A multi-disciplinary study of the 2002-03 Etna eruption: Insights into a complex plumbing system

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RESEARCH ARTICLE

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A multi-disciplinary study of the 2002–03 Etna eruption: insights into a complex plumbing system

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Abstract The 2002–03 Mt Etna flank eruption began on 26 October 2002 and finished on 28 January 2003, after three months of continuous explosive activity and discontinuous lava flow output. The eruption involved the opening of eruptive fissures on the NE and S flanks of the volcano, with lava flow output and fire fountaining until 5 November. After this date, the eruption continued exclusively on the S flank, with continuous explosive activity and lava flows active between 13 November and 28 January 2003. Multi-disciplinary data collected during the eruption (petrology, analyses of ash components, gas geochemistry, field surveys, thermal mapping and structural surveys) allowed us to analyse the dynamics of the eruption. The eruption was triggered either by (i) accumulation and eventual ascent of magma from depth or (ii) depressurisation of the edifice due to spreading of the eastern flank of the volcano. The extraordinary explosivity makes the 2002–03 eruption a unique event in the last 300 years, comparable only with La Montagnola 1763 and the 2001 Lower Vents eruptions. A notable feature of the eruption was also the simultaneous effusion of lavas with different composition and emplacement features. Magma erupted from the NE fissure represented the partially degassed magma fraction normally residing within the central conduits and the shallow plumbing system. The magma that erupted from the S fissure was the relatively undegassed, volatile-rich, buoyant fraction which drained the deep feeding system, bypassing the central conduits. This is typical of most Etnean eccentric eruptions. We believe that there is a high probability that Mount Etna has entered a new eruptive phase, with magma being supplied to a deep reservoir independent from the central conduit, that could periodically produce sufficient overpressure to propagate a dyke to the surface and generate further flank eruptions.

Keywords Multi-disciplinary study · Mount Etna · 2002–03 eruption · Eccentric eruptions · Flank activity · Etna feeding system · Volcanic processes

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Introduction

Mount Etna is a basaltic volcano 3300 m high and covers an area of 1250 km^2 in Eastern Sicily, Italy (Fig. 1). A multi-disciplinary approach to its surveillance system has been active since the 1980s. More recently, the monitoring system has been further diversified, with a number of different investigations being carried out on a regular basis. These include: (1) regular field surveys of intra-crater activity; (2) three measurements of SO_2 flux from the summit craters using a correlation spectrometer (COSPEC); (3) frequent measurements of the chemical composition of magmatic gas emissions using Fourier Transform Infrared Spectroscopy (FTIR); (4) structural surveys to analyse the pattern of brittle deformation; (5) thermal imaging surveys carried out from both ground and helicopter to detect new fractures and intra-crater activity; (6) quantitative analyses of ash components; (7) petrology of ash fall-out, scoria and lava emitted during eruptive activity. The use of fixed cameras, streaming images of the volcano from various perspectives directly to the web, has also significantly improved the visual monitoring of the volcano. In this paper we present the results of these techniques, integrated to understand the dynamics and eruptive behaviour of the last eruption.

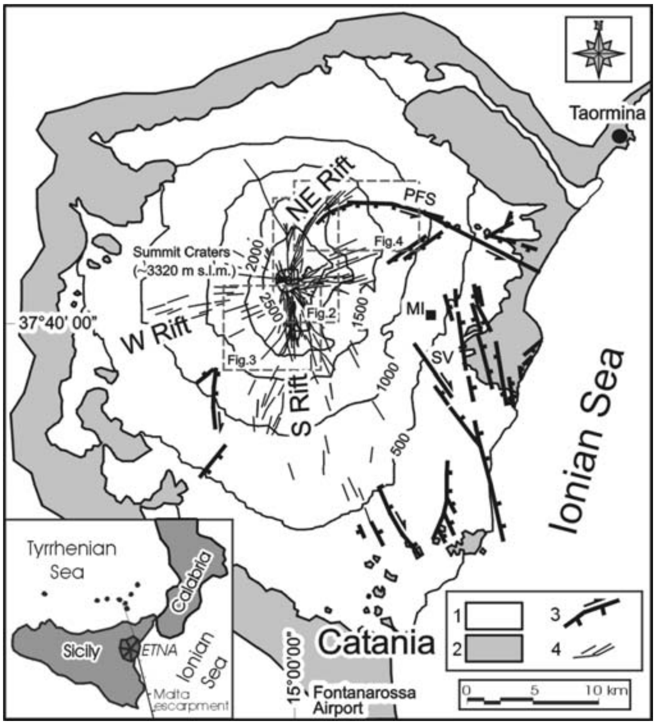


Fig. 1 Simplified tectonic map of Mount Etna, modified after Acocella and Neri (2003). The sedimentary basement is made up of units of the Apennine-Maghrebian Chain (N and W sectors) and of Early-Quaternary clays (S sector). PFS=Pernicana Fault System; SV=Santa Venerina fault; MI=Milo video camera. 1: Etnean volcanics; 2: sedimentary rocks; 3: main faults (arrows indicate lateral component of movement); 4: eruptive fissure

After the 1991–93 flank eruption (Calvari et al. 1994), activity at Mt. Etna was typified for several years by mild degassing, alternated with summit eruptive activity. This consisted of lava flow emission, strombolian explosions and paroxysmal events (Coltelli et al. 1998, 2000a; Calvari et al. 2002; Calvari and Pinkerton 2002; Harris and Neri 2002; Alparone et al. 2003) at the summit craters (Fig. 1). This period stopped on 17 July 2001, when magma quickly rose upward (Calvari and INGV-CT 2001; Acocella and Neri 2003; Behncke and Neri 2003a; Lanzafame et al. 2003), producing intense explosive and effusive activity from several vents on the south-east flank of the volcano. Although relatively short, the 2001 eruption displayed some important features: a very intense seismic swarm lasting about a week before the onset of the eruption, the opening of two main systems of eruptive fissures (Billi et al. 2003; Lanzafame et al. 2003), each one characterised by magma with peculiar composition and petrography (Calvari and INGV-CT 2001), conspicuous lava emission threatening inhabited and tourist areas, and violent explosive activity that led to the formation of a 100 m high cinder cone (Behncke and Neri 2003a; Calvari and Pinkerton 2004) near La Montagnola cone (Fig. 2).

After a 15 month pause in activity, lava began to erupt again on 26 October 2002. A short seismic swarm (Patanè 2002) preceded the almost simultaneous magma output from opposite flanks of the volcano. The 2002–03 eruption was characterised by moderate emission of lava, intense explosive activity, and abundant ash emission, which caused damage to agriculture, housing and the local economy.

The 2002–03 eruption involved two distinct magma intrusion zones, the NE-Rift and the S-Rift (Fig. 1) (Kieffer 1975; McGuire and Pullen 1989). The NE-Rift extends for about 7 km from the summit craters down to 1500 m a.s.l., consisting of a network of N to NE-striking eruptive fissures closely spaced in an area about 1–2 km wide (Garduño et al. 1997). The NE-Rift is linked eastward with the Pernicana Fault System (PFS in Fig. 1), a complex E-W oriented transtensive tectonic structure that dissects the NE flank of the volcano (Azzaro et al. 1998; Groppelli and Tibaldi 1999; Neri et al. 2004). The last eruption occurred there, in 1947, when a system of fissures developed from the North-East Crater (NEC, ~3300 m elevation, Fig. 3) down to 2150 m altitude, forming a 6 km-long lava flow field (Cumin 1947; Ponte 1948; Cucuzza Silvestri 1949). The S-Rift (Fig. 1) comprises eruptive fissures distributed over a wider area, extending from the summit craters to S and SE down to 600–700 m a.s.l. One third of the fissures on this sector of the volcano developed as a consequence of eruptive activity over the last 2 ka (Del Carlo and Branca 1998). The upper portion of the S-Rift has been the preferential site of magma intrusion during the twentieth century, as indicated by the high occurrence of flank eruptions when compared to other sectors of the volcano (Behncke and Neri 2003b; Branca and Del Carlo 2004).

The 2002–03 eruption shares many features with the 2001 event: (1) involvement of the same eruptive area on the south flank (Fig. 2); (2) strongly explosive style and lava output dynamics; (3) distinct magma compositions from the upper and lower fissure systems. In detail, the 2001 lower vents and the 2002–03 southern flank eruptions show features typical of the Etnean eccentric eruptions. Eccentric is the definition (Rittmann 1965) used for those Etnean eruptions fed by magma which bypasses the central conduit. These eruptions are characterised by a high tephra/lava ratio with prevalent ash emission, and low to medium phenocrysts content (Porphyritic Index<20%), with mafic minerals prevalent (Armienti et al. 1988).

Here we present results obtained using different volcanological techniques, illustrating a multi-disciplinary approach that allowed us to monitor the eruptive events, and thereby promptly inform Civil Protection and local authorities of the possible evolution of the eruption. We use these results here to assess the triggering and eruptive mechanisms that caused the 2002–03 eruption, and by comparing our data with the historical activity of the volcano we infer the possible eruptive behaviour of Mt. Etna in the near future.

