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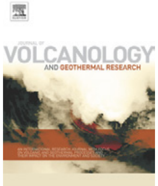

Characterizing high energy explosive eruptions at Stromboli volcano using multidisciplinary data: An example from the 9 January 2005 explosion

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A B S T R A C T

Stromboli is well known for its persistent, normal explosive activity, consisting of intermittent, mild to moderate, Strombolian explosions that typically occur every 10–20 min. All tephras erupted during this activity usually fall back into the crater terrace, and consist of volatile-poor scoriae fed by Highly Porphyritic (HP) magma. More occasionally, large explosions or "paroxysms" eject a greater quantity of tephra, mainly consisting of HP scoriae and pumice clasts of Low Porphyritic (LP) magma, but also including large lithic blocks. In addition to this activity, between 2004 and 2006 high energy explosions, displaying an intermediate eruptive style between that of normal and paroxysmal explosions in terms of column height, duration and tephra dispersal, were observed to occur at a frequency of one to eight events per year. While many volcanological, geochemical and geophysical studies have focused in the last few years on the two end-members of activity, i.e. normal or paroxysmal, a detailed investigation on these intermediate types of events has not been carried out yet. Here we report of a study on the 9 January 2005 explosion, one of the high energy explosions during which the main fountaining phase lasted nearly a minute causing ejection of coarse bombs up to a height of 120 m, and of ash and lapilli to >200 m. An accompanying ash plume rose up to 500 m at the end of the explosion. We present a multidisciplinary approach that integrates the results from analysis of live-camera images with compositional and textural characterization of the erupted products. Major element composition of glassy groundmass and 3D views of textures in the erupted scoriae support the hypothesis based on volcanological observations that this explosion falls between normal and paroxysmal activity, for which we use the term "intermediate". By comparing the video-camera images of the 9 January 2005 explosion with volcanological features of other high energy explosions that occurred at Stromboli between June 2004 and October 2006, we find that three additional events can be considered intermediate explosions, suggesting that this type of activity may be fairly common on this volcano. The results of this study, although preliminary given our limited dataset, clearly indicate that the methodology used here can be successfully applied to better define the range of eruptive styles typifying the normal explosive activity, potentially improving our capability of eruption forecasting and assessing volcanic hazard at Stromboli.

1. Introduction

Stromboli is a 924 m-high volcano in the Aeolian Islands (Italy) that is well known for the persistent explosive activity from its summit vents located in a crater terrace at about 750 m a.s.l. (Fig. 1). The normal activity of the volcano consists of passive degassing (Burton et al., 2007) and intermittent, mild to moderate, Strombolian explosions (Bertagnini et al., 1999; Rosi et al., 2000; Patrick et al., 2007). These explosions usually occur from a single vent every 10–20 min on average and last between a few to 20 s, ejecting coarse material up to a height of 100–150 m that falls back to the crater terrace (Bertagnini et al., 1999). Within the range of this type of activity, the strongest explosions produce jets of magma and gas higher than 150-200 m, with material that may occasionally fall outside the crater rims. All tephras erupted during normal explosive activity are volatile-poor scoriae fed by Highly Porphyritic (HP) magma (Francalanci et al., 1999, 2004; Corsaro et al., 2005).

The eruptive history of Stromboli is also characterised by the occurrence of more violent events that exhibit much greater explosivity with respect to the normal bursts. Barberi et al. (1993) defined two classes of powerful events based on their intensity: more frequent and less hazardous "major explosions", and rarer and powerful "paroxysms". Bertagnini et al. (1999) simplified this classification naming all these events paroxysms due to the difficulty of distinguishing, in terms of the intensity of the phenomena, between the two classes of explosive activity. Later, Métrich et al. (2005) introduced the term "small-scale" paroxysm to name events of significantly lower intensity than paroxysmal explosions. More recently, Landi et al. (2008) suggested distinguishing "small-" from "large-scale" paroxysms. The former represent explosive events constituting a serious risk for people at the

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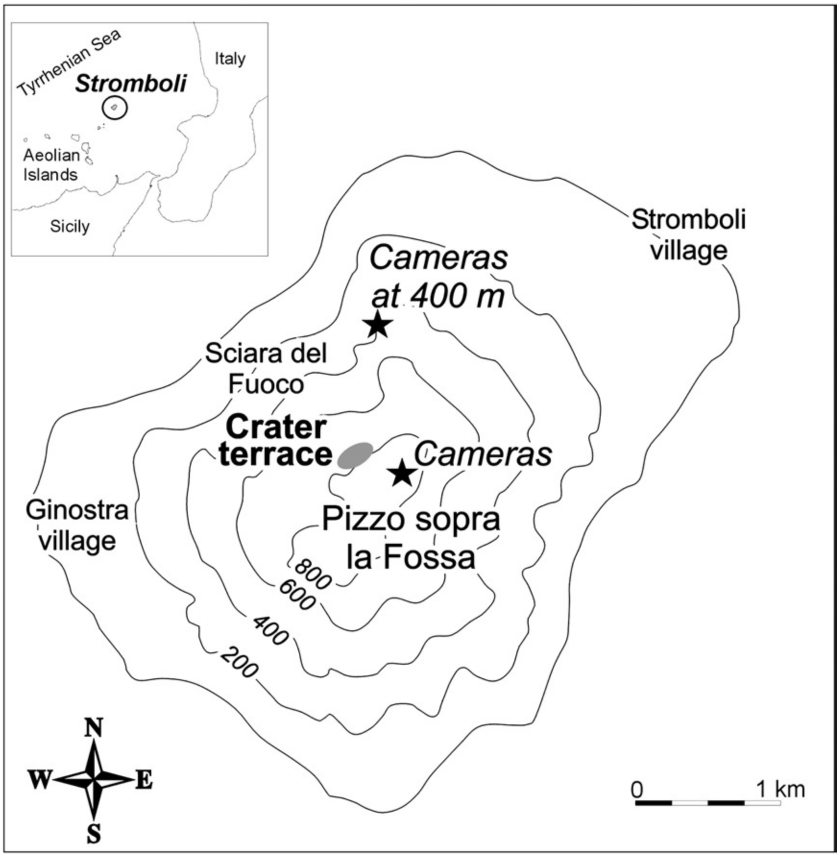

Fig. 1. Map of Stromboli volcano with locations of video-cameras.

summit of the volcano, like those occurring in September 1996, August 1998 and August 1999 (Métrich et al., 2005), while the latter may represent a potential hazard also for people living or staying at the foot of the volcano. Examples of this second kind of event are the 1919 and 1930 eruptions (Ponte, 1919; Imbò, 1928; Rittmann, 1931). In addition to HP scoria erupted during normal Strombolian explosions, large-scale paroxysms typically produce volatile-rich pumice clasts of Low Porphyritic (LP) magma (Métrich et al., 2001; Bertagnini et al., 2003; Métrich et al., 2005), as well as mingled products of the LP and HP type (Rosi et al., 2006). Frequently, but not always, small-scale paroxysms discharge also LP magma, like the August 1998 and 1999 major explosions of Bertagnini et al. (2003), re-named small-scale paroxysms by Landi et al. (2008).

