Bull Volcanol (2014) 76:841
DOI 10.1007/s00445-014-0841-7

RESEARCH ARTICLE

Major eruptive style changes induced by structural modifications of a shallow conduit system: the 2007–2012 Stromboli case

S. Calvari · A. Bonaccorso · P. Madonia · M. Neri · M. Liuzzo · G. G. Salerno · B. Behncke · T. Caltabiano · A. Cristaldi · G. Giuffrida · A. La Spina · E. Marotta · T. Ricci · L. Spampinato

Received: 17 February 2014 / Accepted: 11 June 2014 / Published online: 20 June 2014

Abstract Stromboli is known for its mild, persistent explosive activity from the vents located within the summit crater depression at the uppermost part of the Sciara del Fuoco (SdF) depression. Effusive activity (lava flows) at this volcano normally occurs every 5–15 years, involving often the opening of eruptive fissures along the SdF, and more rarely overflows from the summit crater. Between the end of the 2007 effusive eruption and December 2012, the number of lava flows inside and outside the crater depression has increased significantly, reaching a total of 28, with an average of 4.8 episodes per year. An open question is why this activity has become so frequent during the last 6 years and was quite rare before. In this paper, we describe this exceptional activity and propose an interpretation based on the structural state of the volcano, changed after the 2002–2003 and even more after the 2007 flank effusive eruption. We use images from the Stromboli fixed cameras network, as well as ground photos, plume SO_2 and CO_2 fluxes released by the summit crater, and continuous fumarole temperature recording, to unravel the interplay between magma supply, structural and morphology changes, and lava flow output. Our results might help forecast the future behaviour and hazard at Stromboli and might be applicable to other open-conduit volcanoes.

Editorial responsibility: M.R. Patrick

S. Calvari (✉) · A. Bonaccorso · M. Neri · G. G. Salerno · B. Behncke · T. Caltabiano · A. Cristaldi · A. La Spina · L. Spampinato
Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo-sezione di Catania, Piazza Roma 2, 95125 Catania, Italy
e-mail: sonia.calvari@ct.ingv.it

A. Bonaccorso
e-mail: alessandro.bonaccorso@ct.ingv.it

M. Neri
e-mail: marco.neri@ct.ingv.it

G. G. Salerno
e-mail: giuseppe.salerno@ct.ingv.it

B. Behncke
e-mail: boris.behncke@ct.ingv.it

T. Caltabiano
e-mail: tommaso.caltabiano@ct.ingv.it

A. Cristaldi
e-mail: antonio.cristaldi@ct.ingv.it

A. La Spina
e-mail: alessandro.laspina@ct.ingv.it

L. Spampinato
e-mail: letizia.spampinato@ct.ingv.it

P. Madonia · M. Liuzzo · G. Giuffrida
Istituto Nazionale di Geofisica e Vulcanologia, sezione di Palermo, Via Ugo La Malfa, 153-90146 Palermo, Italy

P. Madonia
e-mail: paolo.madonia@ingv.it

M. Liuzzo
e-mail: marco.liuzzo@ingv.it

G. Giuffrida
e-mail: giovanni.giuffrida@ingv.it

E. Marotta
Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano–sezione di Napoli, Via Diocleziano 328, 80124 Naples, Italy
e-mail: enrica.marotta@ov.ingv.it

T. Ricci
Istituto Nazionale di Geofisica e Vulcanologia, sezione di Roma 1, Via di Vigna Murata 605, Rome, Italy
e-mail: tullio.ricci@ingv.it

Keywords Stromboli · Effusive activity · Structural and morphology changes

Introduction

Stromboli volcano is well known for its mild, persistent explosive activity at the summit crater characterised by discrete bursts every 5–20 min (e.g. Chouet et al. 1974; Patrick et al. 2007). With a frequency of about twice a year between 1999 and 2002, major explosions occur at the summit (Bertagnini et al. 1999; Landi et al. 2008; Andronico and Pistolesi 2010), causing ejection of bombs for several hundred metres around the crater area. Paroxysms are rarer and greater explosive events, throwing blocks up to 4 m wide to 2-km distance, causing destruction of buildings and severe damage to the inhabited areas, located less than 2 km away from the summit (e.g. Rittmann 1931; Calvari et al. 2006, 2011c). The last two paroxysmal events occurred on 5 April 2003 (Calvari et al. 2006; Harris et al. 2008) and 15 March 2007 (Calvari et al. 2010; Bonaccorso et al. 2012; Andronico et al. 2013). The persistent strombolian activity is fed by a degassed, high-porphyritic (HP) magma residing in the upper part of the volcanic conduit (Métrich et al. 2001; Lautze and Houghton 2005; Landi et al. 2008), whereas paroxysms usually involve the gas-rich and crystal-poor low-porphyritic (LP) magma of deeper source (Bertagnini et al. 1999; Métrich et al. 2005; Landi et al. 2008). Effusive activity occurs every 5–15 years (Barberi et al. 1993), mainly with lava flows from flank eruptive fissures spreading along the Sciara del Fuoco (SdF), a depression that cuts the NW flank of the island (Fig. 1). Overflows from the summit crater or intracrater lava flows (i.e. lava flows confined within the summit crater depression) are quite rare, normally small (less than 500 m long) and of short duration (hours), and their occurrence indicates a very high magma level within the feeder conduit that has often preceded major flank effusive events (e.g., Calvari et al. 2005a, b; Burton et al. 2008; Di Traglia et al. 2014). Thus, when overflows happen, there is an increasing concern for the possibility of an impending flank eruption (Bertolaso et al. 2008). Between the end of the 2007 effusive eruption, in April and December 2012, the output of lava flows has increased significantly, with 28 episodes (Table 1) bringing the average to 4.8 effusive events/year. In this paper, we describe this activity and relate it to the structural context of the volcano, deeply modified by the flank effusive eruptions and lateral failure that occurred along the SdF after 2002 (Bonaccorso et al. 2003; Tommasi et al. 2005; Acocella et al. 2006; Neri et al. 2008; Neri and Lanzafame 2009; Di Traglia et al. 2013, 2014). We describe the eruptive activity using the Istituto Nazionale di Geofisica e Vulcanologia (INGV) network of fixed cameras (Fig. 1) and field surveys detailing the morphological changes of the crater area over time. We use SO_2 and CO_2 flux measurements representative of the bulk plume (e.g. Aiuppa et al. 2009) and continuous temperature monitoring of low temperature (t<100 °C) fumaroles (e.g. Madonia and Fiordilino 2013) to relate the crater and eruptive activity changes with the deep magma supply. We then present an interpretative model that allows some insight on the future behaviour and that might have important implications for the hazard evaluation at this and other open-conduit volcanoes.

Structural framework

The volcanism of the Aeolian Volcanic Arc (AVA, Fig. 1a) is the result of the subduction of the Ionian crust beneath the Calabrian Arc (e.g. Barberi et al. 1974). Stromboli is the easternmost island of the arc, and recent eruptive activity has occurred along a prevailing NE-SW direction (Hornig-Kjarsgaard et al. 1993; Keller et al. 1993). This is also the orientation of the Vallonazzo tectonic structure, an eruptive fissure ~8.7 ka old and 700 m long, striking N40° E (Fig. 1b) and located between 270 and 100 m a.s.l. on the NE flank of Stromboli (Hornig-Kjarsgaard et al. 1993; Keller et al. 1993; Calvari et al. 2011a; Wijbrans et al. 2011; Francalanci et al. 2013) and which has weak fumarolic activity at its upper end. The present persistent explosive activity occurs from an open conduit elongated NE-SW (Hornig-Kjarsgaard et al. 1993; Keller et al. 1993; Acocella et al. 2006; Neri and Lanzafame 2009) and located in the uppermost portion of the SdF depression, which formed by several sector collapses during the last 13 ka (e.g. Tibaldi 2001). The conduit feeds three vent zones aligned NE-SW and located at ~750 m a.s.l. within the summit crater (Fig. 1c): the NE Crater zone (NEC), Central Crater zone (CC) and SW Crater zone (SWC) (Fig. 1d). Several vents are within each of the crater areas. The vents have changed in number and size as a function of the magma level within the conduit (e.g. Spampinato et al. 2008), but their position (Fig. 2a) has been remarkably constant over more than a century (Anderson 1905; Washington 1917; photos Fondo Ponte, www.ct.ingv.it). The source of explosions and tremor is located at depths shallower than 200 m beneath the summit crater (Chouet et al. 1997) and shifted NW towards the SdF (Martini et al. 2007), with most of the seismic energy radiated by a small volume at ~100-m depth beneath the SdF (Chouet et al. 2003). Thus, the uppermost part of the volcanic conduit is close to the SdF surface and is prone to be intersected and/or structurally conditioned by shallow landslides, as happened during the 2002–2003 and 2007 flank eruptions (Bonaccorso et al. 2003; Calvari et al. 2005a, b; Martini et al. 2007; Neri and Lanzafame 2009; Zanon et al. 2009; Casagli et al. 2010; Di Traglia et al. 2014).

At the onset of the 2002–2003 eruption, several fractures opened around the summit crater (Calvari et al. 2005a; Finizola et al. 2009). The spreading of an eruptive fissure triggered a hot avalanche that expanded to the sea (Calvari