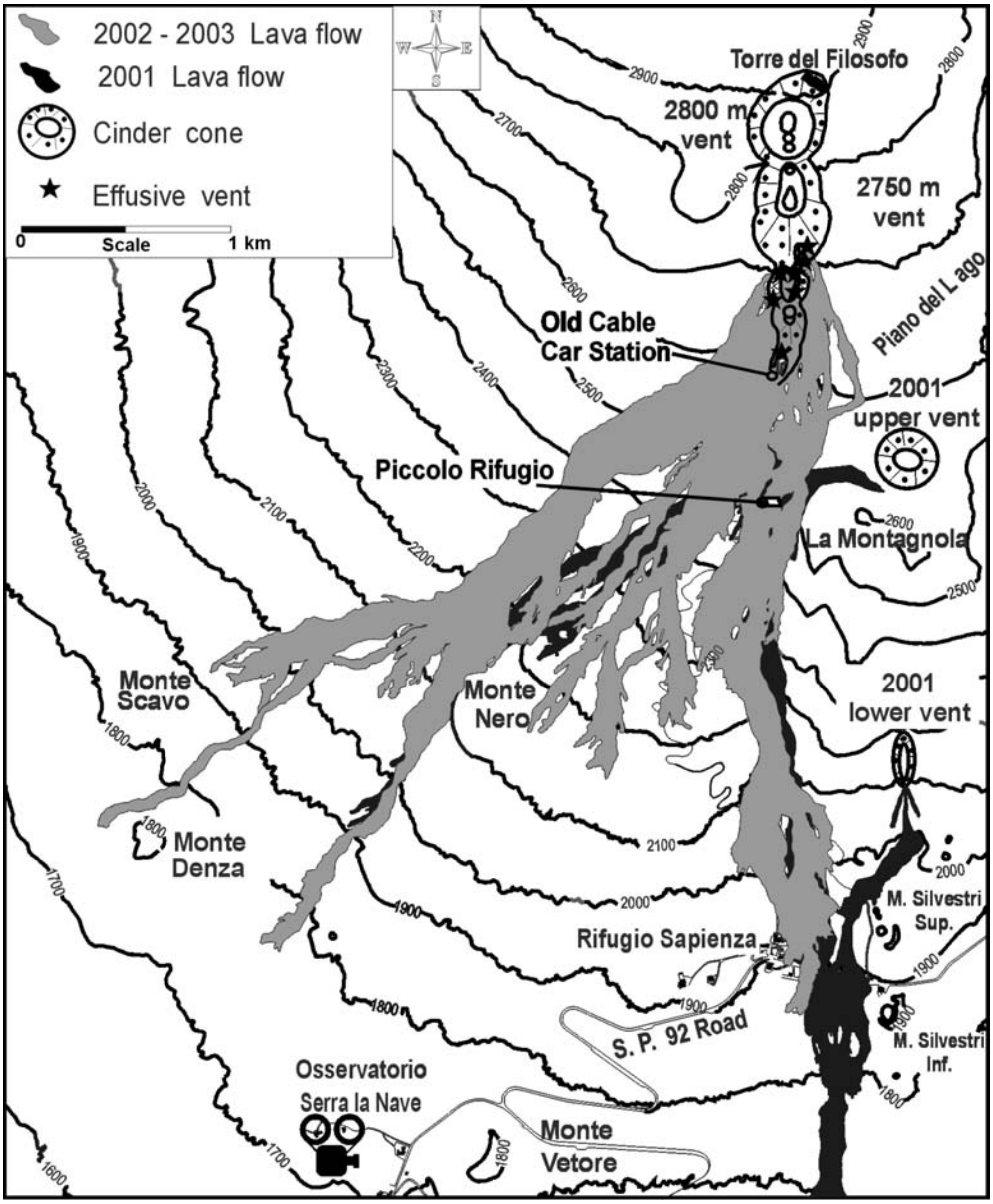


Fig. 2 Map of the 2002–2003 S lava flow field and location of the 2750 m and 2800 m cones. The 2001 lava flow field, including the locations of the 2001 eruptive vents N of La Montagnola and near Mt Silvestri, is in black

Summit eruptive activity prior to the 2002–03 eruption

The opening of a new fissure system across the summit area of the volcano was heralded several months in advance by the development of a field of cracks between North-East Crater (NEC) and South-East Crater (SEC; Fig. 3) in February 2002 (Calvari et al. 2003). The cracks showed a sharp thermal signature that was revealed through routine monthly monitoring carried out by helicopter-borne thermal surveys. Apart from high-temperature fumaroles, the cracks did not show any activity, and after the July–August 2001 flank eruption, no eruptive activity occurred on Etna's summit for several months. On 8 March 2002, ash emission was observed from Bocca Nuova (BN; Fig. 3). This continued until 14 March, when it was observed that the ash emission was caused by failure of the inner crater walls, forming landslides within the crater. Ash emission from BN was particularly intense on 20 March, when ash was reported to have fallen for about an hour between Zafferana and Giarre, about 20 km away from the summit. Ash emission was discontinuous until 25 March. On 28 March the NEC showed the same kind of activity and between April and June 2002 deep, intermittent explosions of variable intensity occurred in the BN and NEC craters. During June 2002, the ash emission from BN and NEC was intense and became continuous at NEC on 14 June, with pulses of dark ash rising to 500 m above the crater rim. Microscope analysis showed that ash emitted after 21 June 2002 contained a juvenile component. On 23 June a helicopter-borne thermal survey showed elevated temperatures inside the NEC, suggesting that magma was very close to the surface. This was confirmed by field

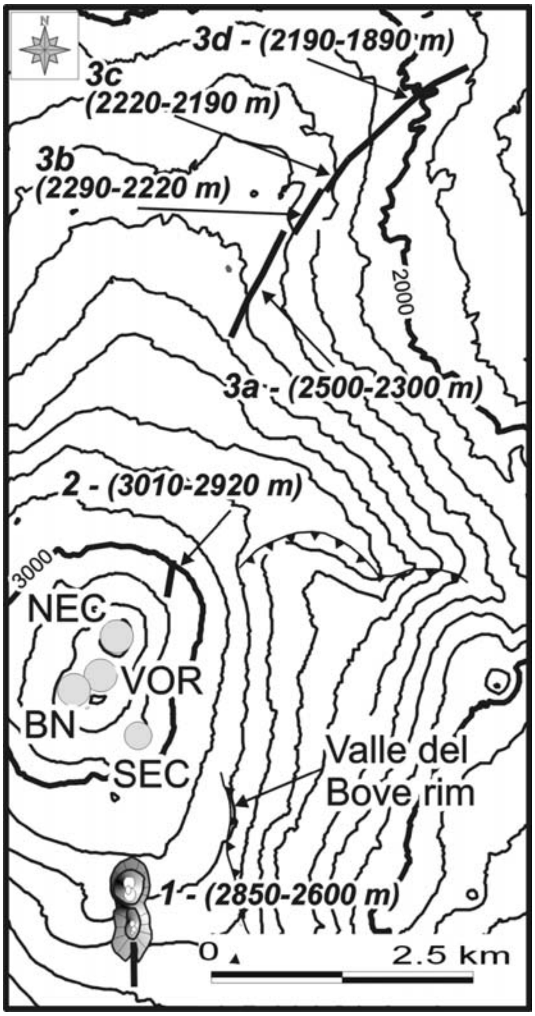


Fig. 3 The 2002–03 eruptive fissure field on the N and S flanks of Etna, with numbers indicating its progressive opening. Etna's summit crater location is also shown: NEC=North-East Crater; VOR=Voragine; BN=Bocca Nuova; SEC=South-East Crater

observations, which revealed low-level strombolian activity inside the crater. Strombolian activity at this crater increased in July, leading to fallout of bombs on the crater's outer flanks. The erupted products were porphyritic (phenocrysts made up 25% of the total volume) trachybasalts with their mineral assemblage dominated by plagioclase. These features are typical of volcanics produced by summit craters over the past 10 years (Corsaro and Pompilio 2004a, 2004b). During this whole period, the SEC remained quiescent, with its conduit obstructed, whilst Voragine (VOR; Fig. 3) showed predominantly quiescent degassing.

On 22 September 2002, an earthquake (Md=3.7, focal depth=5 km; Acocella et al. 2003), accompanied by surface fracturing, occurred along the PFS (Fig. 1). This earthquake strongly remobilised the PFS after about 15 years of quasi-quiescence, marking the beginning of an important displacement of the eastern flank of Etna. A survey on the summit of the volcano carried out immediately after the earthquake revealed that no eruptive activity had occurred within the craters.

Chronology of the eruption

On 26 October 2002 at 20:12 GMT, an earthquake swarm recorded by our seismic network (Patanè 2002; Acocella et al. 2003) preceded and accompanied the formation of eruptive fissures over the S and NE flanks of the volcano (Fig. 3), marking the onset of the 2002–03 Etna eruption. A north-south, 1 km-long eruptive fissure opened on the upper southern flank of the volcano (2850–2600 m a.s.l.), between Torre del Filosofo and the old cable-car station partially destroyed during the 1983 eruption (Figs. 2, 3). The fissure produced 100–300 m high fire fountains that soon evolved into an ash column up to about 5 km a.s.l. that was blown south by the wind. Another north-south, 340 m-long eruptive fissure opened at the northern base of NEC (3010–2920 m a.s.l.; Figs. 2, 4), producing fire fountains that lasted ~0.5 h. During this period NEC, VOR and BN showed increasing levels of explosive activity, consisting of pulsating ash emissions and intense short-lived strombolian activity. This produced distinct ash plumes that merged together and joined those originating from the NE and S fissures, forming a large composite plume and causing abundant ash fall on the S and SE flanks of the volcano (Fig. 5). Table 1 summarizes the eruption chronology.