In agreement with Bertagnini et al. (1999) and Landi et al. (2008), in this paper we use the term paroxysms (both small- and large-scale) to indicate explosive events characterised by higher magma jets, longer duration, more abundant ejection of incandescent material, and wider fallout dispersal in comparison to the normal explosive activity. In addition, we observe that more than one vent within the crater terrace is usually involved in the paroxysmal activity. Such a definition, therefore, includes a wide range of paroxysmal events that may greatly differ in eruptive intensity.

Between 1888 and 1986, the normal explosive activity at Stromboli was interrupted by an effusive eruption every 4 years (Barberi et al., 1993). The last two effusive events occurred in 2002–03 (Calvari et al., 2005) and between February and April 2007. These eruptions were accompanied by paroxysms on 5 April 2003 (Calvari et al., 2006; Rosi et al., 2006) and 15 March 2007 (Andronico et al., 2007). The eruptive magnitude of the 5 April 2003 paroxysm was enough to severely change the morphology of the crater terrace, leaving an almost flat area that does not allow us to recognize a clear morphology of the three summit craters as it was prior to the 2002–03 eruption. In the following, we conventionally refer to the three sectors within the crater terrace as Northern, Central and Southern sectors (Fig. 2), terminology commonly used before the 15 March 2007 paroxysm.

The 2002–03 effusive eruption, together with the 5 April 2003 paroxysmal episode, have marked a turning point in the study of the volcano, in terms of improvement of scientific results and number of research projects carried out. In the past, volcanological observations of Stromboli were performed in a discontinuous way and the range of the normal explosive activity poorly investigated. The first quantitative volcanological studies were those by Chouet et al. (1974) and Blackburn et al. (1976), followed by several other studies (e.g., Ripepe et al., 1993). Although these authors performed rigorous studies of eruption dynamics, they investigated restricted periods of the normal explosive activity, and no attempt was made to examine the eruptive variations in terms of explosion frequency and intensity. Since June 1996, the installing of a remote, live-camera pointing to the crater terrace allowed the researchers of the Istituto Internazionale di Vulcanologia (IIV) of Catania continuous, long-term monitoring of the explosive activity, thereby largely improving the quality and quantity of volcanological observations. This visible surveillance system was further enhanced after the 5 April 2003 paroxysmal episode, when the Istituto Nazionale di Geofisica e Vulcanologia, sezione di Catania (INGV-CT), formerly IIV, deployed a permanent video-camera network on the volcano consisting of four live cameras (Fig. 1).

Visual monitoring of the normal explosive activity is accompanied by periodical sampling of the products erupted from the vents. All the collected samples (ash, lapilli and bombs) are routinely analysed for componentry, morphological and petrochemical characterization at INGV-CT. Recently, synchrotron X-ray computed microtomography has been introduced to study the 3D textural features of scoria clasts (Polacci et al., 2006; 2007). Video-camera recordings help us to correlate sampled tephras to explosive events, a multidisciplinary

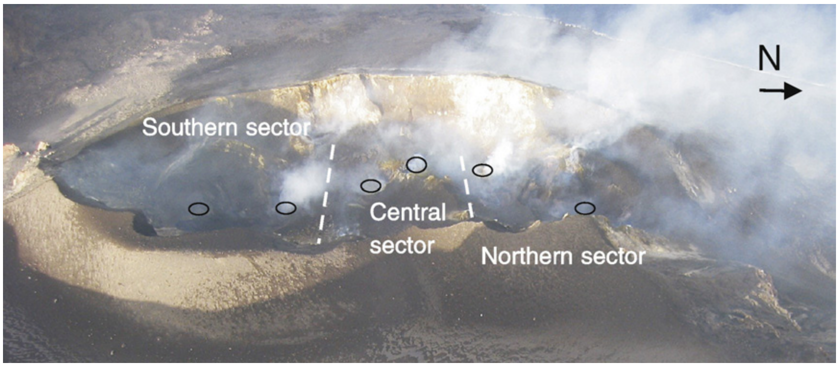

Fig. 2. Panoramic view of Stromboli from E showing the presence of the active vents during the study period. The crater terrace is approximately 240 m in length.

approach that allows us to investigate with unprecedented detail the range of eruptive styles within the normal Strombolian activity.

Between the last two paroxysmal explosions (5 April 2003 and 15 March 2007), the improved visual monitoring system allowed us to detect 16 high energy explosive episodes that interrupted the normal explosive activity. These events, occurring between 16 June 2004 and 16 October 2006, undoubtedly consisted of higher intensity explosions in terms of height, duration of the event and tephra dispersal with respect to the daily average level of activity. In this paper, we report on one of these explosions occurring on 9 January 2005 (Andronico et al., 2006), when a violent explosive eruption took place from two distinct vents in the Southern and Central sectors of the crater terrace. We focus on the 9 January 2005 explosion because the analysis of visual images from live cameras, together with the petrochemical and textural characterization of coarse tephra samples collected a few days after the episode, allowed us to well constrain the volcanological characteristics and the eruptive style of this explosive episode. Although limited to the study of only one explosion, our results suggest the existence of an intermediate class of explosive events between the normal and paroxysmal explosions and provide new perspectives in the assessment of both magma dynamics driving paroxysms at Stromboli and the related volcanic hazard.

2. Methodology

2.1. The video-camera system

The permanent camera system provides a continuous, real time monitoring of the eruptive activity. Two cameras are located at Pizzo sopra La Fossa (infrared and visible), at 918 m a.s.l. and about 100 m above and almost 240 m from and in front of the crater terrace, respectively. They give a favorable view, allowing to distinguish the explosion vent, the height reached by the products (with a maximum height limit of about 200 m) and to characterise the predominant type of ejected pyroclasts (ash vs. bombs). Two other cameras are placed at 400 m a.s.l. (thermal and visible), about 800 m NE of the crater terrace. These cameras provide useful indications in case of large explosions that produce ejecta exceeding 200 m in height. In addition, the different angle of view of these cameras allows detecting potential landslides and lava flows coming from the Northern sector of the summit terrace. For the purpose of this study, we used two different cameras, the OPGAL infrared camera (EYE-M320B model) at Pizzo sopra La Fossa and the FLIR thermal camera (ThermoVision® 320 M model) at 400 m a.s.l. The OPGAL camera provides a visualization of the infrared energy, receives in the 8 to 14 μm band, and consists of an uncooled microbolometer capable of acquiring a 320×240 squared pixel image every 2 s, with a 60°×45° field of view. Over a fixed 240 m distance, this equates to a pixel size of 0.87 m×0.83 m. The FLIR camera uses an uncooled microbolometer that detects the emitted radiation in the 7.5 to 13 μm band, acquires a 320×240 squared pixel image every 2 s, and has a 24°×18° field of view. The pixel size (at a distance of about 1 km) is 1.3 m×1.3 m. The vertical field of view above the crater rim of the infrared camera at Pizzo sopra La Fossa is about 150 m, while for the thermal camera at 400 m a.s.l. is 250–300 m.