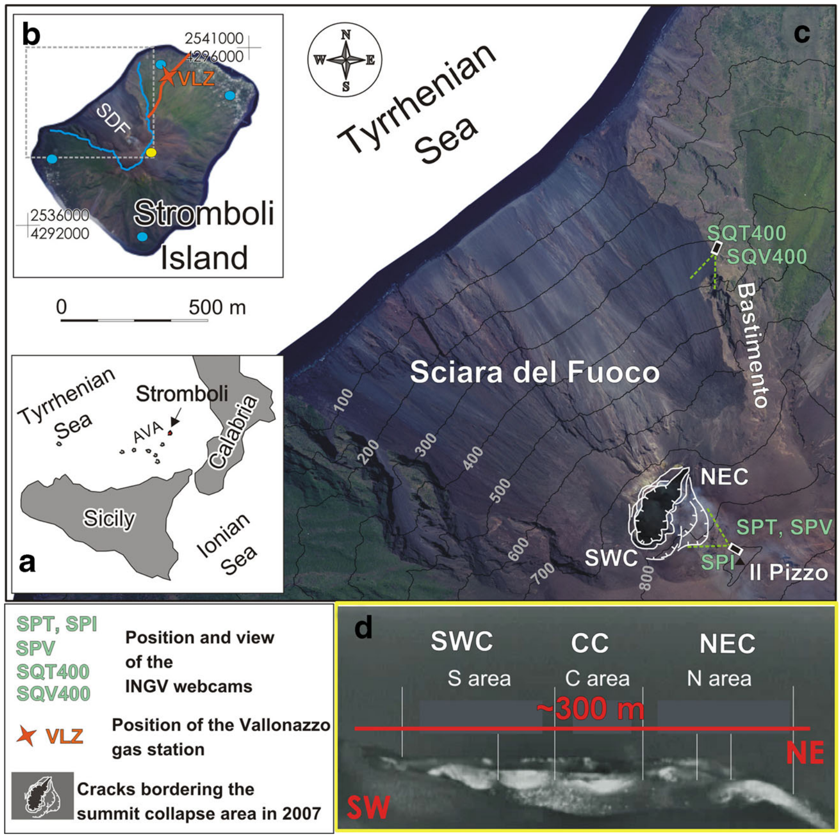

Fig. 1 **a** Location of the Aeolian Volcanic Arc (AVA) in the southern Tyrrhenian Sea, with the easternmost Stromboli island (*arrow*); (**b**) map of Stromboli showing the Sciara del Fuoco depression outline (*SDF*, *blue line*), with the *square* showing the area magnified in "c", the Vallonazzo fault system (*orange line*) with location of the fumarole temperature station (*VLZ*, *orange star*), and the position of the stations for the measurements of SO_2 gas flux (*blue dots*) and of the CO_2/SO_2 MultiGAS stations (*yellow dot*); **c** NW sector of Stromboli showing its summit crater and the three vent areas (*NEC* NE Crater area, *CC* Central Crater area, *SWC* SW Crater area), the location of the INGV monitoring cameras (*green*: *SPI*, *SPT* and *SPV* at Il Pizzo; SQT400 and SQV400 at 400-m elevation on the E flank of the Sciara del Fuoco); **d** view of the summit crater from Il Pizzo, and distinction of the crater areas, with the position of the main vents

et al. 2005a, b; Pioli et al. 2008), and a failure along the SdF caused two large landslides and tsunami (Bonaccorso et al. 2003; Tommasi et al. 2005; Chiocci et al. 2008). Tommasi et al. (2005) considered the shallow intrusion of a magma body as the trigger of the two landslides. The eruptive fissure drained completely the lava from the summit crater, which collapsed into a NE-SW elliptical depression. The NW displacement of the SdF slope due to the landslides formed on the upper SdF a number of step-like blocks (Bonaccorso et al. 2003). A few NW-SE aligned vents opened during this eruption, which Acocella et al. (2006) attributed to dike with this orientation. The unstable eastern portion of the SdF then fragmented into large blocks and caused several small collapses (Tommasi et al. 2005; Falsaperla et al. 2008), but most of the movements ceased after the eruption, and the lava flow field had instead the effect of stabilising the SdF slope from further erosion (Chiocci et al. 2008; Falsaperla et al. 2008). No major deformation was observed until 2007 (Bonaccorso et al. 2008), when during the initial phases of this next eruption the summit crater collapsed (Calvari et al. 2010; Fig. 2b), displacing $1–3\times10^6$ m^3 rocks (Neri and Lanzafame 2009; Casagli et al. 2010). This was a crucial turning point for the volcano, because for the first time ever, the ground deformation monitoring system, emplaced in 1992 (Bonaccorso 1998) and implemented in 2003 (Mattia et al. 2004) and comprising permanent GPS and tilt networks, detected a clear deflation of the entire volcanic edifice (Bonaccorso et al. 2008). The overall volcano deflation was strongly amplified in the summit crater area, where a massive collapse dramatically changed the morphology of the summit crater (Fig. 2a, b). Such a fast and impressive structural change had not been observed at this volcano in over a century (e.g. Anderson 1905; Washington 1917; photos Fondo Ponte, www.ct.ingv.it).

Methods

Morphology changes of Stromboli's summit are herein investigated using images recorded by fixed cameras and sporadic photos taken during field surveys at Il Pizzo (Fig. 1c). Photos have been taken using one of the two Canon PowerShot advanced compact/bridge cameras (S3 and SX1IS), which

Table 1 List of the effusive events (LF) and major explosions (ME) that occurred at Stromboli between 1 April 2007 and 31 December 2012

Date	Time GMT	Activity	Out of the crater/magma type	Reference	Event no.
29 Feb. 2008	02:17	Major expl. from CC vent. Fallout along SdF	HP	INGV Reports	ME 1
9 July 2008	05:40	Major expl. from CC vent, cone disruption; ash expl. from NEC	HP	INGV Reports	ME 2
7 Sept. 2008	07:34	Major explosion from SWC and CC	HP	INGV Reports Calvari et al. 2012	ME 3
12–13 Sept. 2008	00:00–07:00	Lava fountains and lava flow from the rim of SWC spreading around the CC vent area	NO	T. Ricci photos, SPI videos and Cerberus images	LF 1
16 Nov. 2008	13:46	Small lava ponds inside the 2 NEC vents	NO	T. Ricci photos, SPI videos	LF 2
6 Dec. 2008	20:49	Major explosion from the SWC and CC vents. Fallout along the Sciara del Fuoco	HP	T. Ricci photos, INGV Reports	ME 4
17 Dec. 2008	13:32	Major explosion from the SWC and CC vents. Poor visibility	N.A.	INGV Reports	ME 5
3 Jan. 2009	21:07	Major explosion. Poor visibility	N.A.	INGV Reports	ME 6
29 March 2009	02:41	Small overflow from NEC during intense spattering	YES	M. Ripepe personal communication	LF 3
22–26 Apr. 2009		Small lava flow from CC vent, ~40 m long and a few meters wide, lasting 3 days	NO	M. Zaia personal communication, INGV Report	LF 4
3 May 2009	14:58	Major explosions in 2 phases, starting from the CC and then from the SWC vents. Fallout along the Sciara del Fuoco	LP	INGV Reports La Felice and Landi 2011 T. Ricci photos	ME 7
3–5 May 2009		Intracrater lava flow from CC ~60 m long and ~30 m wide	NO	INGV Reports T. Ricci photos	LF 5
17–18 May 2009	16:15–18:00	Low fountaining from 2 CC vents and a small flow from SWC	NO	T. Ricci photos, SPI videos	LF 6
30 Aug. 2009	11:00–21:00	Low fountaining and 2 overflows (NE and SE) ~50 m long from the CC vent	NO	T. Ricci photos, SPI videos	LF 7
8 Nov. 2009	12:28–13:40	Strong explosive sequence and intracrater lava flow from CC vent	NO	Andronico and Pistolesi 2010 La Felice and Landi 2011	LF 8
24 Nov. 2009	11:20	Major explosive sequence from CC vent	LP	Andronico and Pistolesi 2010 La Felice and Landi 2011 T. Ricci photos	ME 8
7–8 Jan. 2010	12:54	Lava flow from the CC vent, spreading within the crater	NO	T. Ricci photos	LF 9
10 Jan. 2010	14:48	Lava flow from the CC vent, spreading within the crater. Destruction hornitos NEC	NO	T. Ricci photos Rosi et al. 2013	LF 10
21 Jan. 2010	20:45	Major explosion from CC	N.A.	Rosi et al. 2013	ME 9
10 March 2010	06:11	Strong explosive event, ejecta outside the crater, rheomorphic lava flows to NE	YES	INGV Reports	LF 11
24 May 2010	19:12	Rheomorphic lava flows	YES	INGV Reports	LF 12
25 June 2010	06:02	Major explosion	N.A.	INGV Reports	ME 10
30 June 2010	16:33	Major explosion with emission of LP magma	LP	INGV Reports, T. Ricci photos	ME 11
19–26 Oct. 2010		Intracrater lava flow from SWC vent	NO	INGV Reports T. Ricci photos	LF 13
10 Dec. 2010	14:37	Major explosion from SWC	N.A.	INGV Reports	ME 12
12 Dec. 2010	02:00–06:00	Intense spattering from CC vent and lava flows along the Sciara	YES	INGV Reports T. Ricci photos	LF 14
19 Dec. 2010	09:55	Major explosion (3 pulses of growing intensity from seismicity)	N.A.	INGV Reports	ME 13
26–27 Jan. 2011	20:00–05:45	Low fountaining from CC vent and emplacement of three intracrater lava flows to NE and E	NO	INGV Reports	LF 15
4 March 2011	12:25	Major explosion (2 pulses) from SWC (from seismicity)	N.A.	INGV Reports Poor visibility from SPT	ME 14
20 June 2011	05:19	Major explosion (2 pulses) from CC	N.A.	INGV Reports	ME 15
5 July 2011	02:45	Major explosion (3 pulses) from CC	LP	INGV Reports	ME 16
10 July 2011	15:21	Major explosion from SWC and CC areas	N.A.	INGV Reports, SPT video	ME 17
17 July 2011	20:45	Major explosion from NEC	N.A.	INGV Reports, SPT images	ME 18
1–2 Aug. 2011	23:00	Lava flow from NEC spreading on Pianoro and along SdF up to ~500 m a.s.l	YES	INGV Reports, SPT video	LF 16
5 Aug. 2011	07:00–09:00	Intense spattering and lava flow from CC	NO	INGV Reports, SPT video	LF 17
9–12 Aug. 2011	07:27–13:25 (9 Aug) 09:00 (12 Aug)	Intense spattering and overflow from CC. Lava flow within the crater only a few tens of metres long	NO	INGV Reports, SPT video	LF 18
15 Aug. 2011	19:33	Major expl. with 2 pulses from NEC and 1 from SWC	N.A.	INGV Reports	ME 19
16–19 Aug. 2011	12:40	Rheomorphic lava flows from SWC hornito spreading along the Sciara del Fuoco for ~100 m	YES	INGV Reports, T. Ricci photos SQT video	LF 19

Table 1 (continued)