Fissure opening and volcanic activity in the northeast flank

At about 4:00 GMT on 27 October, a third fissure opened along the NE-Rift. This fissure was 3.7 km long and trended SW-NE (Figs. 2, 4). It propagated between 2500 m and 1890 m a.s.l. in less than 24 h. In Fig. 3 we show segment 3a between 2500 and 2300 m a.s.l., trending N20–30°E, that was 1.2 km long and showed violent strombolian activity. Segments 3b+3c of the fissure, 0.7 km long and trending N30–45°E, formed in a right en-echelon arrangement between 2290 and 2190 m a.s.l., producing fire fountaining and effusive activity. Lava effusion produced a 1 km-long flow from a vent at 2500 m a.s.l. During the down-slope propagation of the fissure system a series of pit craters formed along the upper segments and the first, upper lava flow became inactive. Meanwhile, a second flow emerged from a vent at 2200 m a.s.l. flowing east and partially submerging the Piano Provenzana tourist infrastructure (Figs. 4, 6a). A shallow seismic swarm associated with the fissure propagation seriously damaged all of the tourist-hotel facilities on Piano Provenzana. The earthquakes caused movements along the whole PFS (~18 km) and up the Ionian coast (Acocella et al. 2003; Neri et al. 2004). On the early morning of 28 October, the northern eruptive fissure (N45–65°E) propagated down-slope for 1.8 km to 1890 m a.s.l. The lower segment (3d, Fig. 3) of the fracture

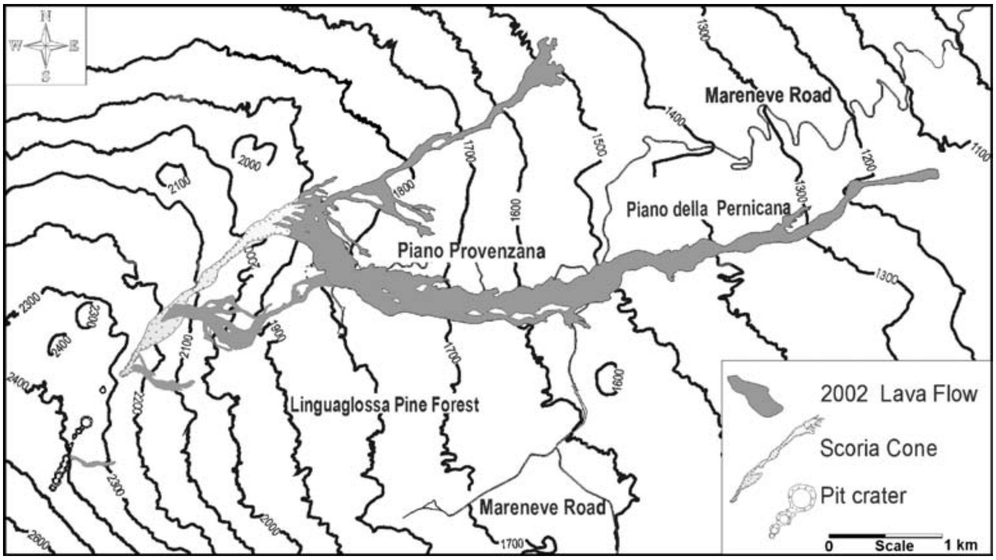


Fig. 4 Map of the 2002 lava flow field that erupted from the NE-Rift

Fig. 5 The eruptive plume on 27 October. Satellite image by MODIS Rapid Response Team at NASA GSFC Goddard Space Flight Center

(~1 km long) showed continuous strombolian activity and a lava flow directed NE (Fig. 4), that travelled a distance of ~2.5 km (Fig. 6b) in a few hours.

On 29 October, a NW-SE tectonic structure (SV in Fig. 1) located on the lower eastern flank of the volcano was activated by seismic swarms of 4.4 maximum magnitude that caused serious damage to houses and infrastructure around S. Venerina (SV in Fig. 1; Acocella et al. 2003). During the same day, the NE lava flow slowed and a new lava flow erupted from the same fissure (segment 3d in Fig. 3) at 1930 m a.s.l., flowing SE and invading Piano Provenzana. The NE flow (Fig. 4) stopped on 31 October after having travelled 2.8 km, when a decline in effusion rate was observed. The explosive activity began to decrease slowly from 29 October and on 1 November it was limited to just two vents on the lower portion of the fissure, between 1950 and 1900 m a.s.l. This indicated a general waning of the eruptive activity on this side of the volcano. The eruptive plume did not exceed an altitude of 1 km above the vents, and fallout affected only the nearby areas. Strombolian activity formed two coalescent spatter cones at 1950–1900 m a.s.l.

The E lava flow reached a final length of 6.2 km, and stopped its expansion on 3 November (Fig. 4). After lava supply from the main vent was cut off, 20 m of downslope movement was observed at the most advanced flow front on 5 November. This late movement was caused by channel emptying, and occurred when lava coming from the main vent was completely crusted over. The ski station and tourist shops on Piano Provenzana were first destroyed by earthquakes then partially covered by lava flows. The flows also caused fires and destroyed parts of the old Linguaglossa pine forest (Fig. 4). Explosive and effusive activity completely stopped at the north fissure on 5 November. The morphology of the lava flows was “aa” in type, and the longer flows showed formation of wide channels.

The eruption on the southern flank

Eruptive activity at the S fissure (Fig. 2) occurred between 27 October 2002 and 28 January 2003, showing several changes in the eruptive style and a two week pause in lava effusion. During the first two days of the eruption, alternate lava fountains and phreatomagmatic explosions formed dense ash columns. On 28 October, effusive activity gave rise to poorly-fed lava flows expanding SW, which stopped on 31 October. Fire foun-

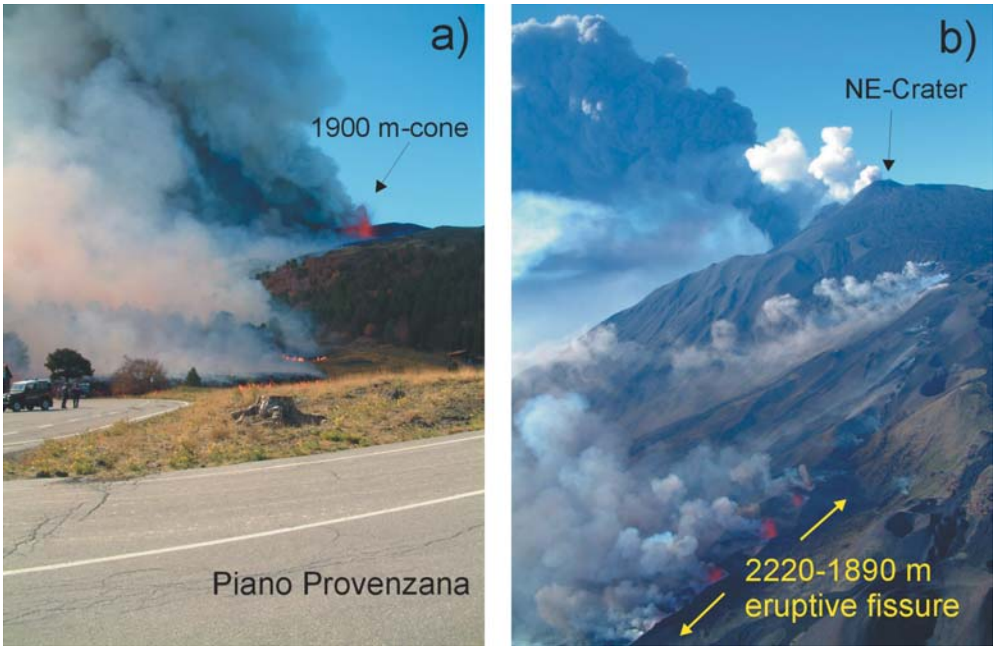
Table 1 Chronology of the 2002–03 eruption

Date/hour (GMT)	Vent	Location	S flank	NE flank
26 October 2002 22:55 h	1	High S flank (2850–2600 m a.s.l.)	Violent phreatomagmatic explosions and formation of dense ash and lapilli columns, lava fountains over 300 m in height contained angular xenolites of white pale-gray quartz.	–
27 October 2002 (early morning)	2	High N flank (3010–2920 m a.s.l.)	–	Lava fountains activity lasts around 30 min.
27 October 2002 (early morning)	3a	NE-Rift (2500–2300 m a.s.l.)	–	Violent strombolian activity, phreatomagmatic explosions and weakly fed lava flow. These activities last around 1.5 h.
27 October 2002 04:00 h	3b	NE-Rift (2290–2220 m a.s.l.)	–	Violent strombolian activity, phreatomagmatic explosions and lava flow lasted about 2 h. The activity at vent 3a stopped.
27 October 2002 08:00 h	3c	NE-Rift (2220–2190 m a.s.l.)	–	Strong strombolian activity and phreatomagmatic explosions. The effusive activity lasted around 20 h. The activity at vent 3b decreased.
28 October 2002 07:30 h	3d	NE-Rift (2190–1890 m a.s.l.)	–	Violent strombolian activity and phreatomagmatic explosions formed dense ash and lapilli columns. Scoria cones began to grow around the principal vent at 1930 m a.s.l. where copious lava outpoured. The eruptive activity at vent 3b stopped.
The eruptive fracture field completed				
28 October 2002	1	–	Intense fire fountain activity formed an eruptive column. A lava flow was emitted toward SW.	Two lava flows were emitted toward E and NE respectively.
31 October 2002	1	–	The effusive activity at vent 1 ceased, while the violent explosive activity persisted forming an eruptive column. Fairly regular scoria cone began to grow around the highest portion of the fissure at 2750 m.	The effusion rate at 1930 m vent decreases. The NE lava flow stopped and the E lava flow reached the Pernicana fault scarp.
1 November 2002	1, 3c	–	Intense fire fountain activity at vent (1) formed an eruptive column.	The explosive activity at the vent (3c) ceased. The E lava flow reached the maximum length of 6.2 km.
4 November 2002	1, 3d	–	Intense fire fountain activity at vent 1 formed an eruptive column.	The effusive activity at vent 3d stopped during the night.
5 November 2002	1, 3d	–	Intense fire fountain activity at vent (1) formed an eruptive column.	Emptying of the main lava channel produced a 20 m down slope movement of the front.
The eruption in the NE flank ceased				
6–11 November 2002	1	–	Intense fire fountain activity formed an eruptive column. Construction of a scoria cone >100 m in height (at 2750 m a.s.l.)	–
12 November 2002	1	–	Mild strombolian activity that interrupted the fire fountain activity for some hours.	–
13–30 November 2002	1	–	Strong jets and ash emission, lava outflows, formation of two new explosive vents (25 November) that opened to the N and SSE of the 2750 m scoria cone.	–
1–7 December 2002	1	–	Strong explosive activity concentrated at the N vent and growth of the 2800 m scoria cone. Lava outflows. Torre del Filosofo shelter (2900 m a.s.l.) is covered by spatter fallouts of the 2800 m vent.	–
8–10 December 2003	1	–	The lava fountaining changed to mild strombolian explosions for a few hours (8 and 10 December), culminating with the opening of two vents on the SSE base of the 2750 m cone. Lava outflows.	–

