclude that the rates of SO_2 degassing and hence magma transport were in steady-state conditions during the months preceding the June 2010 major explosions.

Instead, a more dynamic scenario emerges when the CO_2 cumulative trend is considered in concert with SO_2. We note, in fact, that the SO_2 and CO_2 flux cumulative trends remained almost overlapping in the January–March 2010 period (the CO_2/SO_2 mass ratio remaining close to its time-averaged value of 3.7), but clearly diverged after the 12 March explosion, when the cumulative CO_2 flux decelerated relative to SO_2 flux. Since the CO_2 flux is a proxy for magma supply from the deep LP magma storage zone (Aiuppa et al., 2010b), and SO_2 flux is a proxy for magma supply from 2–4 km depth, we attribute this CO_2-specific deceleration to a phase of partial CO_2-rich bubble retention (and accumulation) somewhere at depth in the plumbing system. This CO_2 accumulation phase persisted until late May 2010 (Fig. 4a). From the magma flow rate constrained by SO_2 degassing, and the difference between the amount of CO_2 that would have been emitted for a steady CO_2/SO_2 of 3.7 and the actual amount of CO_2 degassed until late May, we calculate the retention of ~11,000 tons of CO_2 (Fig. 4b) in the system, likely accumulated in a growing foam layer. By early June 2010 the CO_2 flux accelerated with respect to the SO_2 flux (Fig. 4a), at a quite constant rate, suggesting that gas leakage from the foam was now prevailing over gas accumulation (Fig. 4b). This gas leakage did not provoke a significant change in the explosive regime of the volcano, suggesting that it was very gradual and did not produce significant coalescence events.

Strikingly, it was when the accumulated CO_2 mass had been nearly exhausted that the 25 June major explosion occurred (Fig. 4b). However, we also observe that, even though decaying after this event, the CO_2 flux (and thus the CO_2/SO_2 plume ratio; Fig. 3b, c) remained much higher than its mean background level in the following days and weeks, concomitantly with another major explosion on 30 June. Therefore, carbon dioxide in excess to its time-averaged supply rate was still available and being released for a while after the 25 June explosion.

It is noteworthy that we observe a similar (but smaller) cycle of CO_2 flux decrease then increase prior to the 12 March major explosion (Fig. 4b), despite (but coherent with) its lower energy and duration than the 25 and 30 June events. We thus conclude that the trends of decreasing followed by increasing CO_2 flux in the days or weeks preceding major explosions are fully compatible with passive gas leakage from a previously accumulated, increasingly instable bubble foam layer, soon destined to erupt (Jaupart and Vergniolle, 1989; Woods and Cardoso, 1997; Phillips and Woods, 2001).

Further illustration of this pattern is provided by Fig. 5, in which we have plotted the "normalised" cumulative CO_2 and SO_2 trends for 5 different periods of activity which all ended with at least one major explosion in the period 2006–2010. The horizontal scale describes the "normalised" time elapsed since a previous explosive event, at the beginning of which we assume the clock of "gas accumulation" in the system is reset to 0; in other words, the time lag between 0 and 1 denotes the repose interval between one explosive phase and the following, and is ultimately the period over which a complete cycle of gas bubble accumulation-leakage may occur. We find that the normalised cumulative gas flux trends show similar behaviour in all the 5 considered intervals: all cumulative SO_2 flux curves describe strikingly similar flat trends, while the cumulative CO_2 flux trends show (clearly in 4 of the 5 cases) a phase of deceleration (relative to the SO_2 flux), followed by an acceleration prior to (at $t > 0.8$) the onset of a new explosive phase ($t = 1$). Such similarities in the shapes and timing of the cumulative gas flux curves highlight a systematic and reproducible behaviour in the volcano degassing regime, strongly supporting that a recurrent sequence of CO_2-rich gas accumulation, leakage and then explosive release regulates the periodical occurrence of major explosions at Stromboli, as actually proposed by Allard (2010).