Date	Time GMT	Activity	Out of the crater/magma type	Reference	Event no.
20 Aug. 2011	01:30–10:00	Low fountaining from the SWC hornito forming a rheomorphic lava flow spreading NE for ~60-m distance and widening on the crater floor to ~20-m front, active for 8.5 h	NO	SPT video	LF 20
26 Aug. 2011	01:00–03:30	Intense spattering from the SWC hornito forming a rheomorphic lava flow spreading N for ~40 m, active 2.5 h	NO	INGV Reports, SPT video	LF 21
30 Aug. 2011	05:06	Major explosion from NEC, 1 big bomb to Pizzo, incandescent for ~2 h	N.A.	SPT video	ME 20
30 Aug. 2011	14:00–23:59	A small lava flow with 2 branches ~40 m long and a few meters wide, spreading towards NE and S, forms from the CC zone and remains active for ~10 h	NO	SPT video	LF 22
5 Sept. 2011	03:52	Major explosion from CC and NE crater zones, low lava fountaining from CC	N.A.	SPT video	ME 21
6–7 Sept. 2011	18:50–19:50, 09:00–16:30	Intense spattering from the SW crater zone, with small rheomorphic lava flow inside the crater	NO	INGV Reports, SPT video	LF 23
15 Feb. 2012 16 Febr. 2012	22:08 04:17	Major explosive sequences from NEC with at least 5 pulses followed by a phase of intense fountaining, fallout of bombs on the Sciara and Pizzo and hot landslides	N.A.	INGV Reports, SQT and SQV images	ME 22 ME 23
6 March 2012	06:43 06:45	Major explosions from NEC with fallout of bombs to NNE, probably up to Bastimento, and bombs also at Il Pizzo	N.A.	INGV Reports, SQT and SQV images	ME 24
5 July 2012	20:15	Intense and almost continuous fountaining from the hornito located on the northern rim of SWC, with spatter falling along the Sciara del Fuoco and evolving into a rheomorphic lava flow lasting ~2 h	YES	INGV Reports, SQT and SQV images	LF 24
7–8 July 2012	23:00	Intense and almost continuous fountaining from the hornito located on the northern rim of SWC, with spatter falling along the Sciara del Fuoco and evolving into a lava flow lasting ~1 h	YES	INGV Reports, SQT and SQV images	LF 25
10 July 2012	04:00	Major explosion from the NEC, with a landslide along the Pianoro	N.A.	SQT images	ME 25
26 July 2012	18:31	Major explosion from the NEC, with a small landslide along the Sciara del Fuoco	N.A.	SQT images	ME 26
6 Aug. 2012	12:01	Intense spattering from the CC, with spatter within the crater terrace and a small lava flow spreading up to the base of the cone	NO	INGV Reports, SPT and SPV images	LF 26
22 Nov. 2012	13:18 15:50 20:57	Major explosions from NE and CC crater areas (13:18 and 20:57), with a few bombs to Pizzo, low fountaining from SW (15:50)	N.A.	INGV Reports	ME 27
18 Dec. 2012	12:50–19:00	Strong spattering from the NE crater, with welded spatter flowing along the upper slope of Sciara del Fuoco	YES	INGV Reports	LF 27
23–27 Dec. 2012	07:25	Lava flow pouring out from the NE crater rim on 23 and 25–27 Dec, intense spattering on 24	YES	INGV Reports	LF 28

No explosive or effusive events occurred between 1 April 2007 and 29 February 2008

CC Central Crater, *SWC* SW Crater, *NEC* NE Crater, *HP* high-porphyritic magma, *LP* low-porphyritic magma, *N.A.* information not available, *ME* major explosion, *LF* lava flow

obtains panoramic shots from multiple images (Fig. 3). The quantification of explosive activity was carried out using the INGV visual monitoring system. This comprises thermal infrared and visual cameras located at Il Pizzo (SPI, SPT, SPV, Fig. 1c), at ~250 m from the craters, plus one visual and one thermal infrared camera (SQV400 and SQT400) at 400-m elevation on the E flank of the SdF (Fig. 1c). The latter two cameras are located at ~800 m from the crater terrace and allow a view from NE of the NEC and of the upper eastern sector of the SdF. All images also record date in the format dd/mm/yy and time in UT format hh:mm:ss. To obtain a semi-quantitative description of the eruptive activity, we used the images recorded by the SPI, SPT and/or SPV cameras, viewing the entire crater area. We manually counted the total number of events that occurred during each day of cloud-free observation and divided by 24 h, plotting the results as an integer. On average, less than 5 % of the days were affected by clouds. When the Il Pizzo cameras were not available, the counting was carried out using the SQT400 and SQV400 cameras.

SO_2 was measured by means of the FLAME network (Burton et al. 2009; Salerno et al. 2009a, b), which comprises

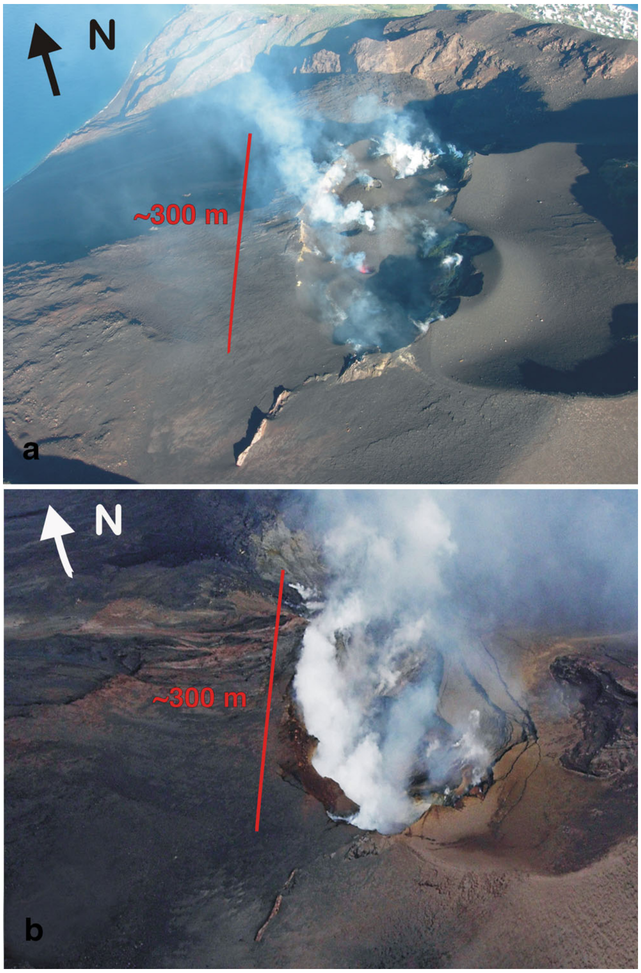

Fig. 2 **a** Helicopter photo of Stromboli summit taken from SW on 20 January 2006 and showing the summit crater area before the start of the 2007 flank effusive eruption. The floor of the summit crater area is close to the crater rim and displays several degassing vents and cinder cones. Photo INGV. **b** Helicopter photo of Stromboli taken from SW on 7 March 2007 showing the summit collapses and the opening of large arcuate fractures surrounding the crater depression. Photo by A. Bonaccorso

four scanners installed in late 2004 at a distance of ~2 km from the summit of the volcano (Fig. 1b). Each scanner comprises a S2000 spectrometer from Ocean Optics Inc. with optical resolution of 1.1 nm FWHM in the 290–380 nm UV wavelength region. An anemometer measures wind speed and direction. SO_2 was measured daily and observations spanned from 6:00 to 14:30 and from 5:30 to 17:30 UT in winter and summer time, respectively. Error in SO_2 flux ranged between −22 % and +36 % (Salerno et al. 2009b). CO_2 flux is calculated by combining the measurements of the CO_2/SO_2 plume ratio from the MultiGAS network and the SO_2 flux obtained from the FLAME network using a procedure described by Aiuppa et al. (2010). The MultiGAS network consists of two fully automated instruments for the determination of CO_2 and SO_2 concentrations in the volcanic plume, located at Il Pizzo (Fig. 1b), that are equipped with a Gascard NG spectrometer for CO_2 (measurement range 0–3,000 ppm; accuracy ±2 %; resolution 0.1 ppm) and an electrochemical sensor (CiTicel, City Technology Ltd., calibration range 0–30 ppmv; repeatability 1 %; resolution 0.1 ppm) for SO_2. Fumarole temperature, representative of water vapour flux variations (Madonia and Fiordilino 2013), was monitored at Vallonazzo (Fig. 1b) using an Onset Micro-Station logger equipped with a 12-bit temperature smart sensor operating in the range −40–85 °C with a resolution of 0.03 °C, installed at 2-m depth inside the fracture. Sampling period was 4 min, and an hourly value records the average of 15 measurements.

Intracrater lava flows and overflows before 2007

Between the 1975 and 1985–1986 flank eruptions (Capaldi et al. 1978; De Fino et al. 1988) and the 1990s, documentation of eruptive activity at Stromboli is rather incomplete, and therefore, only the period since 1990 is considered here. Intracrater lava flows and minor overflows between 1990 and 2002 are documented only in five cases: (1) April–May 1993, (2) August 1994, (3) August 1996, (4) sometime between May 2000 and May 2001, and (5) November 2002. The April–May 1993 lava flow followed a phase of vigorous spattering from the NEC and culminated with the emission of two lava flows ~100 m long exiting the NEC area (Smithsonian Institution 1993). During the second half of August 1994, a small lava flow extruded from the NEC and descended a few tens of metres down the NE portion of the SdF. The August 1996 lava flow was emitted from SWC and advanced only a few metres within the crater depression (Smithsonian Institution 1997). A small lava flow was emplaced sometime between May 2000 and May 2001 within the crater (Smithsonian Institution 2001), and another small lava flow on the N outer flank of the crater depression was observed on November 2002 (Burton et al. 2008). No further effusive episodes were detected between the end of the 2002–2003 eruption and the start of the 2007 flank eruptive event (Calvari et al. 2010).

The 2007–2012 eruptive activity

Morphological changes and eruptive activity

A list of the major eruptive events characterising the 2007–2012 period is given in Table 1, and they are also represented in Fig. 4a. Figure 3 shows the morphology changes of the summit, and Fig. 4b displays the trend of explosive activity at the summit crater obtained from the INGV camera network. The graph shows four eruptive phases (E1 to E4, Fig. 4b). The first (E1) heralded the 2007 flank effusive eruption. After its end on 2 April, Stromboli's crater remained obstructed (Fig. 3a) until 1 July 2007, when strombolian activity