Table 1 (continued)

Date/hour (GMT)	Vent	Location	S flank	NE flank
11–31 December 2003	1	–	Pulsating fire-fountaining alternating with strombolian activity caused a discontinuous ash column. Lava outflows mainly directed toward SW and S where they interrupted the SP 92 road. A new effusive vent opened on 17 December at the S base of the 2750 m cone and lava flows expanded toward the SW that cut supply to the S flow. Construction of the main scoria cone along the highest portion of the eruptive fissure at 2800 m a.s.l.	–
1–27 January 2003	1	–	The frequency and intensity of the explosive activity progressively decreased, while lava outflows continued to erupt from the base of fthe 2750 m cone.	–
28 January 2003 (late evening)	1	–	The effusive activity at vent 1 ceased.	–
The eruption in the S flank ceases				

Fig. 6 Opening of the eruptive fissure along the NE-Rift early in the morning of 27 October. **a** Eruptive plume from vents opening along the fissures and lava flow effusion into Piano Provenzana. **b** Fire fountaining activity along segments 2 and 3 of the NE-Rift eruptive fissures, viewed from N



taining activity continued and was very intense, with lava jets from at least three eruptive vents between 2800 and 2600 m elevation, reaching up to 600 m height and forming a sustained column to 6 km a.s.l. After about a week, explosive activity concentrated at the 2750 m vent, and gradually started to build up a cinder cone.

Between the afternoon of 12 November and the following day, lava fountains were replaced by strombolian activity after some hours of quiescence. On 13 November, effusive activity resumed and lava flows began to spread SW from the base of the 2750 m cone, running parallel to the October flows towards Monte Nero. On 14 November lava fountaining resumed at the 2750 m cinder cone, producing sustained columns to less than 5 km a.s.l. (Fig. 7a). On 17 November two new explosive vents opened within the 2750 m cinder cone, producing alternating powerful ash (Fig. 7b) and spatter output. Fountaining activity was not as continuous as in the first period, but showed brief intervals of lower intensity, and frequent changes from fire fountaining to violent strombolian explosions. Between 20 and 21 November a new effusive vent opened at the SSE base of the 2750 m cinder cone, producing a lava flow that spread S towards Rifugio Sapienza (Fig. 2). This stopped on 24 November, a few metres before reaching the SP92 road near Rifugio Sapienza, after having travelled 3.6 km from the main vent.

On 25 November two new explosive vents opened N and SSE of the 2750 m cinder cone, accompanied by a temporary cessation in activity at the 2750 m cone. Within a few days, strong strombolian activity from the N vent formed a new cone at 2800 m, whose north slope

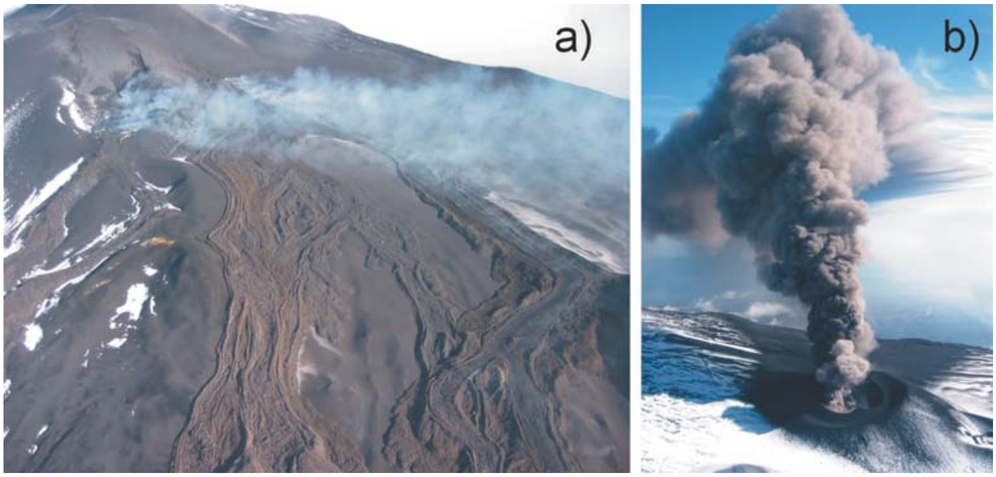


Fig. 7 Eruptive activity along the S fissure. **a** Lava flows from the effusive vents at the 2750 m cone. **b** Ash column on 17 November viewed from W

buried the Torre del Filosofo building completely (Fig. 2). The SSE vent showed mainly weak ash emission after 30 November, and new overflows from the cone spread SW over the previous flow channels, covering the lava flows directed to Monte Nero. A maximum flow length of 4 km was reached on 1 December, when the flows stopped. The explosive activity was replaced for a few hours on 8 December afternoon by strombolian explosions.

On 10 December, cessation of the activity at the 2800 m vent coincided with the resumption of fire-fountaining at the 2750 m vent, and with the opening of two new effusive vents on the SSE base of the 2750 m cone, feeding two lava flows toward SW and S. The S lava flow crossed the SP92 road on 17 December, and an overflow from the main lava channel covered a building at Rifugio Sapienza (Fig. 2) belonging to the Nicolosi town council. On the same day a new effusive vent opened at the S base of the 2750 m cinder cone, a few metres W of the previous vents. A lava flow soon started from this vent, spreading SW towards Monte Nero. The new vent cut supply to the flows expanding S towards Rifugio Sapienza. The lower lava output caused shorter flows, which spread up to 2.5 km from the vent, without threatening the tourist facilities of Rifugio Sapienza.

In general, from 10 December onward, we observed a slow decrease of the effusive phenomena until they ended on 28 January 2003. Up to 24 December 2002, pulsating fire-fountaining alternating with strombolian activity caused a discontinuous ash column. From the end of December 2002 to 27 January 2003, mild strombolian activity at the 2750 m cone prevailed, causing weak intra-crater explosions. Effusive activity decreased in January 2003, forming short lava flows to the S and SW. Flow fronts did not descend beneath 2500–2400 m elevation. The effusive activity at the S vent ceased on 28 January 2003.

Thermal mapping and lava flow field parameters

Since July 2001, Etna's activity has been monitored with a handheld thermal camera, FLIR TM 695. During the 2002–03 Etna eruption, helicopter-borne thermal mapping was carried out on a daily basis. In this way, we followed the morphological and structural evolution of the lava flow fields and recognised the active flows spreading below a curtain of gas, ash and smoke, even during flow advances within forests, when direct field surveys were necessarily limited. Additionally, the thermal camera allowed us to distinguish overlying lava flows, the presence of lava tubes, and the location of ephemeral vents. Flow mapping with the aid of this device allowed daily calculation of the area covered by new lava flows. This was carried out from October 27 2002 up until early January 2003 and the results are shown in Figs. 2 and 4. The total area covered by new lava flows for the flow fields of the NE-Rift and for the S fissure was calculated for the period 28–31 October 2002 and for the S fissure between 13 November 2002 and 28 January 2003. A maximum and minimum flow thickness, averaged for the whole flow field, was estimated on the basis of daily field surveys, and eruption rates were calculated (Table 2). Errors in the

Table 2 Duration, total covered area, volume and eruption rates estimated for the three effusive phases of the 2002–03 eruption

Date and fissure system	Duration (days)	Total covered area (km^2)	Estimated thickness min-max (m)	Estimated volume min-max (10^6 m^3)	Estimated mean eruption rate min-max (m^3 s^{-1})
27 Oct to 4 Nov (N fissure)	9	1.9	4–6	7.8–11.8	10.1–15.1
28–31 Oct (S fissure)	4	0.52	1.5–2	0.8–1.0	2.2–3.0
13 Nov 02 to 28 Jan 03 (S fissure)	77	2.64	8–11	23.8–32.7	3.6–4.9