The video-analysis of the permanent camera system is used to compile weekly reports on the Frequency of Explosions per day (avFE) based on the average of the number of explosions per hour, published since October 2003 on the INGV-CT website www.ct.ingv.it. Each report contains a plot showing the avFE vs. time, a synthetic description of explosive activity, including the type of the erupted products (fine ash and/or coarse lapilli and bombs) and a qualitative description of the explosion intensity based on the height reached by ballistic clasts. We refer to low activity if coarse ejecta reach up to 80 m, moderate when their height ranges between 80 and 150 m, high if they reach 150–200 m, and finally very high if they exceed 200 m.

2.2. Glass matrix composition and textural analysis

The samples used in this study were collected in the Fossetta area a few days after the explosion, about 50 m away from the Southern sector (Landi et al., 2008). Glass matrix compositions were measured in two samples that markedly differ for their macroscopic features: sample 090105A is a pale brown scoriaceous lapillus, whilst sample 090105B is a significantly darker specimen. Because different lithologic characteristics of products erupted at Stromboli can herald the occurrence of a compositional variation in the magma (Corsaro et al., 2005), we planned detailed glass matrix measurements using a grid of regularly distributed beam spots that covered entirely the two thin sections under investigation. Analyses were performed at INGV-CT with a LEO-1430 scanning electron microscope (SEM), equipped with an Oxford EDS micro-analytical system, at 20 keV acceleration tension, 1.2 nA probe current and performing a XPP data reduction routine. In order to minimize alkali loss during analysis, a square raster of 10 μm was used. Replicate analyses of the international standard VG-2 Glass basaltic, USNM 111240/52 (Jarosewich et al., 1980), ensured an analytical precision expressed as relative standard deviation of <1% for SiO_2, Al_2O_3, FeO_t, MgO and CaO and <3% for TiO_2, Na_2O and K_2O (Miraglia, 2006). About 50 analyses were performed in sample 090105A and 90 in sample 090105B because this latter clast displayed a much more heterogeneous composition.

Three scoria clasts of the same type and size of sample 090105B (see above) were cut into small parallelepipeds with a height of about 2.5 cm and a square base of about 2×2 cm^2 and processed via X-ray computed microtomography. This is the only high-resolution, non-destructive technique that allows us to reconstruct the internal structure of porous materials in 3D. Because samples of the 090105A scoria type have the same texture and composition (see Section 5) of scoria erupted during normal Strombolian activity, their 3D textures were not analysed in this work. The tomographic experiments were conducted at the SYRMEP beamline of the ELETTRA synchrotron radiation facility in Basovizza

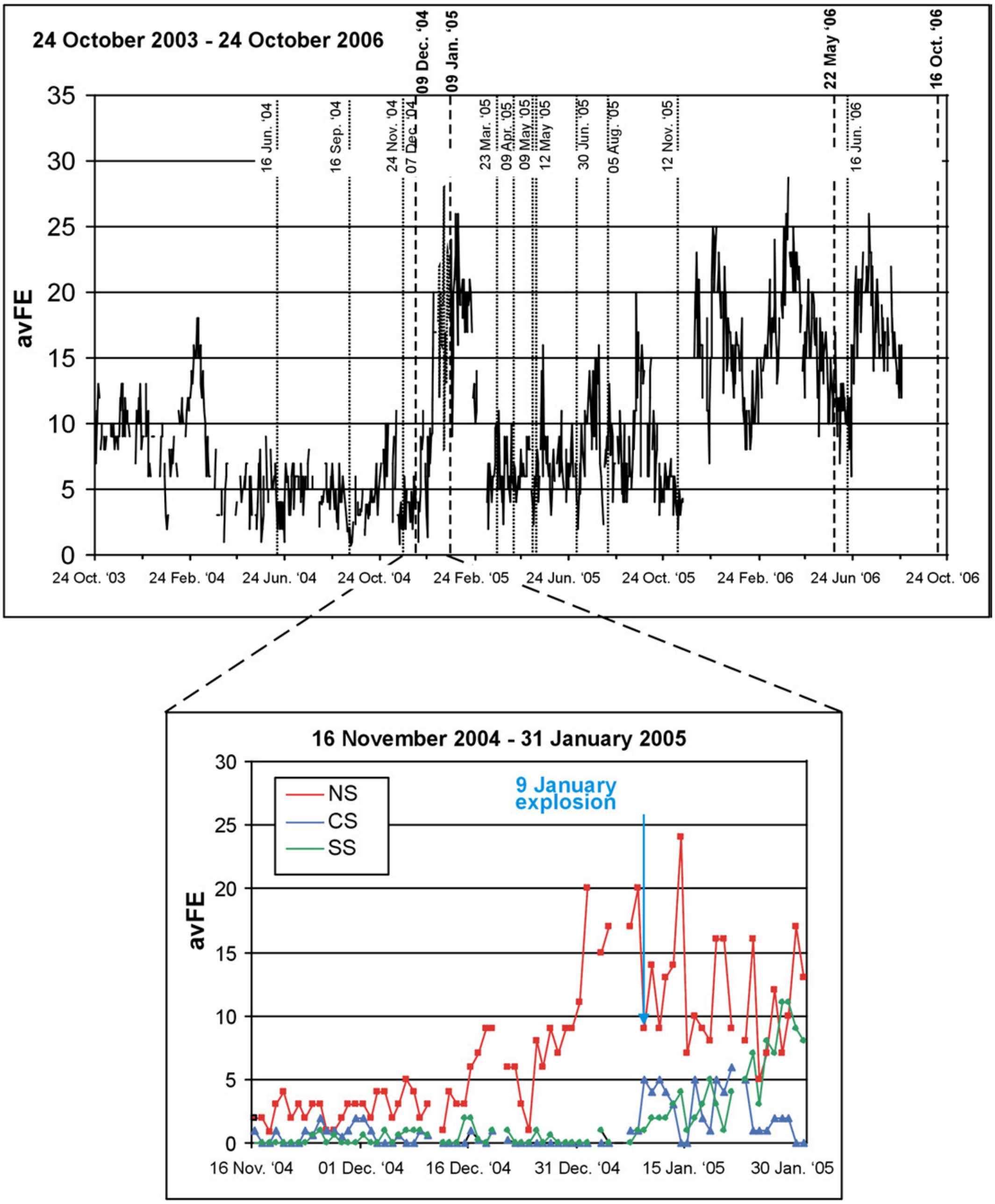

Fig. 3. Plots showing the average Frequency of Explosions per day (avFE) based on the average number of explosions per hour at Stromboli: in a) avFE represented as total number of explosions in the period 24 October 2003–17 September 2006; in b) avFE for each of the three crater sectors in the period 16 November 2004–30 January 2005. Vertical lines in a) indicate the 16 high energy explosions mentioned in the text. The four intermediate explosions (as reported in Section 6.1) are labelled at the top of the plot. Blank spaces indicate no images or insufficient data.