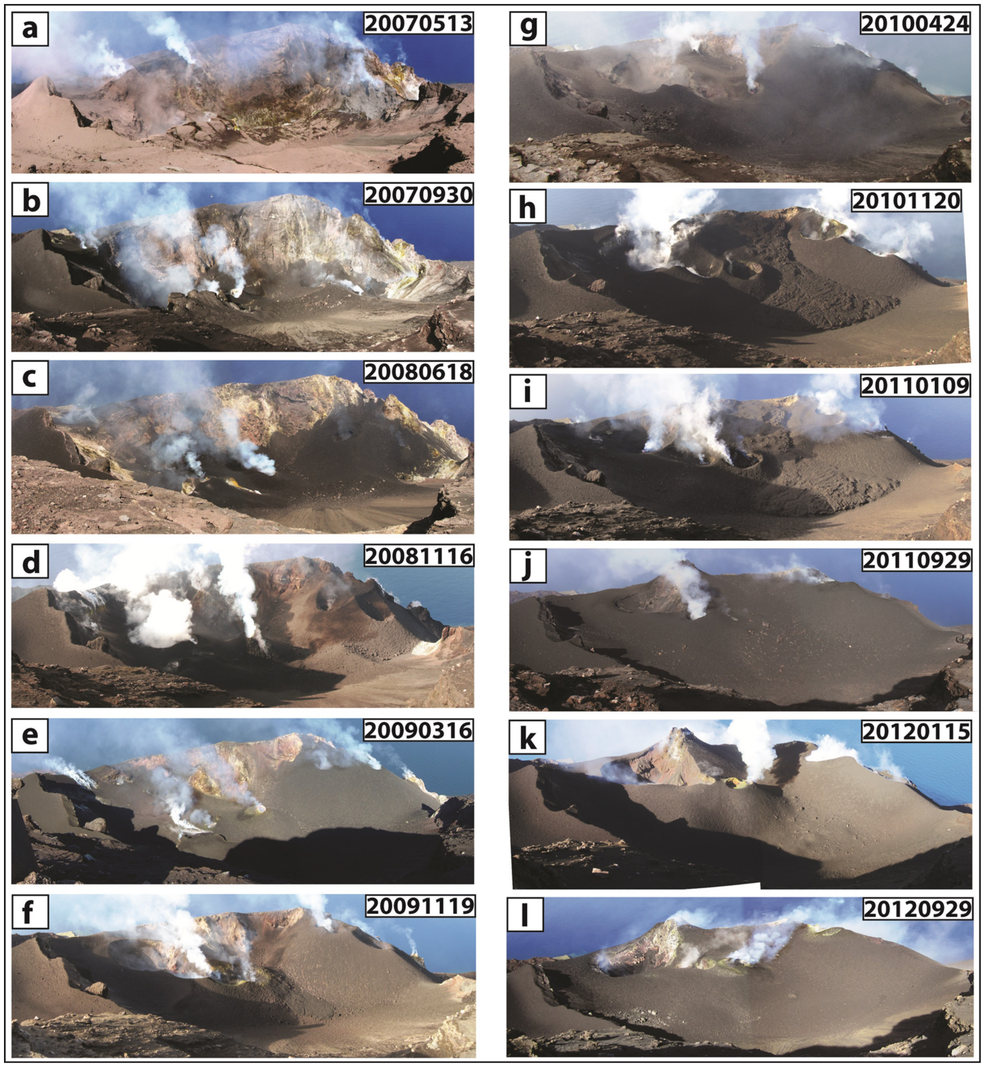

Fig. 3 Photos collected from Il Pizzo showing a view from SE of the crater area, and the morphology changes occurred between 13 May 2007 and 29 September 2012. View is like in Fig. 1d, with orientation of the crater terrace SW-NE (left-right) and field of view ~300 m. The numbers on the top right of each frame represent date in the format yyyymmdd. Photos by T. Ricci

resumed, producing small cinder cones on the crater floor (Fig. 3a, b). From July to the end of 2007, explosive activity was mild, without major explosions or lava flows (Fig. 4a, b). It gradually increased in 2008, including three major explosive events (Table 1, Fig. 4a), and contributing significantly to the growth of the cinder cones, especially on the NEC (Fig. 3c, d). On 13 September 2008, the first effusive event within the crater depression occurred, ~1.5 years after the end of the 2007 flank eruption (Table 1, Fig. 4a). The explosive activity decreased again between September and November, and by December 2008, ejecta and rubble filled most of the summit depression (Fig. 3d, e). The eruptive activity during early 2009 increased significantly (E2 in Fig. 4b, where uncertainty in time is due to a data gap), with several effusive events confined within the crater area and lasting a few days rather than just a few hours (Table 1, Fig. 4a). The growth of the cinder cone on the NEC right above the crater rim (Fig. 3e, f) caused frequent landslides of ejecta falling on the steep SdF slope. A major explosive event occurred on 3 May 2009 (Table 1), during which LP magma was erupted (La Felice and Landi 2011) for the first time since the 15 March 2007 paroxysm (e.g. Pistolesi et al. 2011; Bonaccorso et al. 2012).

The explosive activity was rather mild in 2010, but punctuated by six effusive events and five major explosions (Table 1, Fig. 4a), with the largest flow on 12 December spreading on the SW portion of the SdF (Fig. 5) and reaching an elevation as low as ~400 m a.s.l. During 2010, a hornito started to grow on the SW rim of the crater terrace (Fig. 5). Explosive activity increased early on November (E3, Fig. 4b), followed by a pulsing decline. The January–March 2011 period was characterised by an overall declining trend that increased again in the second half of the year. Nine effusive episodes and eight major explosions characterised the year (Table 1). From April, an increasing explosive trend (E4, Fig. 4b) was followed by a large lava flow erupted between 1 and 2 August from NEC (Fig. 5) which spread along the NE part of the SdF and had the most advanced flow front at ~500-

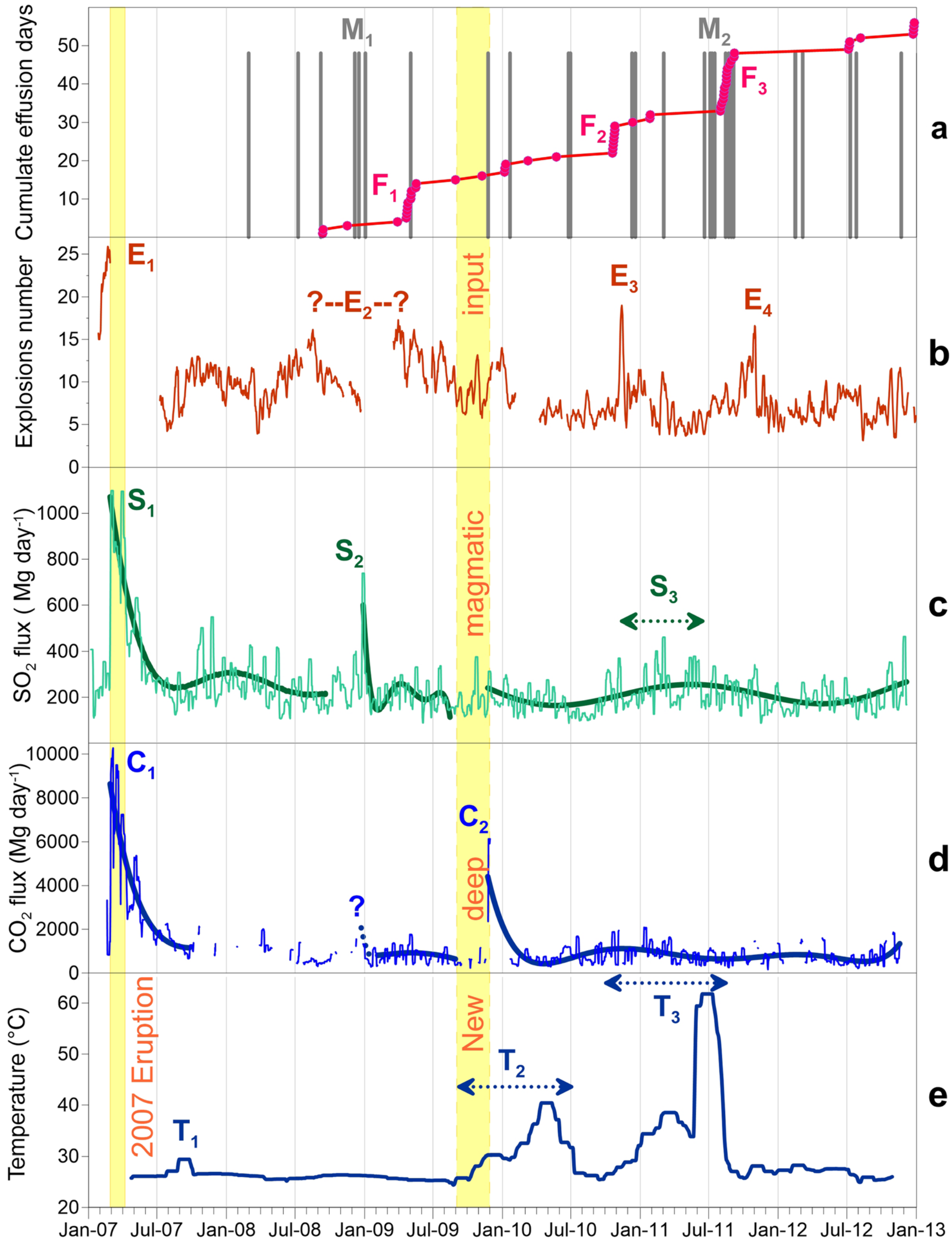

Fig. 4 **a** Time distribution of major explosions (*grey vertical bars*) and cumulative lava flows (*red dots*) occurred at Stromboli between January 2007 and December 2012 and listed in Table 1. The 2007 eruption and the 15 March 2007 paroxysm are comprised within the *first yellow vertical band*. **b** Average daily number of explosions/hour at Stromboli summit crater against time. **c** 95th percentile of the SO_2 flux from the summit crater in Mg/day with polynomial best-fit line. **d** 95th percentile of the CO_2 flux from the summit crater in Mg/day with polinomial best-fit line. **e** 95th percentile of the temperature (°C) recorded at the Vallonazzo fumarole. See text for further explanation

m elevation. The summit crater depression was filled, and a large hornito (Figs. 3i, j and 5) formed on the SWC rim. During 2012, explosive activity was rather stable. Six major explosions and five effusive events occurred in this time, with four flows along the SdF (Table 1, Fig. 4a). Summarising, between January 2007 and December 2012, we observed 28 major explosions and 29 lava flows, with an average of 4.7 and 4.8 episodes per year, respectively. This displays a substantial increase when compared to the frequency of ~2 major explosions per year recorded before 2002 (Bertagnini et al. 1999) and to 1 effusive event every 5–15 years on average over the last three centuries (Barberi et al. 1993).