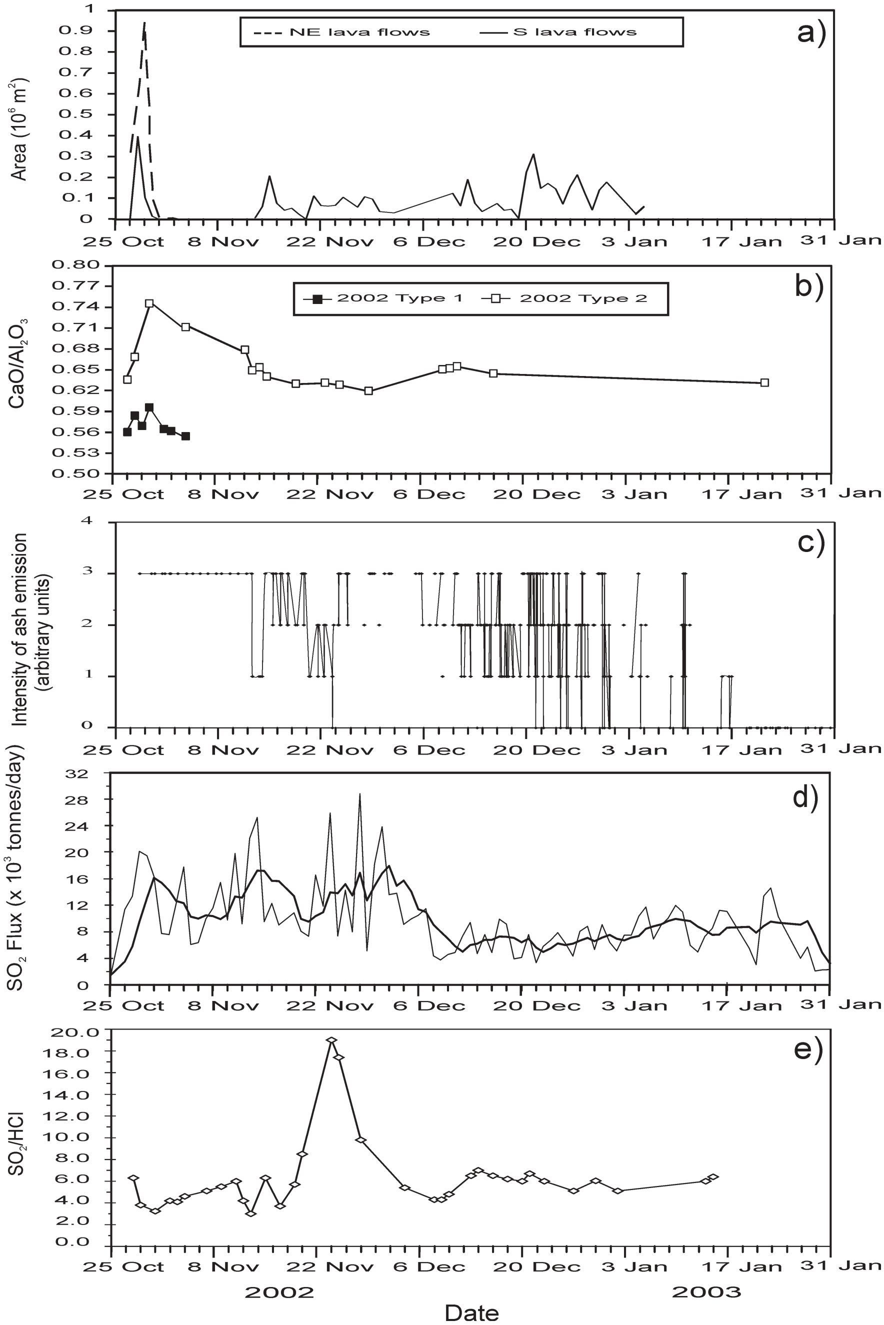


Fig. 8 Plot comparing results from different techniques. **a** Semi-quantitative analysis of ash emissions from the S fissure based on images recorded by our web camera system. **b** Daily area covered by new flows during the eruption. **c** CaO/ Al_2O_3 measured in bulk rocks of both Type 1 and Type 2 magma during the 2002–03 flank eruption. **d** FTIR measurements of the SO_2/HCl ratio of the plume from the 2750 m vent. **e** COSPEC SO_2 flux from the summit craters (thin line). Thick line is the 7 day moving average

calculated daily and total areas are considered to be less than 10%. A higher error is associated with the eruption rate due primarily to uncertainty in the mean thickness of the flows, which may be as much as 50%. Erupted volume is dependent on mean flow thickness, so this value also has an error of ~50%. Figure 8b shows that the NE and S flow fields show distinct styles in lava emission. The NE flow field was characterised by a fast lengthening of the lava flows that, having reached their maximum flow length, had only minor increases, essentially due to passive channel emptying. Conversely, the pulsating lava output from a number of vents on the S flank of the volcano generated a fan-shaped lava flow field, where single flow units overlapped each other without significantly increasing the total lava flow field area.

An area of 1.9 km^2 was covered by lava in 9 days in the NE lava flow field, with maximum flow lengths of 6.2 km. The lava flow volume, estimated using average minimum and maximum flow thicknesses of 4 and 6 m, was 7.8–11.8×10^6 m^3, with eruption rates of 10.1–15.1 m^3 s^{-1}.

The S lava flow field formed in two phases. Between 28 and 31 October, lava flows reached a maximum length of 2.4 km, and covered a total area of 0.52 km^2. The resulting volume, calculated considering minimum and maximum flow thicknesses of 1.5 and 2 m, was 0.8–1.0×10^6 m^3, with eruption rates of 2.2–3.0 m^3 s^{-1}.

The second effusive phase from the S vents lasted between 13 November and 28 January 2003, with maximum flow length of 4 km, and a total covered area of 2.64 km^2. The minimum and maximum volume calculated for the resulting lava flow field, obtained considering mean flow thicknesses of 8 and 11 m, is 23.8–32.7×10^6 m^3, with an eruption rate of 3.6–4.9 m^3 s^{-1}, about twice the value during the first three days of effusion on the S slope of the volcano, when the NE fissure system was also active.

Petrography and geochemistry of erupted products

During the 2002 Etna eruption, two magmas with distinct petrography were erupted at the same time from distinct portions of the fissure system: (i) Type 1 magma was erupted from the NE fissure and had a total phenocryst abundance (P.I.) ranging 25–30% by volume, that was dominated by plagioclase with subordinate clinopyroxene, olivine and magnetite (Pl/ol+cpx+mt=0.9–1.2); (ii) Type 2 magma, erupted from the S fissure, had a lower phenocryst content (average P.I.=15% vol.) and a mineral assemblage dominated by mafic phases (Pl/ol+cpx+mt always <0.4). Type 2 magma contained less than 1% subhedral crystals or fragments of brown, sub-millimetre amphibole (kaersutite-hastingsite) with breakdown rims. Moreover, cognate xenoliths with allotriomorphic textures composed of plagioclase, clinopyroxene, Ti-magnetite, and amphibole were observed. Sedimentary xenoliths commonly occurred in Type 2 magma, most of them formed exclusively of equigranular quartz grains, ranging from 0.5–2 mm in size, rounded to sub-rounded in shape. Both Type 1 and Type 2 products are essentially trachybasalts (Fig. 9; Table 3), showing a K-affinity as already observed in the Etnean volcanics erupted since 1989 (Tonarini et al. 1995). Type 2 volcanics are of the most primitive composition ever measured during the historical period (from 1329 to 2001) (Corsaro and Pompilio 2004b); an alkali basalt sampled on 30 Oct demonstrated Mg# [$Mg/(Mg+Fe^{2+})$] moles per 100 higher than 60 and an CaO/Al_2O_3 ratio=0.75 (Fig. 8c).

Most of the features described earlier for Type 1 magma have been already observed in the 2001 volcanics erupted by the upper vents (by the south eruptive fissures higher than 2700 m a.s.l.) and by the Valle del Leone system (Pompilio et al. 2001; Calvari and INGV-CT 2001). They share the same features as products erupted by the summit, flank and sub-terminal activity of the last 300 years (Corsaro and Pompilio 2004b).

Conversely, Type 2 magma shows a petrographic character similar to that described for the 2001 lower vent volcanics – in other words the southern eruptive fissures at 2600–2100 m a.s.l. (Pompilio et al. 2001; Calvari and INGV-CT 2001). These are typical of Etnean “eccentric” eruptions, or eruptions in which magma bypasses the central conduit (Rittmann 1965), or where it rises very quickly toward the surface (like the 3930 BP Sub-plinian eruption; Pompilio et al. 1995; Coltelli et al. 2000b). Figure 10 shows that the products of eccentric Etnean eruptions are generally poorly to moderately porphyritic (P.I.<20% vol.), with a sialic/mafic mineral ratio <1, with

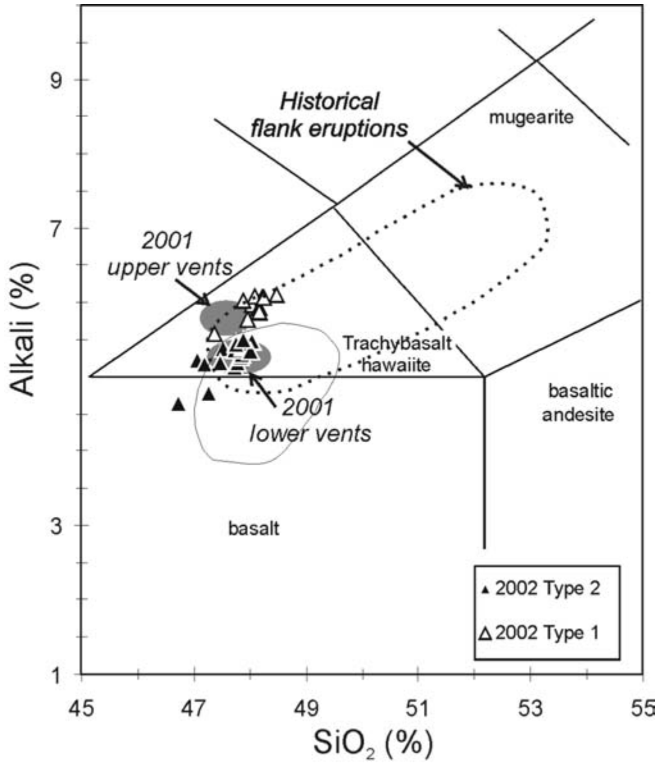


Fig. 9 Total Alkali Silica diagram (Le Maitre 1989) for 2002–03 flank eruption volcanics. Type 1 magmas are trachybasalts. Type 2 magmas are alkali basalts and trachybasalts. Historical (1329–2000 A.D.) flank eruptions field (dotted line) and eccentric flank eruption field (continuous line) are also plotted for comparison. Grey-coloured areas represent 2001 eruption products (upper and lower vents)

Table 3 Major element composition (average values and related standard deviations) for Type 1 and Type 2 magmas erupted during the 2002–03 eruption. Major elements (by ICP-AES) in the bulk rocks were measured at the Centre National de la Recherche Scientifique, Vandoeuvre Les Nancy Cedex, France