(Trieste, Italy). Reconstruction of the tomographic images was performed applying a software code based on a filtered backprojection algorithm (Herman, 1980). The reconstructed 2D image slices were stacked and processed via the ImageJ software (Abràmoff et al., 2004) to display a complete 3D view of the sample. Via this procedure it was possible to visualize the textural features of the investigated scoriae in 3D, and hence the size, shape, distribution and interconnectivity of vesicles in each sample. Vesicle volume fractions and vesicle number densities (total number of vesicles per unit volume) were then quantified using the BLOB3D software package (Ketcham, 2005), after vesicles were segmented and separated using the same software. Details of the experimental set up, experimental conditions and processing of the reconstructed tomographic volumes can be found in Polacci et al. (2006, 2007).

3. Summary of the explosive activity at Stromboli between April 2003 and January 2005 analysed from video-camera images

During the 2002–03 effusive eruption, the explosive activity at the summit vents of Stromboli was limited to a few episodes in March 2003 consisting of ash emissions causing ash fallout at the foot of the volcano (Calvari et al., 2005). The 5 April 2003 paroxysm was then followed by a slow, gradual resumption of explosions, with normal low energy Strombolian activity clearly restarting by the end of June (Lodato et al., 2007). After the lava effusion ceased (21 July 2003), the explosions increased further in frequency and intensity between September 2003 and the end of the year, when the eruptive activity resumed the typical normal Strombolian activity observed before the onset of the 2002–03 eruption (Ripepe et al., 2005). Fig. 3a

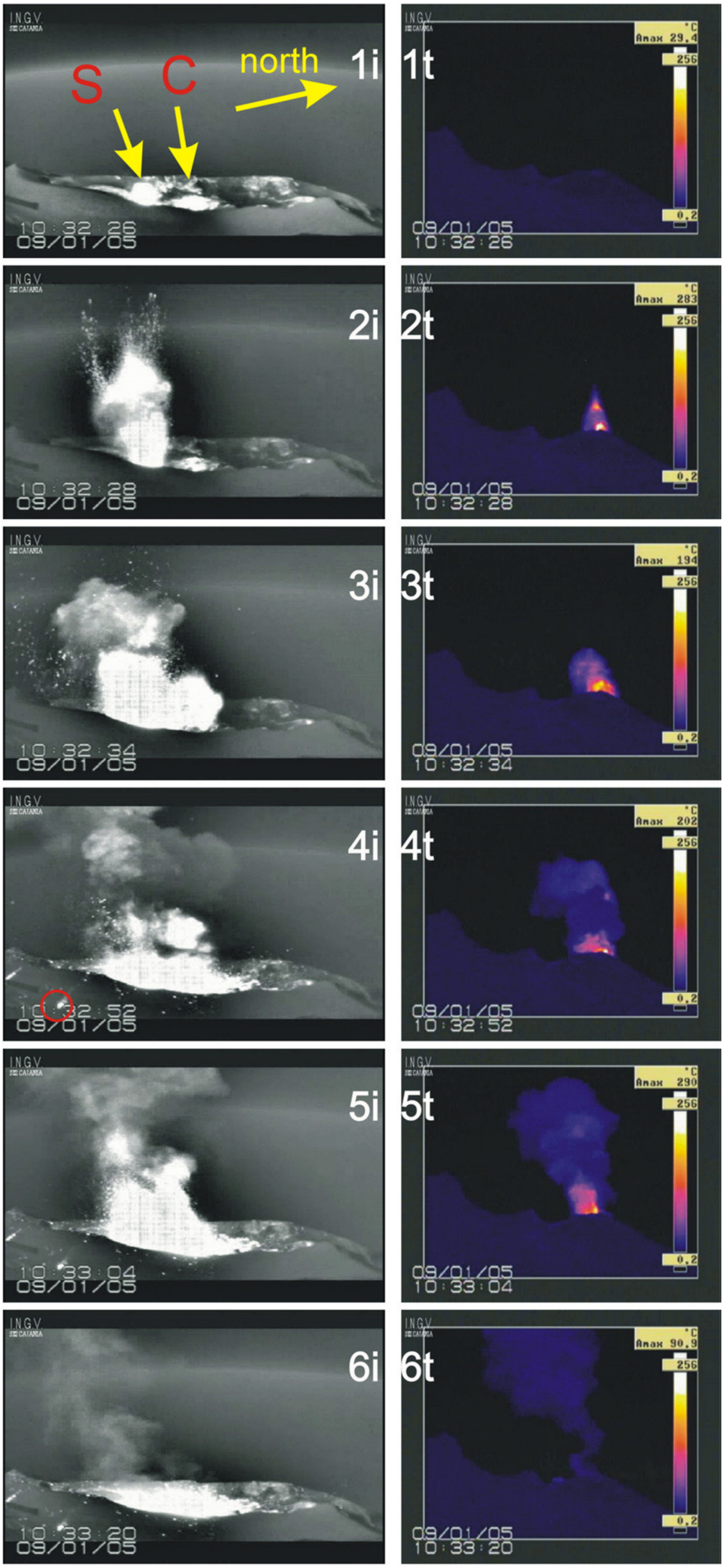

Fig. 4. The 9 January 2005 explosive event as recorded by the INGV video-cameras. Left: images from the infrared camera located at about 900 m a.s.l. on Pizzo sopra La Fossa (1-6i); right: images from the thermal camera located at 400 m a.s.l. (1-6t).

summarises the avFE in the period October 2003–October 2006. In the first months of 2004 the eruptive activity was characterised by an increasing avFE, reaching a peak between the end of February and the beginning of March (>15 explosions per hour). The explosive activity was low in the following months, with the avFE ranging between 4–7 explosions per hour up to October 2004. Despite the overall decrease in activity, the 16 June 2004 explosion marked the start of a series of high energy explosions that characterized the activity of the volcano up to October 2006. In mid-September 2004 a short period of almost absence of activity preceded an anomalous, high energy explosion that occurred on 16 September. After this episode, the avFE started again to increase until the first ten days of November 2004. Then, the explosive activity diminished (avFE<5) (Fig. 3b) and was mostly characterised by spattering (low energy Strombolian bursts causing almost continuous expulsion of large magma clots up to 20 m above the vent) at the four vents in the central area of the crater terrace (two in the Central sector, and one in the Southern and Northern sectors, respectively; see Fig. 2 for the location of such vents). During this period, only the northernmost vent of the Northern sector displayed typical Strombolian activity. This eruptive pattern was interrupted on 24 November 2004 by a high energy explosion that destroyed a hornito located in the middle portion of the crater terrace. After this event, a new period of activity started at the Northern sector, with the most central vent of this sector characterised by spattering alternating with high intensity explosions, while at the northernmost vent (of the same sector) Strombolian activity was continuing. On 7 and 9 December, two stronger explosions occurred in the Central sector, one of which involving and breaking another hornito. After these explosions, the total avFE was largely discontinuous, fluctuating between 1 and 11 explosions per hour, although the most active vents were always those in the Northern sector. In the first days of 2005, the explosive activity, almost totally confined to these latter vents, rose to 20 explosions per hour just a few days before the 9 January 2005 explosion. The vents in the Southern and Central sectors, conversely, were affected by a low, discontinuous spattering that started in mid-December and lasted until 8 January 2005.