Degassing regime

The different pressure-related solubility of CO_2, H_2O and SO_2 (Lesne et al. 2011) and the consequent fluxes released by the summit crater and fumarolic field give important signals when gas-rich magma enters the feeder system from the source region (e.g. Allard et al. 1994; Aiuppa and Federico 2004; Aiuppa et al. 2009; Salerno et al. 2009b; Calvari et al. 2011b; Madonia and Fiordilino 2013). Daily fumarole temperature and CO_2 and SO_2 fluxes for the period January 2007-December 2012 (temperature data available since April 2007) are represented in Fig. 4c–e. We plotted the 95th

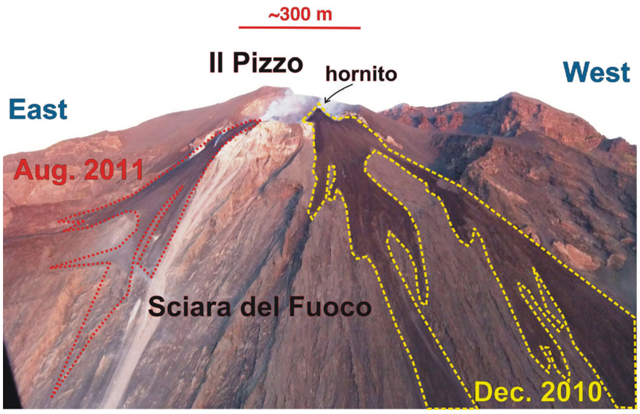

Fig. 5 Helicopter photo taken from NNW on 19 August 2011, showing the hornito growing on the crater rim, the 12 December 2010 (bounded by a *yellow dotted line*) and 1–2 August 2011 (bounded by a *red dotted line*) lava flows. Photo courtesy of Italian national Dipartimento di Protezione Civile

percentile of the measurements, calculated in backward moving weekly windows (1-day step), in order to filter the signals for high-frequency outliers; long-term trends of CO_2 and SO_2 signals are evidenced by polynomial best-fit lines. The thermal signal is characterised by a very stable background value, oscillating 1–2 °C around a mean value of 27 °C, interrupted by three anomalies (T_1 to T_3 in Fig. 4e). The first (T_1) occurred between August and October 2007 and coincided with the renewal of explosive activity from the summit vents. The second (T_2) occurred from September 2009 to July 2010. Despite its larger amplitude (maximum value 42 °C), T_2 occurred in a period of mild explosive activity. The last (T_3, October 2010–July 2011) was the most intense (maximum temperature 65 °C) and accompanied the most turbulent period of volcanic activity (explosion peaks E_3 and E_4, major explosion and effusive event clusters M_2 and F_2–F_3, Fig. 4b, a, respectively). The CO_2 (Fig. 4d) and SO_2 (Fig. 4c) fluxes show a generally similar pattern. Their main peaks (C_1, over 10,000 Mg day^{-1}, and S_1, over 1,000 Mg day^{-1}, respectively) were recorded at the beginning of the 2007 eruption and followed by a rapid decay, modulated by minor oscillations. The second SO_2 peak (S_2, over 700 Mg day^{-1}) occurred on January 2009, at the same time as the E_2 explosion peak (Fig. 4b) and major explosion cluster M_1 (Fig. 4a). The apparent lack of correspondence with a preceding CO_2 anomaly, as expected due to its lower solubility (Lesne et al. 2011), could be ascribed to the paucity of CO_2 measurements during the entire year 2008 (Fig. 4d). A dissimilarity between the two fluxes is evidenced at the end of 2009, when a CO_2 spike (C_2, over 6,000 Mg day^{-1}) was observed on November 2009, in the same period as the onset of thermal anomaly T_2 (Fig. 4e), and not followed by a corresponding SO_2 anomaly. The two signals coupled again few months later and showed a long-lasting (14–16 months) oscillation. This was more evident in the SO_2 flux (S_3, Fig. 4c) with a culmination on March 2011, which was preceded by a weak relative maximum in the CO_2 flux about 2 months earlier. It is noteworthy that the most intense thermal anomaly T_3 (Fig. 4e) occurred at the same time of these oscillations.

Discussion

The structural changes of Stromboli summit crater that occurred between 2002 and 2007 are unprecedented, having not been observed over the past century (e.g. Anderson 1905; Washington 1917; photos Fondo Ponte, www.ct.ingv.it). In addition, 2007 was the first time ever that volcano-wide ground deformation was measured since the installation of our monitoring network in 1992 (Bonaccorso 1998). A clear overall deflation of the entire volcanic edifice in 2007 (Bonaccorso et al. 2008) was strongly amplified in the summit crater area, where a massive collapse dramatically changed the morphology of the summit crater (Fig. 2a, b; Calvari et al. 2010). We believe that these structural changes have modified the shallow feeder conduit from a narrow, straight and efficient pipe, to a wider zone full of hot debris and scoria, partially melted (as represented by Del Moro et al. 2013 in their figure 12), with lava fingering in between. These changes would affect the eruptive style of the volcano by increasing the number of major explosive events and lava overflows from the crater rim and decreasing the possibility of flank effusive eruptions and paroxysms. To support this hypothesis, we use the trends of SO_2 and CO_2 from the plume, and temperature recorded from the Vallonazzo fumarole, which demonstrate that the several-fold increase in the number of lava flows and major explosions is not related to anomalously high supplies of gas-rich magma rising along the conduit. Instead, it relies on shallower processes related to the increased capacity of the uppermost conduit to accommodate a larger amount of magma not in a single, wider volume, but in an articulated fingering system developed beneath the craters.

After the end of the 2007 flank eruption in April, the drainage of magma from the uppermost conduit produced a graben-like summit collapse (Fig. 7a) and a very low magma level. The volcano entered a state of mild activity, with no lava flows or major explosions and a significant decrease in the number of explosions. This was matched by a decreased output of CO_2 (Fig. 4d) and SO_2 (Fig. 4c) from the summit crater. The almost stable temperature measured at the Vallonazzo fumarole (Fig. 4e), interrupted by only a small anomaly (T_1), seems related to changes in the degassing partition ratio between the conduit and the fractures feeding the fumarole (De Gregorio et al. 2007; Madonia and Fiordilino 2013). It took almost 1 year to observe an increase of eruptive activity. The first major explosion occurred on 29 February 2008, followed by the first effusive event inside the crater on 12 September 2008 (Table 1, Fig. 4a). The major explosive events of end 2008–early 2009 (M_1 in Fig. 4a) are associated with a degassing anomaly mainly evidenced by the SO_2 peak S_2 (Fig. 4c), indicating a normal, periodic recharging phase of the shallow magmatic system. The M_1 events did not erupt LP magma that was instead detected during a major explosion on 3 May 2009 for the first time since 2007 (Table 1). The involvement of gas-rich LP magma and the increasing tendency of effusive episodes to spread along the outer slope of the crater in 2009 is indicative of a new phase of deep magmatic recharge, clearly remarked by the CO_2 spike C_2 (Fig. 4d) and by the multi-step increase in fumarole temperature (T_2 and T_3, Fig. 4e). This is accompanied by the filling of the crater depression and by the growth of cinder cones and hornitos on the NE and SW edges of the crater terrace (Fig. 3). This increment was mirrored by a significant increase of radiative power detected by satellite (Coppola et al. 2012). In addition, inflation of the summit during 2009 became detectable by ground-based interferometric synthetic aperture radar (GBInSAR; Di Traglia et al. 2013), and significantly increased before major explosions or effusive events, suggesting the involvement of greater magma volumes in the uppermost conduit when compared to the previous year. With effusive events spreading increasingly outside the crater terrace, also the erupted lava flow volume grew, passing from hundreds to thousands of cubic metres, and with the episodes of 12 December 2010 and 1–2 August 2011 being the largest (Fig. 5).

The intense volcanic activity here described displays some anomalous features when compared to the period preceding the last two flank eruptions: (i) no paroxysmal events accompanied the observed supply of gas-rich LP magma from the source, given that the last paroxysm occurred during the 2007 eruption (e.g. Calvari et al. 2010; Bonaccorso et al. 2012; Andronico et al. 2013); (ii) during its final degassing stage at shallow depth, an upwelled magma batch massively releases SO_2 (see peaks $S_{1–2}$ in Fig. 4c), but this did not happen during the 2010–2011 activity, characterised instead by a relatively quiet, long-lasting degassing; (iii) the ash and bombs erupted during the 2008 persistent explosive activity displayed mingling between LP and HP magma (D'Oriano et al. 2011; Gurioli et al. 2014), whereas before 2002, LP magma was erupted only during paroxysmal or major explosions (Bertagnini et al. 1999; Francalanci et al. 2004; Lautze and Houghton 2005). Following the above considerations, another process should be considered to explain the recent several-fold increase in eruptive activity.

We have shown that the 2002–2003 and 2007 flank eruptions have significantly modified the uppermost conduit of the volcano (e.g. Acocella et al. 2006; Calvari et al. 2005a, b, 2010; Neri and Lanzafame 2009). In fact, the eruptive vents directly connected to the feeder conduit that formed between the crater and the lowest elevation of 400 m a.s.l. along the SdF drained the magma from the upper conduit and caused several collapses of the summit area (Fig. 6). The fractures developed during the initial phases of the 2002–2003 eruption and the landslide scars occurred along the SdF, although shallow, have intersected the outer part of the central conduit (Bonaccorso et al. 2003; Calvari et al. 2005a, b; Tommasi et al. 2005; Acocella et al. 2006) that is located close to the SdF surface (Chouet et al. 2003, 2008; Martini et al. 2007). The further gradual NW displacement of the SdF triggered the opening of two parallel eruptive fissures during the initial phases of the 2007 eruption (Calvari et al. 2010) that evolved into a graben-like collapse structure (Figs. 2b and 6; Neri and Lanzafame 2009), widened by the drainage of $\sim 7–10 \times 10^6$ m^3 of magma (Calvari et al. 2010; Marsella et al. 2012). The plug of solid rock that likely formed within the uppermost conduit produced the downward shift (~100 m deeper from the previous ~500 m a.s.l.) of the seismicity associated to the persistent explosive activity (Martini et al. 2007). Also, the final digestion of this plug by the rising magma was detected by seismicity that moved upwards returning to its previous depth after the end of the 2007 eruption (Martini et al. 2007). The summit collapses, comprising the nested ring fractures (Fig. 2b) and the funnel-like vertical failure of the summit zone, have modified the uppermost conduit from a narrow, straight and efficient pipe to a wider zone full of hot debris and scoria with lava fingering in between, increasing its volume and enhancing its capability to store and keep hot a greater amount of magma (Fig. 7). An upward migration of the isotherm has been recently postulated on the basis of the composition of thermally altered ejecta erupted during the 15 March 2007 paroxysm (Del Moro et al. 2013), displaying the partial melting of the tephra accumulated within the crater during the persistent strombolian activity. Petrologic studies on ash and bombs erupted in 2008 revealed for the first time mingling between degassed (HP) and gas-rich (LP) magma occurred in the uppermost 250 m of the conduit even during persistent, mild strombolian activity (D'Oriano et al. 2011; Gurioli et al. 2014). It is here worth noting that LP magma is normally erupted only during paroxysms or major explosions, not during the mild, persistent strombolian activity (e.g. Bertagnini et al. 1999; Métrich et al. 2005). Thus, a new process must have caused the mingling of LP and HP magma in the uppermost conduit during the persistent strombolian activity. We propose a model based on the observations that suggest the absence of a unique shallow magma storage where critical overpressures can generate paroxysms. Conversely, the accumulation of magma in a finger-like system composed of a network of smaller volumes might have allowed the observed mingling between HP magma resident in the shallow system and the LP magma rising from depth (D'Oriano et al. 2011; Gurioli et al. 2014), thus improving its ability to produce several major explosions rather than few paroxysms. This wider and hotter upper conduit (Fig. 7b) might have