	Type 1 magma		Type 2 magma	
	Average (of 13)	σ	Average (of 13)	σ
SiO_2	47.73	0.28	47.20	0.38
TiO_2	1.65	0.02	1.67	0.05
Al_2O_3	17.59	0.19	16.67	0.51
FeOtot	10.08	0.14	10.36	0.19
MnO	0.18	0.01	0.17	0.00
MgO	5.45	0.21	6.47	0.71
CaO	10.03	0.29	10.91	0.35
Na2O	3.82	0.11	3.26	0.14
K2O	2.08	0.05	1.90	0.10
P2O5	0.51	0.02	0.47	0.03
LoI	0.70	0.08	0.69	0.07
Mg_v	52.23	0.73	55.70	2.44

Mg#: [(Mg/Mg+Fe2+) moles per 100]

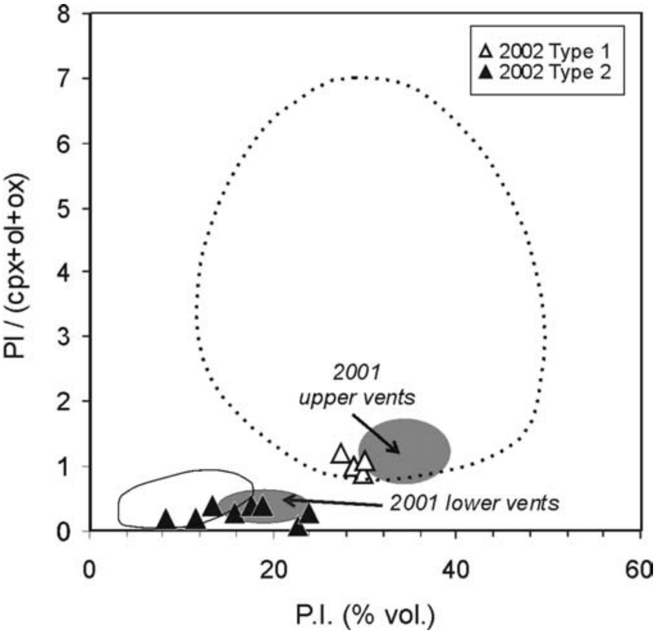


Fig. 10 Porphyricity Index (P.I.=total phenocrysts abundance vol%) versus Plagioclase/mafic minerals (clinopyroxene, olivine and Ti-magnetite). For symbols (areas and lines) refer to Fig. 9. Type 2 magma and 2001 lower vents products show mineralogical features typical of eccentric flank eruption

clinopyroxene and olivine being the most abundant phases (12–15%) with respect to plagioclase (5–7%). They differ significantly from products of most historical eruptions (from 1329 up to 2000 and 2001 upper vents), that show P.I. values commonly ranging from 25–30% and Pl/ol+cpx+mt values greater than 1, with plagioclase being the most common mineral phase.

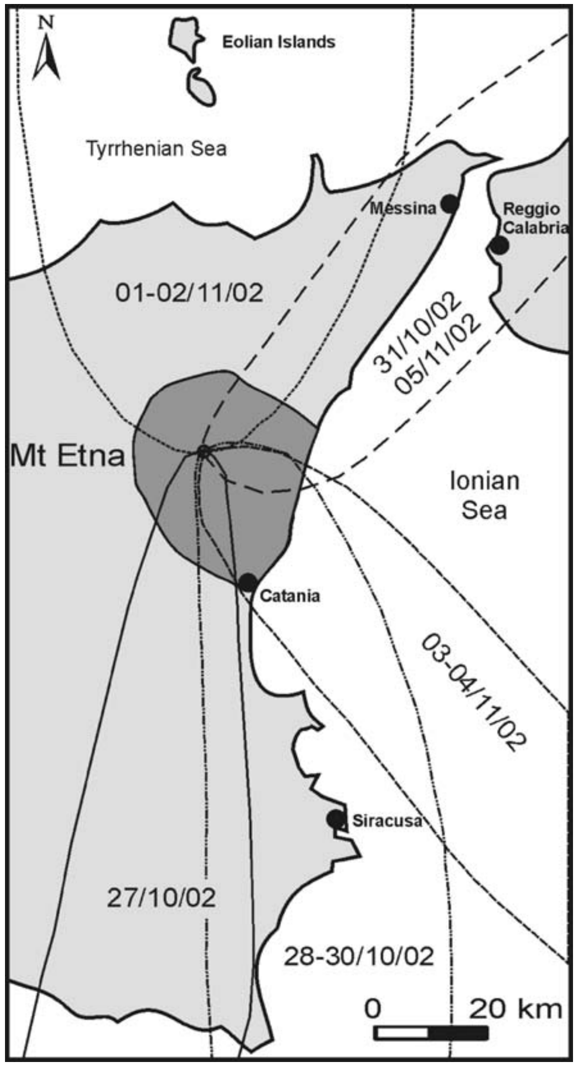


Fig. 11 Map of the areas covered by lapilli and ash fall deposit between 27 October and 5 November 2002

Explosive activity

The most striking feature of the 2002–03 Etna eruption was the extraordinary explosive activity, characterised by powerful column-forming fire fountains that caused quite continuous tephra fallout on the slopes of the volcano during most of the eruption. The height of the ash column ranged between 4–6 km a.s.l. We frequently measured the height of the eruptive column during the daily survey, using the barometric altimeter in Civil Protection helicopters.

Copious scoria, lapilli and ash covered all of the volcano's flanks, particularly the east sector due to the prevailing wind direction. Fine ash reached the Aeolian Islands, the Campania region, west Greece and Libya, up to 500 km from the source. Proximal areas covered by tephra fallout between 27 October and 5 November are represented in Fig. 11. Weight per unit area measurements of the ash deposited between 27 and 30 October gave: 2.1 kg/m^2 at Catania, ~15 km away from the summit, where mean grain-size was 0.125–0.25 mm; 9.7 kg/m^2 at Nicolosi, about 14 km distance from the fissure, where mean grain-size was 0.5–1 mm, and 38.8 kg/m^2 at Rifugio Sapienza, ~4 km from the summit, where mean grain-size was 1–2 mm (Andronico et al. 2003a). The total amount of ash that fell on Catania by the end of December was 4 kg/m^2. The proximal fallout deposit formed two large scoria cones, about 150 m high, that coalesced in the upper segment of the eruptive fissure. Tephra volume has been calculated using the method of Pyle (1989) for the 27 and 28 October and 4 November deposits, and then extrapolated for the entire period of the eruption. The resulting volume estimate is 40–50×10^6 m^3, giving an explosivity index (volume of pyroclastic products divided by total erupted volume) of ~0.55.

The ash comprised tachylite, sideromelane, crystals and lithic clasts, the relative proportions of which changed throughout the eruption. Generally, lithic and crystal contents were lower than during the 2001 eruption as reported by Taddeucci et al. (2002). In particular, the analysed samples of the first day of the 2002 eruption, derived both from the NE and S fissures, had a 30% lithic clast component, whereas on 28 October this value dropped to 9%. Generally, for the entire eruption, the proportion of lithics in the ash was low, between 0 and 3%, with values of 13% on 13 November and about 5% on 12 December. Some juvenile clasts (tachylite and sideromelane) ejected during the first two days of the eruption showed cracks formed by rapid quenching, and thick vesicle walls typical of uncompleted gas expansion, and many pyroclasts were coated by adhering dust (Andronico et al. 2003b). These features, in addition to the higher lithic content, suggest an initial magma-water interaction during the opening phase of the southern fissure. During most of the following days, the juvenile ash components (tachylite, sideromelane and loose crystals) represented 100% of the total, indicating that the process of magma fragmentation during the eruption was produced mostly by exsolution and expansion of magmatic gases.

Intensity of the explosive activity

Since 1994 a network of video cameras on the lower slopes of the volcano have provided a continuous view of the volcanic activity from different locations. In order to quantify the intensity of the explosive activity at the S fissure and its changes during the eruption, we have analysed the images recorded by two video cameras. The first fixed video camera was located at Milo (Fig. 1), 20.5 km distance from the summit. The second video camera was a mobile system that has been located at the Serra La Nave Observatory, 5 km from the fissure, since 4 November 2002 (Fig. 2). The explosive activity during the first month of the eruption has been analysed using images from photographs, videos and direct observations taken during daily helicopter flights. Continuous video images were not available during this period due to the damage caused by the S. Venerina earthquake on 29 October 2002.

We have estimated the intensity of ash emission using a qualitative observation of the density and height of the ash column, taking into account the wind speed and direction. We divided the observed ash intensity into four levels, ranging from 0 for no ash emission to 3 for the maximum intensity of ash emission during the eruption. We have assigned a value of 1 to an ash emission intensity corresponding to 25% of the maximum intensity, and value of 2 to 25–75% of the maximum intensity. These data have been plotted in Fig. 8a, and show a general decreasing trend, with several variations in intensity during the eruption. In particular, from 27 October to 12 November, the activity was very stable and characterised by high intensity of ash emission. Between 12 and 14 November there was a sharp decrease in ash emission due to a change from fire fountaining to mild strombolian explosions. From 14 to 25 November ash emission exhibited some pulses. On 24 November it reached the value 0 due to the temporary cessation of explosive activity at the 2750 m cone, which occurred just before the opening of two effusive vents at 2800 m. Between 26 November and 10 December, ash emission was intense and quite stable, with values between 3 and 2. Finally, from 10 December onwards there was a general decrease in the intensity of ash emission, with sudden changes between 3 and 0 (alternation of fire fountains and strombolian activity) in a few hours, until the end of the eruption when the expulsion of ash eventually ceased.