However, a novel and striking implication of our results is that, in terms of mass balance, passive CO_2 bubble release due to foam leakage before a major explosion could by far prevail over instantaneous explosive gas release during the event itself (Fig. 4b). In other words, slug genesis by foam collapse would involve a comparatively minor quantity of the accumulated gas, and the explosions would represent brief ultimate events superimposed on a dominant process of quiescent gas drainage from the plumbing system. This unexpected observation does not fit well with the foam collapse model, in which much of the foam empties upon collapse (Jaupart and Vergniolle, 1989). Its quantitative interpretation will require additional measurements and falls beyond the scope of this paper. Here we just outline that the behaviour of a bubble foam over time strongly depends on the geometry of the gas accumulation zone, on the evolution of the gas supply rate from depth, and on the balance between the rates of foam growth and foam leakage (Jaupart and Vergniolle, 1989). These latter two rates may even equilibrate when the total gas flux approaches a critical value, thus maintaining the foam in nearly steady sate. Beneath Stromboli, whose eruptive regime involves the generation of small slugs every 15 min on average (driving the Strombolian explosions) and of larger slugs 1–3 times per year (producing the major explosions), one cannot exclude that a bubble foam layer (or bubble foams) persistently exist at depth, whose leakage could contribute to the time-averaged CO_2 emission rate of 6.4 kg s^{-1} (550 t/d). In that case, much more gas could be available for generating a major explosion than inferred, for instance, from our data for cumulative CO_2 storage prior to the 25 June 2010 major explosion (Fig. 4b).

5 Conclusions

We have analysed a >4 years long record of systematic (daily) measurements of SO_2 and CO_2 gas fluxes from Stromboli volcano in 2006–2010. The results show that the major explosions which punctuate the volcano's regular (mildly explosive) activity apparently cluster in periods when CO_2 is emitted at a higher rate than normal (>1300 t/d). Inspection of gas flux cumulative trends reveals that these explosions appear to be systematically preceded by cycles of CO_2 retention (CO_2 flux decelerates relative to SO_2 flux) and then passive release (CO_2 accelerates relative to SO_2). These cycles are compatible with phases of accumulation and then leakage of a bubble-melt foam layer at depth, until its sudden collapse and the generation of CO_2-rich gas pockets which rapidly rise to the surface and produce a major explosion. Our observations are thus fully consistent with the proposed model (Allard, 2010) of a CO_2-rich gas trigger of Stromboli's major explosions. We thus highlight that CO_2 flux monitoring can provide key warning signals for risk mitigation at Stromboli in the future. Finally, we propose that systematic CO_2 flux observations be extended to other open-vent basaltic volcanoes in order to verify whether the processes described here are specific to Stromboli or, instead, of general relevance.

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Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
|◀ | ▶|
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