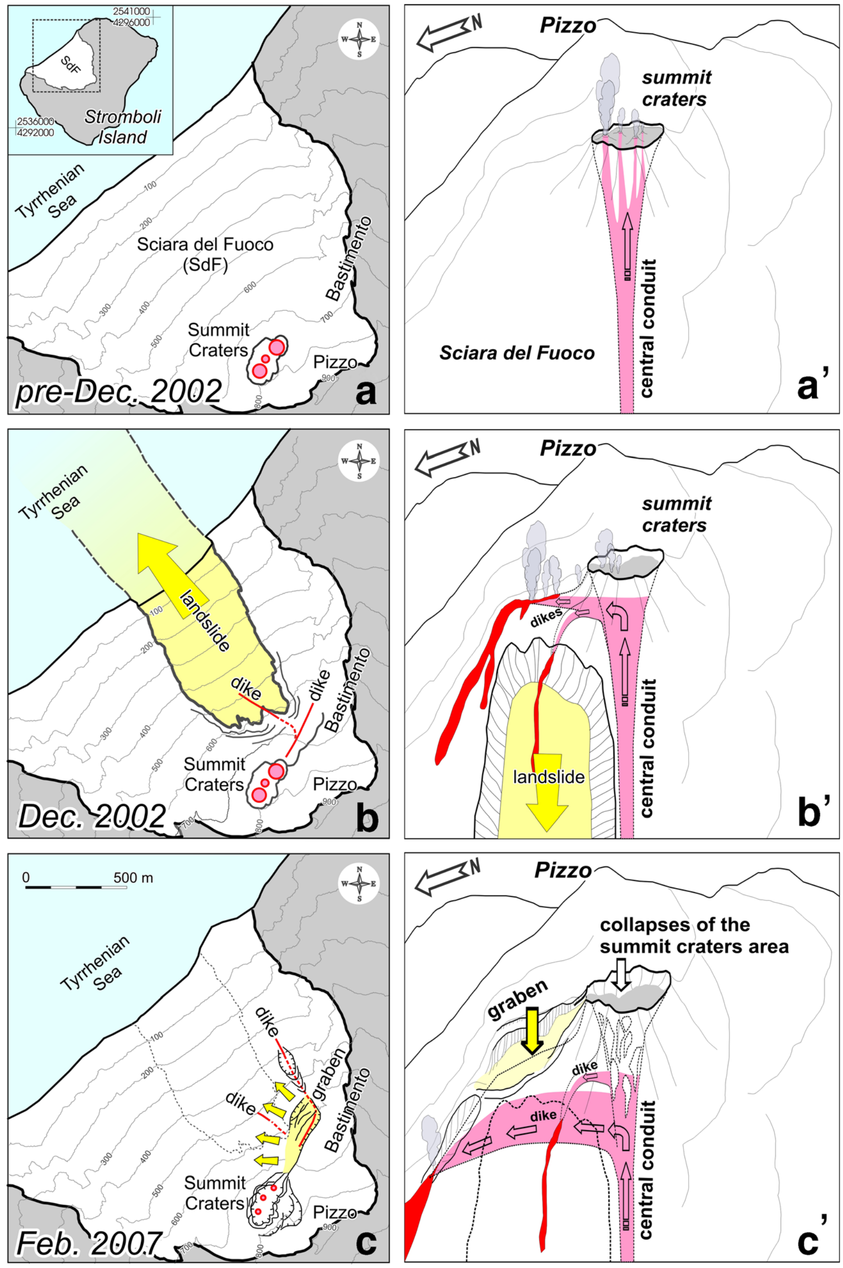

Fig. 6 Plan view (*a*, *b*, *c*) and associated frontal sections (*a'*, *b'*, *c'*) of the shallow feeder system of Stromboli volcano between 2002 and 2007, displaying changes following dike intrusions, landslides and graben-like collapse formation

favoured lava flow inside the crater depression and along the SdF slope, whereas the presence of hot debris within the conduit would have allowed fingering of the rising lava and the growth of cinder cones and hornitos on the edges of the crater. It is worth noting that normally fingering of magma into the country rock produces thin sills that quickly cool down. The process described here instead, involving the uppermost feeder conduit, promotes heat accumulation and promote re-melting of the ejecta previously accumulated within the crater depression during the persistent strombolian activity. This is made possible by the fact that fingering of lava occurs within a volume of hot scoria and ejecta that comprise the uppermost conduit and that is bounded by country rock (Fig. 7b).

The existence of a shallow magma storage articulated in a network of small volumes is well supported by degassing data. Temperature data show large anomalies (T_2 and T_3, Fig. 4e), indicating a shallow source for advective heat, very efficient in transferring water vapour from the magma to the surrounding country rock. This is compatible with the higher surface/volume ratio of a finger-like degassing system rather than of a simple cylindrical conduit. The large, impulsive and short-lasting C_2 anomaly (Fig. 4d), associated to thermal anomaly T_2 (Fig. 4e), can be interpreted as the early clue of

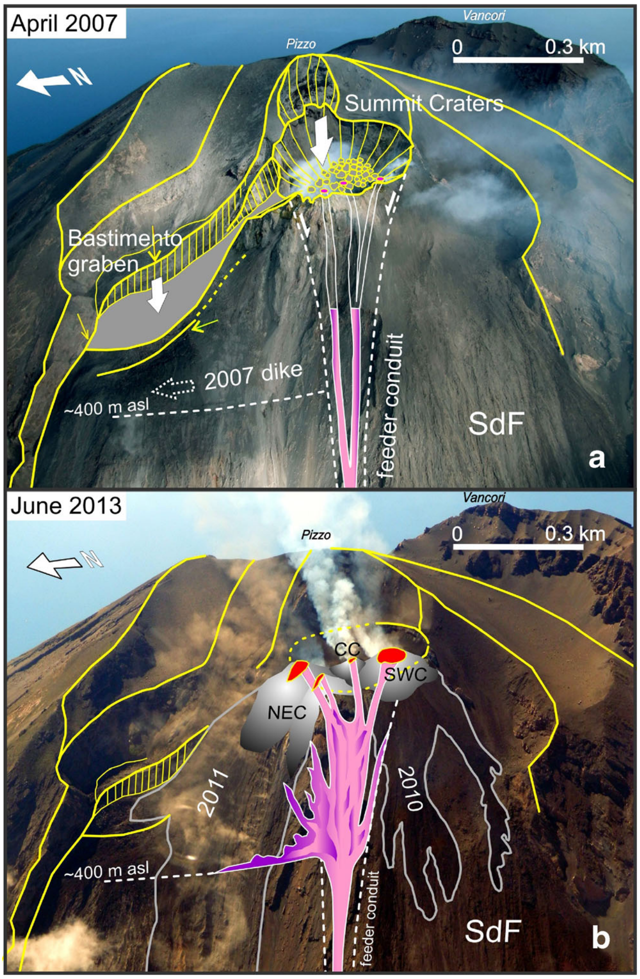

Fig. 7 Aerial photos of Stromboli taken from N, displaying **a** the graben-like collapse formed during the 2007 eruption, and in *pink* the corresponding narrow, pipe-shaped shallow feeder conduit, and **b** the same situation as on June 2013, with the much wider shallow feeder conduit where lava (in *pink*) is fingering in between the debris and scoria. Eruptive vents are in *red*. *Grey lines* in (**b**) indicate the boundaries of the December 2010 and August 2011 lava flows. *SdF* Sciara del Fuoco

the upwelling of a gas-rich LP magma batch. This is later accommodated in the shallower, finger-like storage, where it mingles with an older, degassed magma. During this process, it "quietly" releases its volatile content. The signature of this degassing style is given by the behaviour of CO_2 and SO_2 flux curves (S_3 in Fig. 4c and associated CO_2 signal in Fig. 4d), characterised by mild, long-lasting oscillations rather than by short-lasting, high amplitude spikes.

Concluding remarks

The data presented in this paper show a remarkable increase in effusive activity by overflows from the summit at Stromboli volcano during the more than 5 years spanning the end of the last flank eruption (April 2007) and December 2012. This frequency has increased more than 25 times, passing from one episode every 5–15 years (Barberi et al. 1993) to an average of 4.8 episodes per year between January 2007 and December 2012 (Table 1). Also, during this time period, the number of major explosions increased, passing from the 2 events per year before 2002, to an average of 4.7 episodes per year between January 2007 and December 2012. A supply of gas-rich magma from the source region was detected at the end of 2009 and perhaps also at the end of 2008, by peaks of fumarole temperature, and CO_2 and SO_2 signals (Fig. 4c, d). While this has typically been linked to triggering of paroxysms, no paroxysms occurred in the period of time here considered. This volcano is reckoned for being characterised by a remarkable steady supply (Calvari et al. 2011c; Francalanci et al. 2012), and we lack signs of a greater input from the source region, given that the supply detected between 2008 and 2009 is much less than that causing the 2007 eruption (Fig. 4c, d). Thus, we suggest that the increase of eruptive activity observed at Stromboli from April 2007 to December 2012 was not caused by a greater supply of gas-rich magma from the source, but instead resulted from a wider and hotter uppermost conduit, initiated by movements that occurred in the SdF after the 2002 landslide events (Acocella and Neri 2009; Falsaperla et al. 2008) and that followed the graben-like collapses that occurred during the 2007 eruption, which involved the entire summit crater zone (Neri et al. 2008; Neri and Lanzafame 2009; Zanon et al. 2009; Di Traglia et al. 2013). This is also confirmed by more recent GBInSAR results that indicate an increased magmastatic pressure within the shallow plumbing system causing its lateral expansion (Di Traglia et al. 2014). The summit of the volcano has evolved through the years to form a wider collapse depression in the uppermost conduit, elongated NE-SW. This allows a greater volume of magma to be stored (Fig. 7), which degas at quasi-equilibrium conditions (Fig. 4 and related discussion). This would keep magma hot for longer, thus enhancing the possibility for the HP magma here contained to mingle with the LP magma fed from depth even during the persistent strombolian activity (D'Oriano et al. 2011; Gurioli et al. 2014), rather than forming obstructions below which the LP magma can accumulate and increase its pressure up to the Vulcanian style disruption, typically observed during the paroxysmal events (e.g. Calvari et al. 2006, 2010). This process will probably eventually end with restoration of the previous central conduit path. The present geometric configuration of the shallow portion of the feeder conduit could also favour the release of the magma pressure along conduit walls, decreasing the probability of dike intrusions across the upper conduit walls and favouring an increase of activity at craters. Undetected summit morphology changes might occur at other open-conduit volcanoes; thus, it is extremely important to continuously monitor the summit activity in order to interpret their eruptive behaviour.