Gas geochemistry

COSPEC SO_2 flux measurements

During the eruption, daily measurements of sulphur dioxide (SO_2) flux were carried out using a correlation spectrometer (COSPEC) mounted on a vehicle travelling underneath the plume. The analyses of data collected daily provided essential information on magma behaviour within the upper part of the feeder system of the volcano. Additionally, in several cases it was possible to distinguish the SO_2 flux emission from separate sources (N fissure, Summit Craters, and S fissure) that allowed investigation of the magma supply rate to each eruptive vent. SO_2 flux in the plume of Mt. Etna has been routinely carried out using a COSPEC since 1987 (Caltabiano and Romano 1988; Caltabiano et al. 1994; Bruno et al. 1999, 2001). This long data set shows that SO_2 flux has a background value of about 5300 t/d (metric tons per day) during non-eruptive periods. After the 2001 flank eruption, SO_2 flux from summit craters showed atypical behaviour, with values below 1000 t/d for ~15 months. This represented the longest continuous period of low SO_2 flux observed at Etna since 1987. This low rate of degassing could have been caused by a reduced magma supply to the upper part of the main feeder system of the volcano (Salerno et al. 2003). A slightly increasing trend in the SO_2 flux was observed beginning mid-March 2002, which coincided with the resumption of eruptive activity first at NEC and then at BN, suggesting a slow increase in the efficiency of convective mechanisms of the magma in the upper part of the main feeder system of the volcano. On 25 October 2002, the SO_2 flux increased abruptly, coincident with the onset of the eruption, reaching a peak on 29 October. During the 2002–03 eruption, three main SO_2 emission stages were identified (Fig. 8e), coinciding with changes in eruptive activity.

The period between 26 October and 14 November was marked by the onset of the eruption and ended with a significant SO_2 increase up to a peak on 14 November that correlated with changes in strombolian activity at the S fissure and the renewal of lava effusion. During this phase, the minimum SO_2 flux was recorded on 5 November, when lava effusion ceased at the N fissure.

The period between 14 November and 28 November was characterised by a huge increase in SO_2 flux emission up to the highest value ever recorded at Mt. Etna (~29000 t/d, 28 November). This value occurred during the maximum explosive activity at the newly formed vent at 2800 m a.s.l.

In contrast, the period between 28 November 2002 and 28 January 2003 was marked by a decrease in SO_2 emissions down to minimum values on December 2002, followed by a weak increase, which corresponded to a weak increase in eruptive activity at the S fissure. SO_2 flux oscillated, with the amplitude and period of these oscillations increasing over time. This behaviour, also seen in other Etnean eruptions, seems typical of the waning stage of an eruption, and preceded the end of this eruption on 28 January 2003.

Remote sensing measurements of SO_2 and HCl with Fourier transform infrared spectrometry

Routine measurements of the relative amounts of SO_2, HCl and HF in the volcanic plume emitted from Mt. Etna have been carried out since March 2000 with a Fourier transform infrared spectrometer (FTIR), using the sun as a source of radiation (Francis et al. 1998). Variations in the ratio of SO_2/HCl are related to initial dissolved amounts for each species and to the degree of gas/magma separation that occurs during magma ascent within the volcanic edifice (Burton et al. 2003). During the 2002 eruption of Mt. Etna the SO_2/HCl ratio of gases emitted from the explosive vent at 2750 m was measured regularly (Fig. 8d). The first SO_2/HCl ratio of 6.3 was measured on 28 October, after which the ratio decreased to 3 on 29 October before increasing at an approximately constant rate to 6 on 11 November, prior to a significant decrease to 3.5 on 12 November. This change was coincident with a temporary cessation of effusive activity, followed by a cyclic explosive activity that was measured continuously throughout the night of 12–13 November. After 12 November a strong increase in SO_2/HCl ratio was observed from southern vent gas emissions, reaching a peak of 19 on 24 November, before declining and reaching a value of ~5 that was maintained until the end of the eruption with small variations. We believe that the variations observed during the first phase of activity (from 28 October to 12 November) were controlled primarily by the degree of gas/magma. A SO_2/HCl ratio of 3 in the gas phase is consistent with complete equilibrium degassing of magma, suggesting that no gas/magma separation occurred, possibly assisted by magma fragmentation that strongly increased the surface area available for diffusion of volatiles from magma to the gas phase. As the eruption progressed, magma/gas separation began to become more important and became an increasingly significant factor in controlling the SO_2/HCl ratio, primarily by inhibiting the diffusion of HCl into the gas phase either through accumulation of degassed magma at the conduit head or by less efficient fragmentation within the conduit. This was seen as an increasing SO_2/HCl ratio between 30 October and 11 November that reached a critical point on 12 November when the amount of degassed magma in the conduit head was finally sufficient to inhibit fragmentation, and the magma/gas mixture collapsed within the conduit for some hours, before gradually rising again, exhibiting strombolian and effusive activity.

Historical context

In order to understand if the 2002–03 southern flank activity showed uncommon volcanological features we compared it to past eruptions of Mt. Etna, examining in detail both eruptive style and intrusion dynamics. We were able to make this comparison for eruptions observed after 1700, when the location and timing of eruptive events started to be recorded and increasing scientific quality of the records allow us to define each event from a volcanological point of view (Branca and Del Carlo 2004).

Searching the historical record for an eruption showing features similar to that of 2002–03, we find that during the last three centuries only one eruption, which occurred in the summer of 1763 (Recupero 1815), had similar characteristics to that of the 2002–03 S fissure. The 1763 eruption lasted 84 days, and started from an eruptive vent located very close to the area of the 2002-03 S fissure. It was characterised by intense and continuous explosive activity and by subordinate lava output that produced a 3.5 km-long lava flow. The explosive phase consisted of long periods of fire fountaining and minor strombolian activity that formed the La Montagnola scoria cone at 2500 m a.s.l. (Fig. 2). Fire fountain activity led to a few km-high eruptive columns, producing abundant lapilli and ash fallout on the SE flank down to Catania. The formation of a continuous lapilli and ash deposit caused considerable damage to cultivated areas.

During the nineteenth century, several eruptions were characterised by strong explosive phases with lava effusion, such as the 1811, 1852–53, 1886 and 1892 eruptions. Vigorous explosive activity produced eruptive columns that caused an almost continuous tephra fall for a long period of time. During the twentieth century, no eruption showed similar explosive features compared to those of the nineteenth century. However, remarkable explosive activity occurred during the 2001 eruption (Calvari and INGV-CT 2001). This event was characterised by continuous explosive activity at the 2550 m vent, where a large scoria cone formed, and by effusive activity at the 2100 m vent that produced a 6.2 km-long lava flow field. Discontinuous ash emission from the 2550 m vent formed a 2–4 km-high sustained column. Lapilli and ash fell copiously for about ten days on the eastern flank of the volcano from Taormina to Catania (Fig. 1). In contrast, the 2002 eruptive activity along the NE-Rift showed the same explosive features and typical lava flow field evolution as the historical eruptions of this sector of the volcano (Branca and Del Carlo 2004).

If we consider the composition of erupted products, the 2002–03 eruption showed the presence of two different magmas, as was the case in 2001 (Fig. 9). None of the historical eruptions of the last 300 years showed this double and distinct magma output. In fact, although the eruptive fissures opened in two different areas of the volcano in 1879 and 1949 (Blaserna et al. 1879, Silvestri 1879, Cumin 1950), forming a several km-long fissure system that dissected the summit cone, these eruptions were connected to a single dike intrusion from the central conduit feeding system.

Discussion

The multi-disciplinary approach to volcano monitoring at Mt. Etna allows evaluation of several features of the eruptive dynamics of the 2002–03 eruption, and therefore allows us to determine in great detail the evolution of the eruption. Before the onset of the eruption, the presence of magma in the upper portion of the volcanic edifice had been revealed by several lines of evidence, such as: the renewal of strombolian activity at NEC, the increase in SO_2 flux at the summit craters, and development of hot cracks across the summit. Recently, Patanè et al. (2003) argued that geodetic and seismic data recorded between 1994 and 2001 indicate a continuous injection of magma from 6–15 km depth into the shallow (3–5 km) magma reservoir, with magma accumulation in the upper part of Mt. Etna's plumbing system. Starting from these considerations, we propose two alternative hypotheses for the mechanism that triggered the rise of magma. (1) The radial stress accompanying the deformation caused by magma instrusion at 6–15 km depth caused the earthquake along the PFS on 22 September 2002. This could have favoured the gradual upward magma movement and its emergence on the surface about one month later. This is supported, on a local scale, by thermal camera monitoring and field surveys which allowed the recognition of new fractures in the summit area some months before the eruption onset. SO_2 flux measurements showed a slight increase from March 2002 onwards. (2) An alternative possibility is that depressurisation caused by active spreading of Etna's eastern flank may have triggered magma output along the NE-Rift system (Acocella and Neri 2003, Acocella et al. 2003; Branca et al. 2003; Neri et al. 2004). In fact, the eastern unstable area is bordered to the north by the E-W trending PFS. Data collected during the 2002–03 eruption (Neri et al. 2004) indicate that: a) the fracture pattern along the PFS migrated from the NE Rift east toward the coastline, nearly 20 km distant, and b) then the deformation transferred along most of the structures and faults on the eastern flank of Etna, migrated southwards. These data are consistent with the eastern flank of Mt. Etna spreading toward the east, corresponding to model (2) proposed above. The decompression caused by the spreading led to buoyant magma at depth rising upward.

Regardless of the trigger mechanism, the extraordinary explosivity makes the 2002–03 eruption a unique event in the last 240 years of recorded activity on Etna. On the basis of available historical data we observe that the eruptive style of the S fissure, characterised by predominant explosive activity, is comparable only with the La Montagnola 1763 and the 2001 Lower Vents eccentric eruptions. Another unusual aspect is that the 2002–03 eruption involved two simultaneous, independent lava effusions showing different magma compositions and styles of lava flow field emplacement. In this respect, the NE-Rift system was fed by a hydrostatic supply of magma, whereas the S fissure was fed by discrete pulses of magma. The NE fissure system followed the general trend of the NE-Rift eruptions, being characterised by a high effusion rate that rapidly declined, with long lava flows of short duration. The S fissure system had a rather different behaviour with short lava flows and effusion rate characterised by several short-term pulses and rather constant peak values. Pulses in the magma supply rate were also seen as pulses in the SO_2 flux.