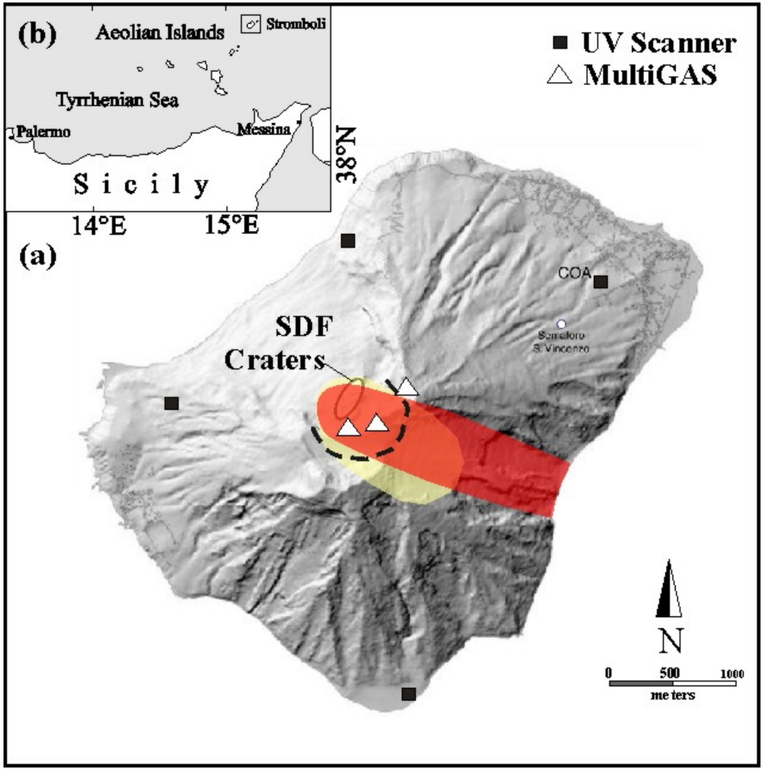

Fig. 1. **(a)** Map of Stromboli with location of MultiGAS and UV scanner stations; the typical dispersal area of fallout deposits of Stromboli's major explosion is given by the 24 November 2009 major explosion example (modified from Andronico and Pistolesi, 2010): red area: pumice fallout; yellow area: spatter and bombs; back dashed line, limit of the area affected by ballistic lithic fallout; **(b)** Position of Stromboli relative to mainland.

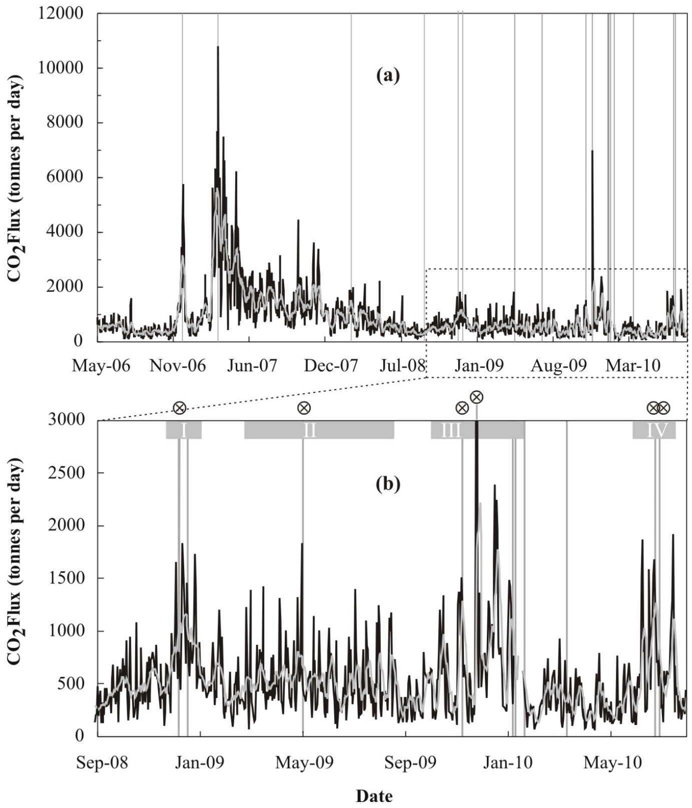

Fig. 2. (a) Daily averages of CO_2 plume fluxes (in tonnes per day) from Stromboli's summit crater, between May 2006 and July 2010 (the weekly mobile average is given as a light grey line). The period from 15 September 2008 to 30 July 2010 is detailed in **(b)**. The dashed areas labelled I to IV denote the 4 main phases of CO_2 flux increase, discussed in the text. Major explosions, indicated by the vertical grey lines (and crosses for the strongest ones), typically clustered during these phases of high CO_2 flux.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀I
▶I
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