Acknowledgments This paper was partially supported by the Project INGV-DPC Paroxysm V2/03, 2007–2009 funded by the Istituto Nazionale di Geofisica e Vulcanologia and the Italian Civil Protection. We would like to thank Maurizio Ripepe for providing videos of the eruptive activity and Mauro Rosi for making available an early preprint of his paper; Mario Pruiti and Mario Zaia for their information and field assistance during summit surveys on the volcano; the Italian Civil Protection for making available their photos from helicopter; Filippo Muré for his technical assistance with the FLAME network; and Emilio Pecora, Emilio Biale, Michele Prestifilippo and Francesco Ciancitto for the maintenance of the INGV webcamera monitoring network. We warmly thank the Associate Editor Matthew R. Patrick, as well as Anthony Finizola, Nicole Lautze and an anonymous reviewer for their appreciation of our work and for the suggestions that have significantly contributed to improve the clarity of a previous version of the paper.

References

Acocella V, Neri M (2009) Dike propagation in volcanic edifices: overview and possible developments. Tectonophysics 471:67–77. doi:10.1016/j.tecto.2008.10.002

Acocella V, Neri M, Scarlato P (2006) Understanding shallow magma emplacement at volcanoes: orthogonal feeder dikes during the 2002–2003 Stromboli (Italy) eruption. Geophys Res Lett 33 (L17310). doi:10.1029/2006GL026862

Aiuppa A, Federico C (2004) Anomalous magmatic degassing prior to the 5th April 2003 paroxysm on Stromboli. Geophys Res Lett 31 (L14607). doi:10.1029/2004GL020458

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

Aiuppa A, Bertagnini A, Métrich N, Moretti R, Di Muro A, Liuzzo M, Tamburello G (2010) A model of degassing for Stromboli volcano. Earth Planet Sci Lett 295:195–204. doi:10.1016/j.epsl.2010.03.040

Allard P, Carbonnelle J, Métrich N, Loyer H, Zettwoog P (1994) Sulphur output and magma degassing budget of Stromboli volcano. Nature 368:326–330

Anderson T (1905) On certain recent changes in the crater of Stromboli. Geogr J 25:123–138

Andronico D, Pistolesi M (2010) The November 2009 paroxysmal explosions at Stromboli. J Volcanol Geotherm Res 196:120–125. doi:10.1016/j.jvolgeores.2010.06.005

Andronico D, Taddeucci J, Cristaldi A, Miraglia L, Scarlato P, Gaeta M (2013) The 15 March 2007 paroxysm of Stromboli: video-image analysis, and textural and compositional features of the erupted deposit. Bull Volcanol 75:733. doi:10.1007/s00445-013-0733-2

Barberi F, Innocenti F, Ferrara G, Keller J, Villari L (1974) Evolution of Eolian Arc volcanism (Southern Tyrrhenian Sea). Earth Planet Sci Lett 21:269–276

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

Bertagnini A, Coltelli M, Landi P, Pompilio M, Rosi M (1999) Violent explosions yield new insights into dynamics of Stromboli volcano. EOS Am Geophys Union Trans 80:633–636

Bertolaso G, Bonaccorso A, Boschi E (2008) Scientific community and civil protection synergy during the Stromboli 2002–2003 eruption. In: Calvari S, Inguaggiato S, Puglisi G, Ripepe M, Rosi M (eds) The Stromboli Volcano: an integrated study of the 2002–2003 eruption. AGU Geophys Monogr Ser 182:387–397. doi:10.1029/182GM31

Bonaccorso A (1998) Evidence of a dyke-sheet intrusion at Stromboli volcano inferred through continuous tilt. Geophys Res Lett 25: 4225–4228

Bonaccorso A, Calvari S, Garfì G, Lodato L, Patané D (2003) Dynamics of the December 2002 flank failure and tsunami at Stromboli volcano inferred by volcanological and geophysical observations. Geophys Res Lett 30(18):1941–1944

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

Bonaccorso A, Calvari S, Linde A, Sacks S, Boschi E (2012) Dynamics of the shallow plumbing system investigated from borehole strainmeters and cameras during the 15 March 2007 Vulcanian paroxysm at Stromboli volcano. Earth Planet Sci Lett 357–358: 249–256. doi:10.1016/j.epsl.2012.09.009

Burton MR, Calvari S, Spampinato L, Lodato L, Pino NA, Marchetti E, Murè F (2008) Volcanic and seismic activity at Stromboli preceding the 2002–2003 eruption. In: Calvari S, Inguaggiato S, Puglisi G, Ripepe M, Rosi M (eds) The Stromboli Volcano: an integrated study of the 2002–2003 eruption. AGU Geophys Monogr Ser 182:93–104. doi:10.1029/182GM09

Burton MR, Caltabiano T, Murè F, Salerno GG, Randazzo D (2009) SO_2 flux from Stromboli during the 2007 eruption: results from the FLAME network and traverse measurements. J Volcanol Geoth Res 18:214–220. doi:10.1016/j.jvolgeores.2008.11.025

Calvari S, Spampinato L, Lodato L, Harris AJL, Patrick MR, Dehn J, Burton MR, Andronico D (2005a) Chronology and complex volcanic processes during the 2002–2003 flank eruption at Stromboli volcano (Italy) reconstructed from direct observations and surveys with a handheld thermal camera. J Geophys Res 110 (B02201). doi:10.1029/2004JB003129

Calvari S, Spampinato L, Lodato L, Harris AJL, Patrick MR, Dehn J, Burton MR, Andronico D (2005b) Correction to "chronology and complex volcanic processes during the 2002–2003 flank eruption at Stromboli Volcano (Italy) reconstructed from direct observations and surveys with a handheld thermal camera". J Geophys Res 110 (B04201). doi:10.1029/2005JB003723

Calvari S, Spampinato L, Lodato L (2006) The 5 April 2003 vulcanian paroxysmal explosion at Stromboli volcano (Italy) from field observations and thermal data. J Volcanol Geoth Res 149:160–175. doi:10.1016/j.jvolgeores.2005.06.006

Calvari S, Lodato L, Steffke A, Cristaldi A, Harris AJL, Spampinato L, Boschi E (2010) The 2007 Stromboli eruption: event chronology and effusion rates using thermal infrared data. J Geophys Res 115 (B04201). doi:10.1029/2009JB006478

Calvari S, Branca S, Corsaro RA, De Beni E, Miraglia L, Norini G, Wijbrans J, Boschi E (2011a) Reconstruction of the eruptive activity on the NE sector of Stromboli volcano: timing of flank eruptions since 15 ka. Bull Volcanol 73:101–112. doi:10.1007/s00445-010-0412-5

Calvari S, Salerno GG, Spampinato L, Gouhier M, La Spina A, Pecora E, Harris AJL, Labazuy P, Biale E, Boschi E (2011b) An unloading foam model to constrain Etna's 11–13 January 2011 lava fountaining episode. J Geophys Res 116 (B11207). doi:10.1029/2011JB008407

Calvari S, Spampinato L, Bonaccorso A, Oppenheimer C, Rivalta E, Boschi E (2011c) Lava effusion—a slow fuse for paroxysms at Stromboli volcano? Earth Planet Sci Lett 301:317–323. doi:10.1016/j.epsl.2010.11.015

Calvari S, Büttner R, Cristaldi A, Dellino P, Giudicepietro F, Orazi M, Peluso R, Spampinato L, Zimanowski B, Boschi E (2012) The 7 September 2008 vulcanian explosion at Stromboli volcano: multi-parametric characterisation of the event and quantification of the ejecta. J Geophys Res 117 (B05201). doi:10.1029/2011JB009048

Capaldi G, Guerra I, Lo Bascio A, Luongo G, Pece R, Rapolla A, Scarpa R, Del Pezzo E, Martini M, Ghiara MR, Lirer L, Munno R, La Volpe

L (1978) Stromboli and its 1975 Eruption. Bull Volcanol 41:259–285

Casagli N, Catani F, Del Ventisette C, Luzi G (2010) Monitoring, prediction, and early warning using ground-based radar interferometry. Landslides 7:291–301. doi:10.1007/s10346-010-0215-y

Chiocci FL, Romagnoli C, Tommasi P, Bosman A (2008) The Stromboli 2002 tsunamigenic submarine slide: Characteristics and possible failure mechanisms. J Geophys Res 113 (B10102). doi:10.1029/2007JB005172

Chouet B, Hamisevicz N, McGetchin TR (1974) Photoballistics of volcanic jet activity at Stromboli, Italy. J Geophys Res 79(32):4961–4976

Chouet B, Saccorotti G, Martini M, Dawson P, De Luca G, Milana G, Scarpa R (1997) Source and path effects in the wave fields of tremor and explosions at Stromboli volcano Italy. J Geophys Res 102:12,915–12,950

Chouet B, Dawson P, Ohminato T, Martini M, Saccorotti G, Giudicepietro F, De Luca G, Milana G, Scarpa R (2003) Source mechanisms of explosions at Stromboli Volcano, Italy, determined from moment-tensor inversions of very-long-period data. J Geophys Res 108(B1):2019. doi:10.1029/2002JB001919

Chouet B, Dawson P, Martini M (2008) Shallow-conduit dynamics at Stromboli Volcano, Italy, imaged from waveform inversions. Geol Soc London Spec Publ 307:57–84. doi:10.1144/SP307.5

Coppola D, Piscopo D, Laiolo M, Cigolini C, Delle Donne D, Ripepe M (2012) Radiative heat power at Stromboli volcano during 2000–2011: twelve years of MODIS observations. J Volcanol Geoth Res 215–216:48–60. doi:10.1016/j.jvolgeores.2011.12.001

De Fino M, La Volpe L, Falsaperla S, Frazzetta G, Neri G, Francalanci L, Rosi M, Sbrana A (1988) The Stromboli eruption of December 6, 1985–April 25, 1986: volcanological, petrological and seismological data. Rend Soc Ital Mineral Petrol 43:1021–1038

De Gregorio S, Madonia P, Gurrieri S, Giudice G, Inguaggiato S (2007) Contemporary total dissolved gas pressure and soil temperature anomalies recorded at Stromboli volcano (Italy). Geophys Res Lett 34 (L08301). doi:10.1029/2007GL029578

Del Moro S, Renzulli A, Landi P, La Felice S, Rosi M (2013) Unusual lapilli tuff ejecta erupted at Stromboli during the 15 March 2007 explosion shed light on the nature and thermal state of rocks forming the crater system of the volcano. J Volcanol Geoth Res 254:37–52

Di Traglia F, Del Ventisette C, Rosi M, Mugnai F, Intrieri E, Moretti S, Casagli N (2013) Ground based InSAR reveals conduit pressurization pulses at Stromboli volcano. Terra Nova 25:192–198