4. The 9 January 2005 explosion as recorded by video-cameras

A few hours immediately preceding the 9 January 2005 explosion, the vents from the Central sector of the crater terrace generated 2–3 low energy explosions per hour that replaced the prolonged spattering activity, which conversely persisted at one of the two vents of the Southern sector, while the other active vent of this sector produced rare, low energy explosions (height<20 m). No significant variation of activity was observed at the two vents of the Northern sector, which produced up to 9–12 low energy explosions per hour. At about 10:32 GMT, a large explosion involved two distinct, adjacent vents located in the Central and Southern sectors of the crater terrace (indicated as S and C in Fig. 4). Fig. 4 shows the chronology of the 9 January explosion as recorded by the video-cameras from two different angles: frames in the left column are provided by the infrared camera (i) at Pizzo sopra la Fossa (view from SE at 918 m a.s.l.), while frames in the right column exhibit the N view provided by the thermal camera (t) at 400 m a.s.l. The infrared camera, placed higher than the crater terrace and pointing to it, recorded very clearly the onset of the explosive event, which was not viewed by the thermal camera due to its lower location. The event can be summarised in the three following points (all times are expressed in GMT; local time=GMT+1).

(1) A first explosion was observed at the S vent from the Southern sector beginning at 10:32:26 (frame 1i). Lava fountaining lasted about 40 s forming a magma jet up to 100–120 m above the S vent, while a few coarse bombs exceeded 200 m of height. Frame 2t shows the initial phase of the fountain as viewed from the camera at 400 m and the formation of a shadow of dark material due to the presence of ash. The fine-grained products (ash and lapilli) were ejected up to >200 m (frames 2-5i), and covered the inner walls of the crater terrace up to its south-western outer portions. Frame 4i clearly shows that some incandescent blocks were ejected, well visible on the southern outer rim of the terrace (red circle in Fig. 4, frame 4i).

(2) At 10:32:34, while the fountaining was going on at the S vent, another explosion started at the C vent (frame 3i). Frame 3t displays the start of the explosion at C in the foreground, while the fountain at S is visible in the background. The ejected material from C produced a 100 m-high lava fountain that fell in the north-western portion of the crater terrace.

(3) Throughout the explosive episode, the height reached by the magma jets changed in time at both the S and C vents (frames 4 and 5). The activity stopped almost contemporaneously, first at the S vent and a few seconds later at the C vent (10:33:20, frame 6i). The thermal images show that an ash plume formed during the explosive activity, rising up to 400–500 m after the end of the explosive event (frame 6t).

About two hours after the 9 January explosion, the typical Strombolian activity resumed at two vents in the Southern sector. In particular, the vent involved in the larger explosion started producing ash emission up to 150 m with avFE ~2–3. After 23 January, the number of explosions increased gradually at the vents of the Southern sector exceeding 5 events per hour, whereas activity at the vents of the Central sector slowly came to an end. The vents of the Northern sector, although characterised by activity oscillating in frequency and with high avFE values (>7 explosions per hour), continued to sustain intense explosions up to 150 m in height. In the following weeks, the eruptive activity started to gradually decline until mid-February, then it was almost constant between February and October 2005 with about 7-8 explosions per hour.

It is worth noting that between March 2005 and October 2006 Stromboli displayed other high energy explosions, some of which similar to that on 9 January 2005 in terms of eruptive style and dispersal of erupted products. Fig. 3a shows the entire sequence of high energy explosions (16 events) observed by the INGV-CT surveillance activity in the period 24 October 2003–30 October 2006. Among these events, the 22 May 2006 explosion was one of the most energetic and, similarly to the 9 January 2005 explosion, occurred during a period of high Strombolian activity in terms of frequency and height of the explosions.

5. Glass matrix compositions and 3D textures of scoria clasts

The glass matrix composition of sample 090105A is overall more homogeneous than that of sample 090105B (Table 1). In the SiO_2 vs.

Table 1
Major elements glass matrix average compositions (±σ) of scoriaceous lapilli erupted on 9 January 2005

Sample	STR090105A		STR090105B	
#	50		90	
	Mean	STD	Mean	STD
SiO_2	52.12	0.18	52.06	0.54
TiO_2	1.74	0.06	1.60	0.12
Al_2O_2	15.46	0.15	16.00	0.38
FeO	10.45	0.20	9.70	0.36
MnO	0.19	0.04	0.18	0.05
MgO	3.44	0.12	3.96	0.35
CaO	8.10	0.14	8.53	0.49
Na_2O	3.11	0.12	3.13	0.18
K_2O	4.39	0.08	3.90	0.30
P_2O_5	0.87	0.05	0.80	0.08
CaO/Al_2O_3	0.52	0.01	0.53	0.02
FeO_{tot}/MgO	3.05	0.13	2.47	0.28

= number of measurements; STD = standard deviation (σ).

K_2O classification diagram (Fig. 5a), 090105A glasses form a cluster with shoshonitic composition that overlaps the compositional field defined by products of the normal Strombolian explosive activity and glass-bearing lava flows erupted from 2002 to 2007 (Landi et al., 2006; Corsaro and Miraglia, 2007a,b and references therein). Glass matrix compositions of sample 090105B are generally more primitive and variable, spanning from shoshonitic basalt to shoshonite. They partly fall within the earlier defined compositional field and mostly spread towards the glass matrix compositions of paroxysmal events that occurred between 2002 and 2007 (Landi et al., 2006; Corsaro and Miraglia, 2007a,b and references therein). The same compositional trends displayed by our data and data from the literature can be observed in the CaO/Al_2O_3 vs. FeO_{tot}/MgO diagram (Fig. 5b). Both compositional plots (Fig. 5a, b) suggest that the glass matrix compositions of sample 090105A are similar to products erupted in the last years during Strombolian and effusive activity, while compositions of sample 090105B result intermediate between those reported for normal Strombolian and paroxysmal activity, partially overlapping with the former.