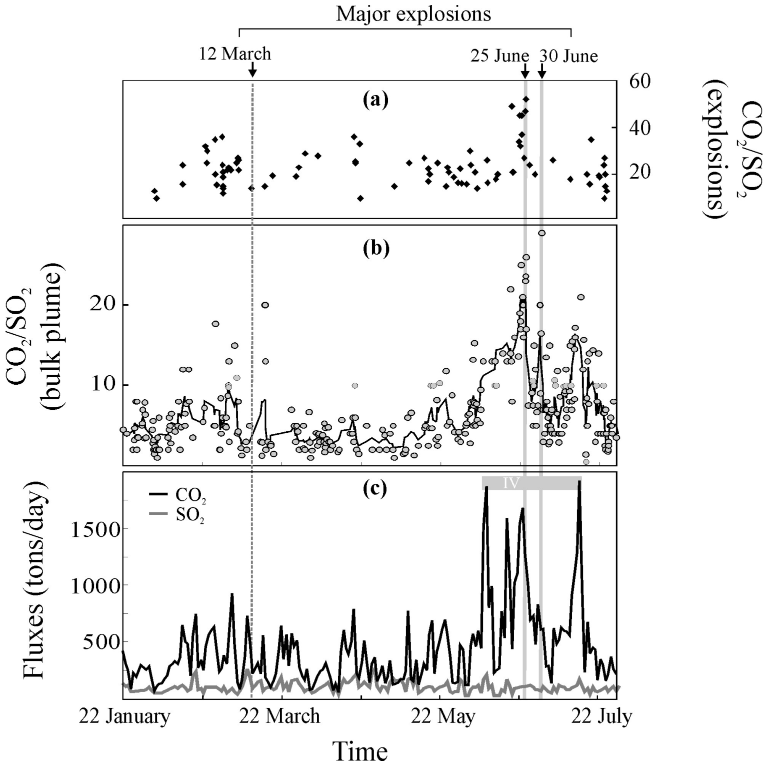

Fig. 3. A detail of plume observations taken in the 22 January to 30 July 2010 period. **(a)** CO_2/SO_2 ratios of the syn-explosive gas phase (the gas phase released during the discrete and short-lived explosions of the regular Strombolian activity); **(b)** CO_2/SO_2 ratios of the Stromboli's bulk plume, which is dominantly contributed by passive (quiescent) degassing in-between Strombolian explosions (Burton et al., 2007a); and **(c)** Daily record of SO_2 fluxes (grey line; derived from the FLAMES network of UV scanning spectrometers; Burton et al., 2009) and CO_2 fluxes (black curve). CO_2 fluxes were calculated by combining the daily averages of the bulk plume CO_2/SO_2 ratio and SO_2 flux.