Di Traglia F, Intrieri E, Nolesini T, Bardi F, Del Ventisette C, Ferrigno F, Frangioni S, Frodella W, Gigli G, Lotti A, Stefanelli CT, Tanteri L, Leva D, Casagli N (2014) The ground-based InSAR monitoring system at Stromboli volcano: linking changes in displacement rate and intensity of persistent volcanic activity. Bull Volcanol 76:786. doi:10.1007/s00445-013-0786-2

D'Oriano C, Bertagnini A, Pompilio M (2011) Ash erupted during normal activity at Stromboli (Aeolian Islands, Italy) raises questions on how the feeding system works. Bull Volcanol 73:471–477. doi:10.1007/s00445-010-0425-0

Falsaperla S, Maiolino V, Spampinato S, Jaquet O, Neri M (2008) Sliding episodes during the 2002–2003 Stromboli lava effusion: insights from seismic, volcanic, and statistical data analysis. Geochem Geophys Geosyst 9 (Q04022). doi:10.1029/2007GC001859

Finizola A, Aubert M, Revil A, Schütze C, Sortino F (2009) Importance of structural history in the summit area of Stromboli during the 2002–2003 eruptive crisis inferred from temperature, soil CO2, self-potential, and electrical resistivity tomography. J Volcanol Geoth Res 183:213–227. doi:10.1016/j.jvolgeores.2009.04.002

Francalanci L, Tommasini S, Conticelli S (2004) The volcanic activity of Stromboli in the 1906–1998 AD period: mineralogical, geochemical and isotope data relevant to the understanding of the plumbing system. J Volcanol Geoth Res 131:179–211

Francalanci L, Avanzinelli R, Nardini I, Tiepolo M, Davidson JP, Vannucci R (2012) (2012) Crystal recycling in the steady-state system of the active Stromboli volcano: a 2.5-ka story inferred from in situ Sr-isotope and trace element data. Contrib Mineral Petrol 163:109–131. doi:10.1007/s00410-011-0661-0

Francalanci L, Lucchi F, Keller J, De Astis G, Tranne CA (2013) Eruptive, volcano-tectonic and magmatic history of the Stromboli volcano (north-eastern Aeolian archipelago). In: Lucchi F, Peccerillo A, Keller J, Tranne CA, Rossi PL (eds) The Aeolian Islands Volcanoes, vol 37, Geol Soc London Mem., pp 397–471. doi:10.1144/M37.13

Gurioli L, Colò L, Bollasina AJ, Harris AJL, Whittington A, Ripepe M (2014) Dynamics of Strombolian explosions: inferences from field and laboratory studies of erupted bombs from Stromboli volcano. J Geophys Res Solid Earth 119. doi:10.1002/2013JB010355

Harris AJL, Ripepe M, Calvari S, Lodato L, Spampinato L (2008) The 5 April 2003 explosion of Stromboli: timing of eruption dynamics using thermal data. In: Calvari S, Inguaggiato S, Puglisi G, Ripepe M, Rosi M (eds) The Stromboli Volcano: an integrated study of the 2002–2003 eruption. AGU Geophys Monograph Ser 182:305–316. doi:10.1029/182GM25

Hornig-Kjarsgaard I, Keller J, Koberski U, Stadlbauer E, Francalanci L, Lenhart R (1993) Geology, stratigraphy and volcanological evolution of the island of Stromboli, Aeolian arc, Italy. Acta Vulcanol 3:21–68

INGV Reports, www.ct.ingv.it/rapporti/vulcanologia.html

Keller J, Hornig-Kjarsgaard I, Koberski U, Stadlbauer E, Lenhart R (1993) Geological map of the island of Stromboli. Acta Vulcanol 3

La Felice S, Landi P (2011) The 2009 paroxysmal explosions at Stromboli (Italy): magma mixing and eruption dynamics. Bull Volcanol 73:1147–1154. doi:10.1007/s00445-011-0502-z

Landi P, Métrich N, Bertagnini A, Rosi M (2008) Recycling and "re-hydration" of degassed magma inducing transient dissolution/crystallization events at Stromboli (Italy). J Volcanol Geoth Res 174:325–336. doi:10.1016/j.jvolgeores.2008.02.013

Lautze NC, Houghton BF (2005) Physical mingling of magma and complex eruption dynamics in the shallow conduit at Stromboli volcano, Italy. Geology 33:425–428

Lesne P, Kohn SC, Blundy J, Witham F, Botcharnikov RE, Behrens H (2011) Experimental simulation of closed-system degassing in the system basalt-H_2O-CO_2-S-Cl. J Petrol 52:1737–1762. doi:10.1093/petrology/egr027

Madonia P, Fiordilino E (2013) Time variability of low-temperature fumaroles at Stromboli island (Italy) and its application to volcano monitoring. Bull Volcanol 75:776. doi:10.1007/s00445-013-0776-4

Marsella M, Baldi P, Coltelli M, Fabris M (2012) The morphological evolution of the Sciara del Fuoco since 1868: reconstructing the effusive activity at Stromboli volcano. Bull Volcanol 74:231–248. doi:10.1007/s00445-011-0516-6

Martini M, Giudicepietro F, D'Auria L, Esposito AM, Caputo T, Curciotti R, De Cesare W, Orazi M, Scarpato G, Caputo A, Peluso R, Ricciolino P, Linde AT, Sacks S (2007) Seismological monitoring of the February 2007 effusive eruption of the Stromboli volcano. Ann Geophys 50:775–788

Mattia M, Rossi M, Guglielmino F, Aloisi M, Bock Y (2004) The shallow plumbing system of Stromboli Island as imaged from 1 Hz instantaneous GPS positions. Geophys Res Lett 31, L24610. doi:10.1029/2004GL021281

Métrich N, Bertagnini A, Landi P, Rosi M (2001) Crystallisation driven by decompression and water loss at Stromboli volcano (Aeolian Islands). J Petrol 42:1471–1490

Métrich N, Bertagnini A, Landi P, Rosi M, Belhadj O (2005) Triggering mechanism at the origin of paroxysms at Stromboli (Aeolian Archipelago, Italy): The 5 April 2003 eruption. Geophys Res Lett 32(L10305). doi:10.1029/2004GL022257

Neri M, Lanzafame G (2009) Structural features of the 2007 Stromboli eruption. J Volcanol Geoth Res 182:137–144. doi:10.1016/j.jvolgeores.2008.07.021

Neri M, Lanzafame G, Acocella V (2008) Dike emplacement and related hazard in volcanoes with sector collapse: the 2007 Stromboli eruption. J Geol Soc Lond 165:883–886. doi:10.1144/0016-76492008-002

Patrick MR, Harris AJL, Ripepe M, Dehn J, Rothery DA, Calvari S (2007) Strombolian explosive styles and source conditions: insights from thermal (FLIR) video. Bull Volcanol 69:769–784. doi:10.1007/s00445-006-0107-0

Pioli L, Rosi M, Calvari S, Spampinato L, Renzulli A, Di Roberto A (2008) The eruptive activity of 28 and 29 December 2002. In: Calvari S, Inguaggiato S, Puglisi G, Ripepe M, Rosi M (eds) The Stromboli Volcano: an integrated study of the 2002–2003 eruption. AGU Geophys Monogr Ser 182:105–116. doi:10.1029/182GM10

Pistolesi M, Delle Donne D, Pioli L, Rosi M, Ripepe M (2011) The 15 March 2007 explosive crisis at Stromboli volcano, Italy: assessing physical parameters through a multidisciplinary approach. J Geophys Res 116 (B12206). doi:10.1029/2011JB008527

Rittmann A (1931) Der ausbruch des Stromboli am 11 September 1930. Z Vulkanol 14:47–77

Rosi M, Pistolesi M, Bertagnini A, Landi P, Pompilio M, Di Roberto A (2013) Stromboli Volcano, Aeolian Islands (Italy): present eruptive activity and hazards. In: Lucchi F, Peccerillo A, Keller J, Tranne CA, Rossi PL (eds) The Aeolian Islands Volcanoes. Geol Soc Lond Mem 37:473–490. doi:10.1144/M37.14

Salerno GG, Burton MR, Oppenheimer C, Caltabiano T, Randazzo D, Bruno N (2009a) Three-years of SO2 flux measurements of Mt. Etna using an automated UV scanner array: comparison with conventional traverses and uncertainties in flux retrieval. J Volcanol Geoth Res 183:76–83. doi:10.1016/j.jvolgeores.2009.02.013

Salerno GG, Burton MR, Oppenheimer C, Caltabiano T, Tsanev V, Bruno N (2009b) Novel retrieval of volcanic SO_2 abundance from ultraviolet spectra. J Volcanol Geoth Res 181:141–153. doi:10.1016/j.jvolgeores.2009.01.009

Smithsonian Institution (1993) Stromboli. Bulletin Global Volcanism Network, Smithsonian Institution, 03/1993 (BGVN 18:04)

Smithsonian Institution (1997) Stromboli. Bulletin Global Volcanism Network, Smithsonian Institution, 03/1997 (BGVN 22:03)

Smithsonian Institution (2001) Stromboli. Bulletin Global Volcanism Network, Smithsonian Institution, 07/2001 (BGVN 26:07)

Spampinato L, Calvari S, Oppenheimer C, Lodato L (2008) Shallow magma transport for the 2002–03 Mt. Etna eruption inferred from thermal infrared surveys. J Volcanol Geoth Res 177:301–312. doi:10.1016/j.jvolgeores.2008.05.013

Tibaldi A (2001) Multiple sector collapses at Stromboli volcano, Italy: how they work. Bull Volcanol 63:112–125. doi:10.1007/s004450100129

Tommasi P, Baldi P, Chiocci FL, Coltelli M, Marsella M, Pompilio M, Romagnoli C (2005) The landslide sequence induced by the 2002 eruption at Stromboli Volcano. In: Sassa K, Fukuoka H, Wang FW, Wang G (eds) Landslide-risk analysis and sustainable disaster management. Springer-Verlag 32:251–258

Washington HS (1917) Persistence of vents at Stromboli and its bearing on volcanic mechanism. Geol Soc Am Bull 28:249–278

Wijbrans J, Schneider B, Kuiper K, Calvari S, Branca S, De Beni E, Norini G, Corsaro RA, Miraglia L (2011) $^{40}Ar/^{39}Ar$ geochronology of Holocene basalts; examples from Stromboli, Italy. Quat Geochronol 6:223–232. doi:10.1016/j.quageo.2010.10.003

Zanon V, Neri M, Pecora E (2009) Interpretation of data from the monitoring thermal camera: the case of Stromboli volcano (Aeolian Islands, Italy). Geol Mag 146:591–601. doi:10.1017/S0016756809005937