The products from the 9 January 2005 event investigated here consist of porphyritic (vesicle-free phenocryst content about 0.25), moderately to highly vesicular (0.46–0.83) scoria clasts that display a range of vesicle sizes spanning from <25 µm up to >1 cm (Fig. 6a, b, c). Values of the vesicle number density typically range between 3×10^5–4×10^5 cm^{-3}. The ability of X-ray tomography to visualize scoria volumes (Fig. 6d) in 3D has revealed features of the internal structure of these clasts that are not possible to determine unambiguously using conventional 2D imaging techniques. Scoriae are characterized by large (>1 mm), highly coalesced vesicles that exhibit complex, irregular shapes in 3D, coexisting with a smaller-scale population of spherical to sub-spherical, less connected vesicles set in a subaphiric groundmass (microlite content <0.05). As shown in Fig. 6e and f, besides compositions also the 3D textural data characterizing the investigated scoriae are intermediate between those displayed by clasts erupted during normal Strombolian and paroxysmal explosions.

6. Discussion

6.1. The 9 January 2005 high energy explosion: Strombolian or paroxysmal activity?

The multidisciplinary monitoring approach described here enabled us to investigate with unprecedented detail the range of

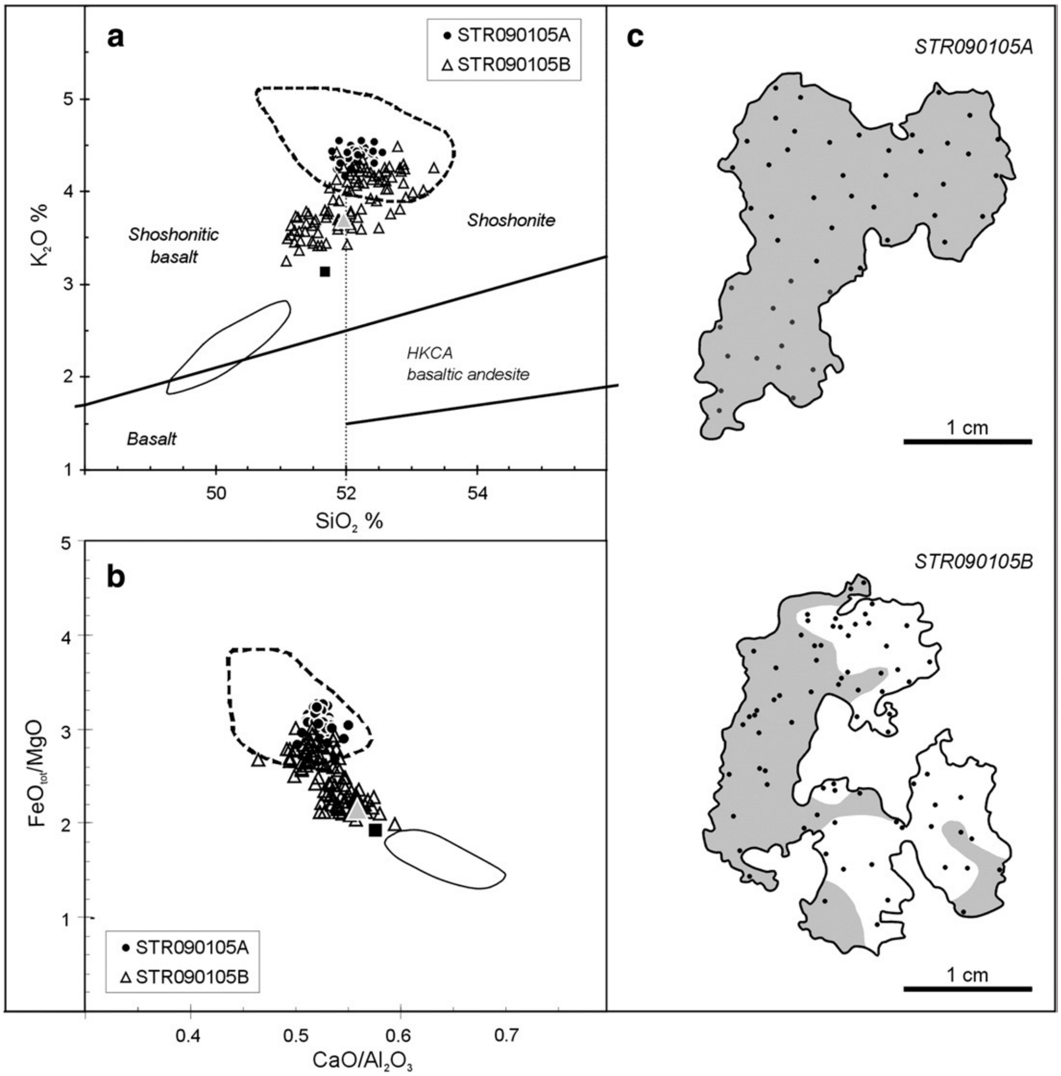

Fig. 5. a) SiO_2 vs. K_2O classification diagram (Peccerillo and Taylor, 1976) and b) CaO/Al_2O_3 vs. FeO_{tot}/MgO diagram for glass matrices of products erupted on 9 January 2005. Literature data on the compositional field of glasses erupted during the 2002–2007 Strombolian and effusive activity (dashed line) and during the 2002–2007 paroxysmal explosions (continuous line) are also reported. White grey triangle and full square refer to glass compositions of pyroclasts erupted on 9 January 2005 and 24 July 2002. See the text for literature references; c) Compositional map of the thin section surface of samples 090105A and 090105B. In c) points correspond to glass matrix measurements. Grey: areas with HP glass matrix compositions; white: areas with glass matrix compositions intermediate between HP and LP magma compositions.