Anomalous features of the 2002–03 eruption are reflected in petrological analyses. These indicate that two different magmas fed the NE and S fissure systems, as occurred during the 2001 eruption. The 2001 and 2002–03 eruptions represent the only cases of two distinct dike intrusions in the eruptive activity of the last 300 years at Etna. In particular, petro-chemical features of the 2002–03 products strongly suggest the presence of a complex plumbing system (Fig. 12). Type 1 magma erupted from the NE fissure represents the partially degassed resident magma of the shallow plumbing system. Type 2 magma erupted from the S fissure is an undegassed, volatile-rich, fast-rising magma that drains the deep portion of the feeding system and bypasses the central conduits. The synthesis of data from SO_2 gas flux, SO_2/HCl gas ratio and bulk rock CaO/Al_2O_3 ratio (Fig. 8c) in tephra allows a unique insight into the processes that controlled the initial stages of the 2002–03 Etna eruption. All three datasets indicate that the first two days of the southern flank eruption produced relatively fractionated magma. Data from ash analyses demonstrate that phreatomagmatic processes played a significant role in the first two days of the eruption, and it is therefore likely that the first eruptive activity was controlled by the interaction of a dike intrusion of evolved magma with a shallow aquifer. Gas emissions in the first two days of the eruption were typified by a relatively low but increasing SO_2 flux and a high but decreasing SO_2/HCl ratio. These data are consistent with both initial scrubbing of HCl by interaction with an aquifer (leading to a high SO_2/HCl ratio) and/or prior degassing of magma at high pressure at the head of the intruding dyke.

Between 28 and 30 October there was a systematic evolution in these parameters, with increasing SO_2 flux and CaO/Al_2O_3 ratio and decreasing SO_2/HCl ratio. This is consistent with the rapid ascent of large volumes (high SO_2 flux) of magma less fractionated than that seen during the first two days of the eruption. The large ash production during this period demonstrates that efficient fragmentation occurred within the conduit. The low SO_2/HCl ratio (~3) observed on 30 October is probably the result of efficient syneruptive degassing, assisted by the large surface area afforded by fragmentation; melt in-

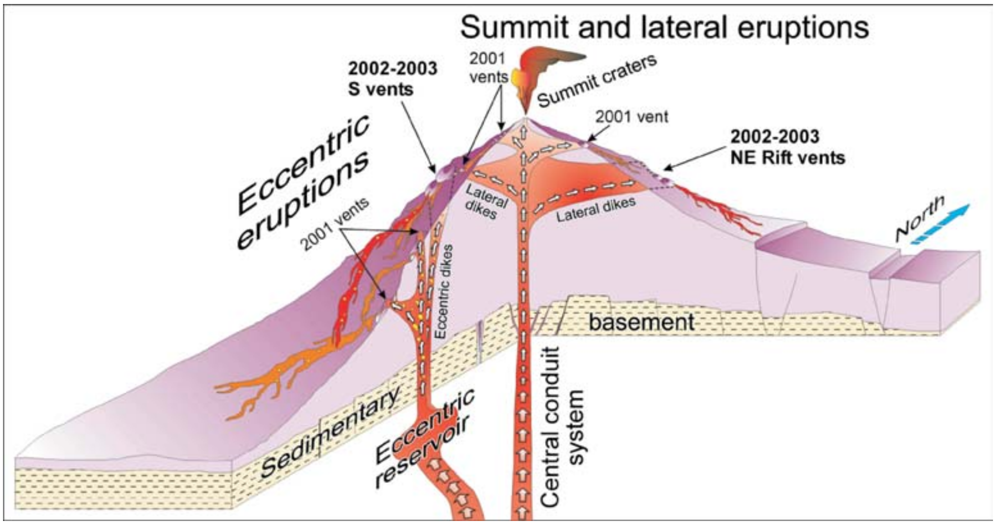


Fig. 12 Schematic diagram of proposed magma feeding system during the 2001 and 2002–03 eruptions (after Benhcke and Neri 2003a)

clusion data (Burton et al. 2003) suggest that complete equilibrium degassing of Etnean magmas would produce gas with an SO_2/HCl ratio of 3.

After 30 October the CaO/Al_2O_3 ratio strongly decreased on 12 November while the SO_2/HCl ratio increased to a peak on 11 November of ~6. There are two possible explanations for these observations. (1) An increasing quantity of degassed, crystallising magma accumulated in the conduit, leading to an increasing gas/magma separation, producing both an increasing SO_2/HCl ratio (due to the reduced efficiency of magma fragmentation) and a decreasing CaO/Al_2O_3 ratio (due to magma evolution). The presence of degassed magma may also decrease the magma ascent rate and therefore explain the slight decrease in SO_2 flux seen after 30 October. (2) Alternatively, the eruption may have been triggered by a relatively small input of magma into a resident magma body emplaced during the 2001 eruption of Mt. Etna. In this case we observed the fast-rising magma associated with the new intrusion only around 30 October (high CaO/Al_2O_3), whereas in the preceding and subsequent periods we observed products from resident magma (lower CaO/Al_2O_3). As before, the SO_2/HCl ratio is controlled by an increasing effect of degassed magma within the conduit, that catalyses a gas/magma separation. The slight decrease in SO_2 flux after 30 October can be explained either by partial prior degassing of the resident magma or a decrease in magma ascent rate.

Comparing the parameters reported in Fig. 8, we can identify some characteristics in the dynamics of the 2002–03 eruption related to the S fissure. In particular, we are able to identify some phases during the magma ascent toward the surface, due to almost contemporaneous variations in several parameters. From the beginning of the eruption several parameters increased, and after three days we observed a maximum of explosivity, covered area, CaO/Al_2O_3 ratio and SO_2 flux, whereas the SO_2/HCl ratio dropped. Lava effusion that was intense during the first days stopped on 31 October. We propose that during the first three days of the eruption these variations mark the arrival of new magma, recorded by the intrusion of a new dike with a more mafic composition.

The evolution of the system results in decreasing gas flux and increasing magma viscosity within the conduit that ultimately leads to the collapse of the magma/gas mixture within the dike on 12 November. This collapse signalled the transition to a new phase of activity, where the weight of degassed magma was sufficient to inhibit continuous fragmentation but allowed cyclicity between effusive and strombolian activity.

From 13 November the CaO/Al_2O_3 ratio, the SO_2/HCl ratio, and the intensity of eruptive activity (both effusive and explosive) increased again, suggesting the beginning of a second phase of the eruption. This was characterised by lava effusion that formed one of the longest lava flows (3.6 km), and intense explosive activity oscillating between fire fountains and strombolian explosions. The second phase finished on 24–25 November, when peaks in the SO_2 and SO_2/Cl values (24 November) demonstrate the arrival of a volume of gas-rich magma that had accumulated at depth.

From early December a general decrease in gas parameters was associated with declining eruptive activity. This waning stage was not continuous, but followed oscillations as indicated by the many variations in the volatile values, in intensity of the explosive activity, and in lava effusion. This trend led to the end of the eruption on 28 January 2003.

Concluding remarks

The 2002–03 eruption was triggered either by (1) the accumulation and eventual ascent of magma at depth or (2) depressurisation of the edifice due to spreading of the eastern flank of the volcano. The eruption was notable due to both the very high explosivity observed and to the simultaneous emission of two different magmas from two separate fissure systems. The NE system exhibited behaviour typical of hydrostatically-driven emptying of magma resident in the shallow plumbing system of the volcano. It was active for nine days, demonstrated prevalent strombolian activity, and produced a lava volume of ~8 to 12×10^6 m^3. The S system was driven instead by undegassed magma rising from depth, independently from the central conduit. Eruptive activity lasted a total of 94 days and was characterised by high explosive and minor effusive activity, that produced a flow field of ~25–34×10^6 m^3. Fire fountaining formed sustained eruptive columns, causing abundant tephra fallout whose volume has been preliminarily estimated to be 40–50×10^6 m^3. The ratio of the volume of pyroclastic products to the total erupted volume gives a value of 0.5–0.6. This is the highest value for this ratio seen for an Etnean eruption since the sixteenth century (Romano and Sturiale 1982).

Petrological, geochemical and ash data indicate that the southern eruption was driven by the fast rise of undegassed magma that either underwent a rapid fractionation or re-activated magma resident from the 2001 eruption. The sudden cessation of explosive activity seen on 12 November is consistent with the collapse of the fragmented magma/gas mixture that had until that day been present within the conduit of the southern vent. This collapse was probably caused by a steady accumulation of degassed magma within the conduit that gradually inhibited magma ascent and degassing.

After 12 November the weight of degassed magma within the conduit was sufficient to inhibit continuous fragmentation but it allowed cyclicity between effusive, strombolian and fire-fountaining activity. Around 24–25 November, peaks in the SO_2 flux and SO_2/HCl ratio indicate the arrival at the surface of a large volume of gas that had accumulated at depth and rapidly ascended within the system. One effect of this sudden rise was the activation of the 2800 m vent within the eruptive fissure. The first clear signs of a decrease in the intensity of activity were observed after 10 December, and this developed into a trend that continued to the end of the eruption on 28 January.

With regard to potential eruptive activity on Etna, we believe that further flank eruptions similar to 2001 and 2002–03 may occur in the near future. This belief is supported by the observation that both the 2001 and 2002–03 eruption were supplied by an eccentric magma reservoir, supplied from depth independently from the central conduit system. If this geometry was not radically altered after the 2002–03 eruption then it is reasonable to assume that this reservoir is currently being recharged, and could therefore be the source of further eruptive activity in the future, once sufficient overpressure is reached.

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