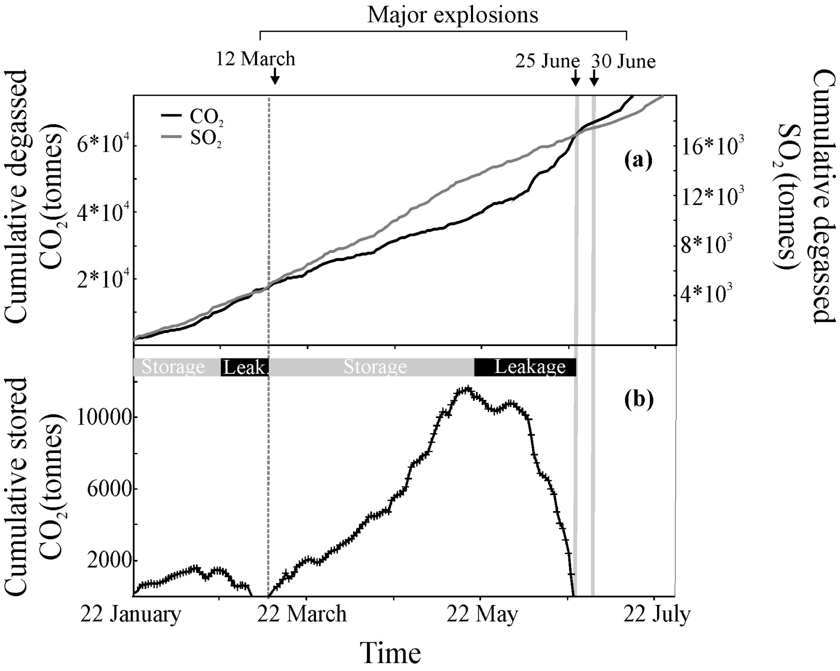

Fig. 4. **(a)** Cumulative CO_2 (black curve) and SO_2 (grey curve) fluxes (in tonnes), from 22 January to 30 July 2010. Note that the CO_2 scale (left) is 3.5 times greater than the SO_2 scale, in order to normalize to the time-averaged CO_2/SO_2 mass ratio of Stromboli's emissions. The two cumulative trends are fairly parallel and overlapping in January–March 2010. After the 12 March 2010 major explosion, the cumulative CO_2 flux first decelerates (during March to May) and then accelerate (in May–June) relative to SO_2 flux. This suggests an episode of gas retention, followed by passive gas leakage, prior to the major explosions on 25 and 30 June (see text). The cumulative masses of stored CO_2 (e.g., CO_2 segregated deep in the system, possibly as a bubble foam layer) are calculated (in **b**) as the difference between the amount of CO_2 which would have been degassed in time-averaged conditions (CO_2/SO_2 of 3.7) and the actual (measured) amount of degassed CO_2. Cumulative storage of CO_2 occurs at a mean rate of 1.4 kg s^{-1} from 13 March to 22 April, then 2.5 kg s^{-1} from 23 April to 20 May, resulting in bulk accumulation of ~11 000 t of carbon dioxide. From 21 May to 10 June (20 days), the stored CO_2 mass remains nearly steady or slightly decreases. Afterwards it suffers a rapid decrease (at a mean rate of 7.7 kg s^{-1}) until the two major explosions on 25 and 30 June (passive bubble foam leakage widely prevails over bubble storage). A similar (but smaller) cycle of CO_2 storage-leakage is observed prior to the 12 March weaker explosion.

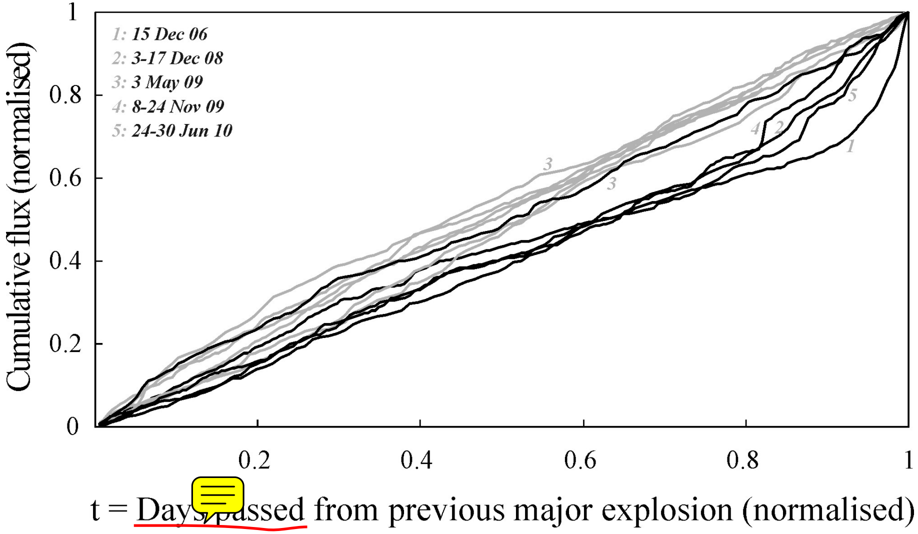

Fig. 5. Normalised cumulative CO_2 (black curve) and SO_2 (grey curve) flux trends for 5 periods of activity of Stromboli. The periods over which the cumulative curves were drawn were all selected in order to start ($t = 0$) on the day after the previous explosive event and to end ($t = 1$) with one (or more) major explosions (numbers 1–5 denote the specific explosion(s) occurring at $t = 1$). Curves 5 for CO_2 and SO_2 are totally analogous, in the normalised form, to those shown in Fig. 4a, and have $t = 0$ on 13 March and $t = 1$ on 30 June. The time interval between 0 and 1 is thus the period over which a complete cycle of gas segregation-gas leakage can occur. The 5 sets of normalised cumulative curves show similar shapes which indicate a reproducible degassing regime prior to each major explosion and, hence, a common recurrent source mechanisms for these events.