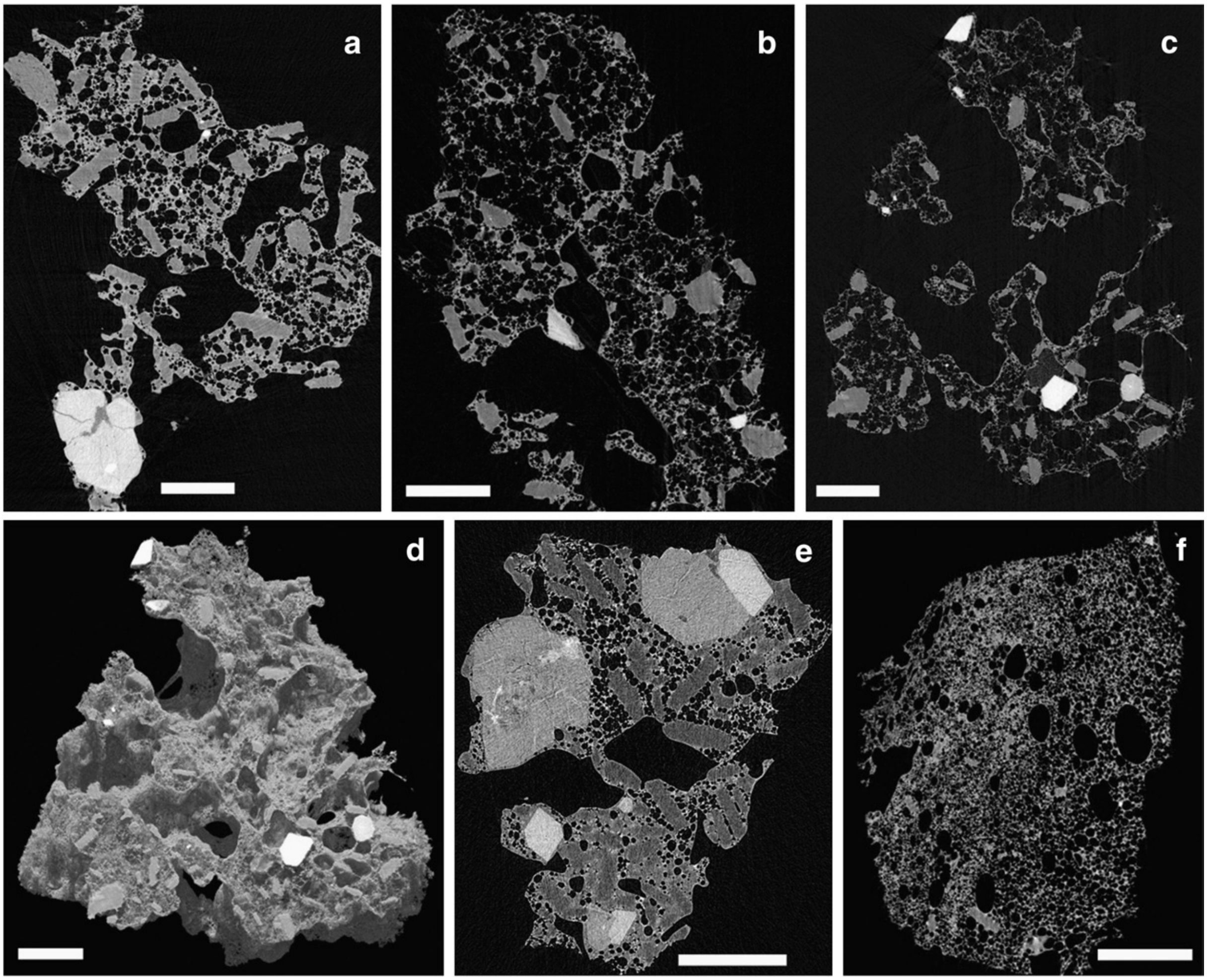

Fig. 6. Synchrotron-based X-ray tomographic images of products from explosive activity at Stromboli. a), b), c) scoriae from the 9 January 2005 explosion; d) 3D volume rendering of sample in c); e) scoria from normal Strombolian activity, and f) pumice from the 5 April 2003 paroxysm. Scale bar 2 mm for all images.

eruptive styles characterising the explosive activity at Stromboli in the past few years. The improved live-camera network allowed recognising 16 events between 16 June 2004 and 16 October 2006 (Fig. 3a) that were characterised by higher energy than the normal explosive activity, mainly in terms of height and dispersal of products. The daily monitoring of the activity, performed via the permanent video-camera surveillance system since October 2003, has clearly revealed that high energy explosions at Stromboli can be generated by different triggering mechanisms, and have therefore a different meaning from a volcanological point of view. The 9 January 2005 and 22 May 2006 explosions occurred, for example, within a period of high Strombolian activity, when the avFE ranged between 15–20 and 14–18, respectively. This suggests that these two events were generated when both the magma supply rate and eruption rate were higher than usual, a hypothesis in agreement with the observations of Lautze and Houghton (2007) on the explosive activity at Stromboli in 2002. The five high energy explosions preceding that on 9 January 2005 (16 June, 16 September, 24 November, 7 and 9 December 2004) occurred instead during periods of low avFE (<5 explosions per hour). All the other explosions corresponded either to sudden drops or periods of gradually decreasing activity. The former situation, which occurred for example on 5 August 2005, can be explained by a temporary obstruction of the vent owing to the combined effects of internal collapses and fall of juvenile material within the vent itself. A decrease in activity may instead be associated with lower rates of supply of new magma which, in turn, would favour magma outgassing, crystallization and cooling of an increasingly viscous crust at the magma free surface. The two conditions (sudden drop and gradually decreasing activity) may lead to over-pressurization of the shallower conduit by the rise and accumulation of large gas bubbles (or gas slugs) either below the viscous crust or the obstruction and, eventually, to the partial or total disruption of the vent.

Because of their lower intensity than that of typical paroxysmal explosions, but higher than that observed during normal explosive activity, not all of the above cited events can be classified following the terminology currently used in the literature (Barberi et al., 1993; Bertagnini et al., 1999; Métrich et al., 2005; Landi et al., 2008). The results of this study suggest using the following criteria to define, among high energy explosions, those whose activity is intermediate between normal Strombolian and paroxysmal activity:

(1) The coarser erupted products (decimetre-sized blocks and bombs) must be ejected to a height of at least 300 m and reach a horizontal distance of 250 m (potentially reaching the area at Pizzo sopra La Fossa in the SE direction). These values agree with the visual field of view of the video-cameras located at 400 m and 918 m.
(2) The explosion must involve multiple vents located in different sectors (Northern, Central or Southern) of the crater terrace.
(3) The duration of the tephra ejection must be longer than 30 s.

Further independent geophysical monitoring also indicates that, with the exception of the 30 June 2005 explosion, all of the high energy explosions reported in Fig. 3a were accompanied by a much larger VLP amplitude than the daily average signal, and had a duration >1 min, as reported in the daily reports provided by the INGV, Osservatorio Vesuviano and available at http://www.ct.ingv.it/Stromboli2002/Main.htm. Therefore, we define each explosion that meets all the three above criteria as “intermediate” between normal Strombolian and paroxysmal activity. Following the proposed classification, only 4 of the 16 explosions listed in Fig. 3a can be identified as intermediate explosions, namely the 9 December 2004, 9 January 2005, 22 May 2006 and 16 October 2006 explosions. All the other explosions can be considered normal explosive activity. It is worth noting, in fact, that although some of those 16 explosions lasted a few minutes, neither did they ejected ballistic clasts up to a height of 250 m above the vent (criterion 1) nor involved two or more vents belonging to different sectors (criterion 2). However, a detailed study of these high energy explosions is beyond the scope of this paper and will be the subject of future research.

6.2. The intermediate nature of the products of the 9 January 2005 explosion

Volcanological observations strongly suggest that the 9 January 2005 explosion is transitional, differing from the normal Strombolian activity in the larger dispersal and height reached by the erupted material, the involvement of at least two vents and the longer duration of the explosion. A further, independent confirmation of the intermediate nature of this event comes from the compositional and textural characterization of the erupted products. Our results clearly show that glass compositions (Fig. 5a, b) and vesicle textures are intermediate between those found in scoriae from normal explosions (Fig. 6e) and those in pumice clasts from paroxysmal events (Fig. 6f). The comparison between our glass compositions with data from the literature (Landi et al., 2006; Corsaro and Miraglia, 2007a,b and references therein) highlights that values of sample 090105A fall inside the compositional field defined by products of the normal Strombolian explosive and effusive activity from 2002 to 2007 (HP magma) (Fig. 5a, b). The glass compositions of sample 090105B partly fall within the earlier defined compositional field, but most of the measurements are outside this field and spread towards the compositional field of paroxysmal explosions that occurred between 2002 and 2007 (LP magma). Such glass matrix measurements compare well (Fig. 5a, b) with both preliminary data acquired during petrologic monitoring of the 9 January 2005 activity (Corsaro and Miraglia, 2005) and matrix glasses of the scoriae in Landi et al. (2008). They are very close to the ”intermediate” glass matrix composition measured in pyroclasts erupted during the 24 July 2002 explosive event (Zanon et al., 2004).

To better visualize the distribution of compositional heterogeneities in sample 090105B at the microscale, we created a compositional map of the thin section surface (Fig. 5c). To this end, we defined two areas: the first (grey), comprises glass matrix measurements with $K_2O>4\%$ and $FeO_{tot}/MgO>2.5$ and corresponds to the compositional field of HP magma (see literature data in Fig. 5a, b); the second (white) groups all the remaining glass matrix measurements which are intermediate between the compositional fields of HP and LP glasses (see literature data in Fig. 5a, b). Using this criterion, we found (Fig. 5c) that, in sample 090105B, large areas of HP and intermediate compositions are separated by a sharp and irregular contact, thus suggesting the occurrence of mingling processes at least at the scale of the sample. Coherently with compositional data (Fig. 5a, b), no heterogeneity is found for the map of sample 090105A (Fig. 5c). Textural characterization via X-ray tomography further supports the results from the compositional analysis and highlights the intermediate textural characters of the investigated products. Vesicularity is in good agreement with the range of values measured in scoriae from normal explosive activity at Stromboli in 2002 (~0.40–0.80) (Lautze and Houghton, 2005) and partially overlaps with values (0.29–0.62) of the 2004 and 2005 normal Strombolian activity (Polacci et al., 2006, 2007). The medium/upper range of vesicularity values also overlaps with those found in pumice clasts from the 5 April 2003 paroxysm (Polacci et al., 2006 and references therein). Vesicle number density exhibits a clearer trend with values respectively higher and lower than those found in HP scoria ($\sim 1\times10^5$–2×10^5 cm^{-3}) and LP pumice clasts ($\sim 6\times10^5$–8×10^5 cm^{-3}) from the same periods of activity cited above. Finally, 3D views of the inner scoria structure display clear coexistence of the two vesicle populations, distinctive of products from either normal Strombolian or paroxysmal activity at Stromboli (Fig. 6d, f): a network of large, highly connected, convoluted vesicles in the former, and, in the latter, small to intermediate, mostly spherical to subspherical vesicles coalescing on a very fine-grained scale. Such coexistence confirms the hypothesis that mingling of magmas with different textures and compositions was on-going during this explosive event, suggesting that this potentially affected the overall magma dynamics.

6.3. Implications on the magma dynamics of high energy intermediate explosions

The dynamics of the magma system at Stromboli have been generally related to conditions of vesiculation (Lautze and Houghton, 2005; Polacci et al., 2007), degassing (Allard et al., 1994; Harris and Stevenson, 1997; Ripepe et al., 2005; Burton et al., 2007) and crystallization (Métrich et al., 2001; Bertagnini et al., 2003), affecting deep magma rising to the surface and determining the different eruptive styles observed (Patrick et al., 2007 and references therein).

It is nowadays widely accepted that the normal explosive activity of Stromboli is sustained by the degassed, crystallized HP magma located in the upper conduit of the volcano and that paroxysms derive from the fast rising and decompression of volatile-rich blobs of LP magma from depth (see the Introduction for references related to these issues). Nonetheless, the presence of an interface between these two distinct magma regions represents one of the most debated arguments among volcanologists working at Stromboli. According to data provided by melt inclusions, Métrich et al. (2001, 2005) inferred that the rising of LP magmas could be triggered at pressures ≥240 MPa, possibly ~300–350 MPa for the most powerful paroxysms. Yet the depth to which the LP magma reservoir extends in the conduit is still poorly constrained.

Determining the exact pressure-depth domain for magma that was discharged during the 9 January 2005 explosion requires knowledge of the original volatile content and is beyond the scope of this paper. Nonetheless, on the basis of the intermediate compositional and textural character of the ejected tephras, we suggest that the 9 January 2005 explosion was generated by the sudden decompression of a magma supplied from a region of intermediate depth between the LP and HP magma reservoirs. Our hypothesis is in agreement with findings from Landi et al. (2008), which indicate that the mineralogical and compositional characteristics of the products from the 9 January 2005 explosion are consistent with crystal dissolution and re-crystallization in a recycled magma pocket rising from a depth ≤1.8 km. The results of our study suggest that this magma rose through and partially mingled with the normal HP magma, and bypassed the upper conduit region of Stromboli producing an explosion with features intermediate between normal Strombolian explosions and paroxysmal activity. This hypothesis may also provide a feasible explanation for magma dynamics of other intermediate explosions occurring at Stromboli.

7. Conclusive remarks

Several implications arise from our multidisciplinary investigation of the 9 January 2005 explosion. First, real time monitoring of eruptive activity, together with characterization of samples collected during high energy explosions, have proved to be a valid tool in investigating the range of explosive styles that characterise Stromboli. Recognizing explosive events whose intensity, style and features of the erupted tephra are intermediate between normal Strombolian and paroxysmal activity opens new perspectives in the assessment of mechanisms triggering paroxysms and the related volcanic hazard. In addition, by analogy to other high energy explosions recorded by the video-camera system and presenting volcanological characteristics comparable to the 9 January 2005 explosion, we suggest that intermediate explosive activity can be recurrent at Stromboli, and that in the past this type of activity has either been overlooked or directly included within normal Strombolian activity. Our preliminary results indeed highlight the need to study a larger number of explosions in detail in order to fully characterize intermediate explosions. Finally, a better understanding of high energy Strombolian explosions may improve new monitoring techniques aimed at detecting precursory signals. This would boost our ability to forecast volcanic events and assess volcanic hazard at Stromboli and other persistently active basaltic volcanoes.

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