Bull Volcanol (2006) 69: 149–173
DOI 10.1007/s00445-006-0061-x

RESEARCH ARTICLE

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The exceptional activity and growth of the Southeast Crater, Mount Etna (Italy), between 1996 and 2001

Received: 22 April 2005 / Accepted: 10 February 2006 / Published online: 27 April 2006

Abstract Between 1971 and 2001, the Southeast Crater was the most productive of the four summit craters of Mount Etna, with activity that can be compared, on a global scale, to the opening phases of the Pu‘u ‘Ō‘ō-Kūpaianaha eruption of Kīlauea volcano, Hawai‘i. The period of highest eruptive rate was between 1996 and 2001, when near-continuous activity occurred in five phases. These were characterized by a wide range of eruptive styles and intensities from quiet, non-explosive lava emission to brief, violent lava-fountaining episodes. Much of the cone growth occurred during these fountaining episodes, totaling 105 events. Many showed complex dynamics such as different eruptive styles at multiple vents, and resulted in the growth of minor edifices on the flanks of the Southeast Crater cone. Small pyroclastic flows were produced during some of the eruptive episodes, when oblique tephra jets showered the steep flanks of the cone with hot bombs and scoriae. Fluctuations in the eruptive style and eruption rates were controlled by a complex interplay between changes in the conduit geometry (including the growth of a shallow magma reservoir under the Southeast Crater), magma supply rates, and flank instability. During this period, volume calculations were made with the aid of GIS and image analysis of video footage obtained by a monitoring telecamera. Between 1996 and 2001, the bulk volume of the cone increased by ~36×10^6 m^3, giving a total (1971–2001) volume of ~72×10^6 m^3. At the same time, the cone gained ~105 m in height, reaching an elevation of about 3,300 m. The total DRE volume of the 1996–2001 products was ~90×10^6m^3. This mostly comprised lava flows (72×10^6 m^3) erupted at the summit and onto the flanks of the cone. These values indicate that the productivity of the Southeast Crater increased fourfold during 1996–2001 with respect to the previous 25 years, coinciding with a general increase in the eruptive output rates and eruption intensity at Etna. This phase of intense summit activity has been followed, since the summer of 2001, by a period of increased structural instability of the volcano, marked by a series of important flank eruptions.

Keywords Mount Etna · Lava fountaining · Microplinian · Remote video monitoring · Volume calculations · Cone growth

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Introduction

Although basaltic volcanic eruptions are typically associated with the effusion of lava flows, they can show significant variations in eruptive styles and volume fluxes and are capable of producing significant amounts of tephra to construct sizeable pyroclastic edifices. The classic example is Kīlauea on Hawai‘i, which is famous for its episodic lava fountaining (e.g., Wolfe et al. 1988) and is currently under-going one of the most long-lived historical effusive eruptions (Heliker and Mattox 2003). Another basaltic volcano which displays similar types of activity is Mount Etna (Italy), where most eruptions produce voluminous lava flows (Chester et al. 1985). However, explosive activity including lava fountaining is also common (Allard et al. 2005; Branca and Del Carlo 2004, 2005). In contrast to Kīlauea, this latter type of activity is generally limited, at Etna, to summit eruptions, and can be considerably more violent. Conditions for direct observation and quantitative analysis are less favorable at Etna than at Kīlauea, because its summit area is remote and often veiled in clouds. In addition, the activity can be hazardous for observers at close range. Nonetheless such observation and analysis is crucial not only for a better understanding of the dynamics of the volcano, but also because explosive summit activity represents a significant hazard, especially for aircraft.

During the past century, the summit area of Etna has undergone significant morphological modifications (Guest 1973). These were mostly characterized by an increase in the number of summit craters from one (Central Crater) to four. The Northeast Crater formed in 1911 outside the former Central Crater (Riccò 1911) and eventually grew into a massive cone which became the highest point on Etna in the early 1980s, gaining an elevation of 3,350 m; by 2002 it remained the highest point of the volcano but collapse had reduced its height to 3,314 m (John Murray, 2004, personal communication). The Voragine and the Bocca Nuova formed within the old Central Crater in 1945 and 1968, respectively (Cucuzza Silvestri 1949; Murray 1980). Finally, the Southeast Crater (SEC) was born in 1971 at the southeast base of the central summit cone (Calvari et al. 1994a). From 1978 through 2001, it was the most active of the four craters and evolved into a tall cone dominating the skyline of Etna.

Here we present a detailed study of the volumes of products erupted by the SEC and its morphological and structural evolution over the period 1996–2001 (Fig. 1). Eruptive activity occurred from late 1996 until the beginning of the July-August 2001 flank eruption (Behncke and Neri 2003a,b; Behncke et al. 2003; Calvari and Pinkerton 2002; Calvari et al. 2002). The crater was inactive prior to November 1996 as well as between July 2001 and September 2004. During September 2004, effusive activity resumed close to the SEC cone (Burton et al. 2005). Although the activity during the 1996–2001 period can be considered near-continuous, it showed wide

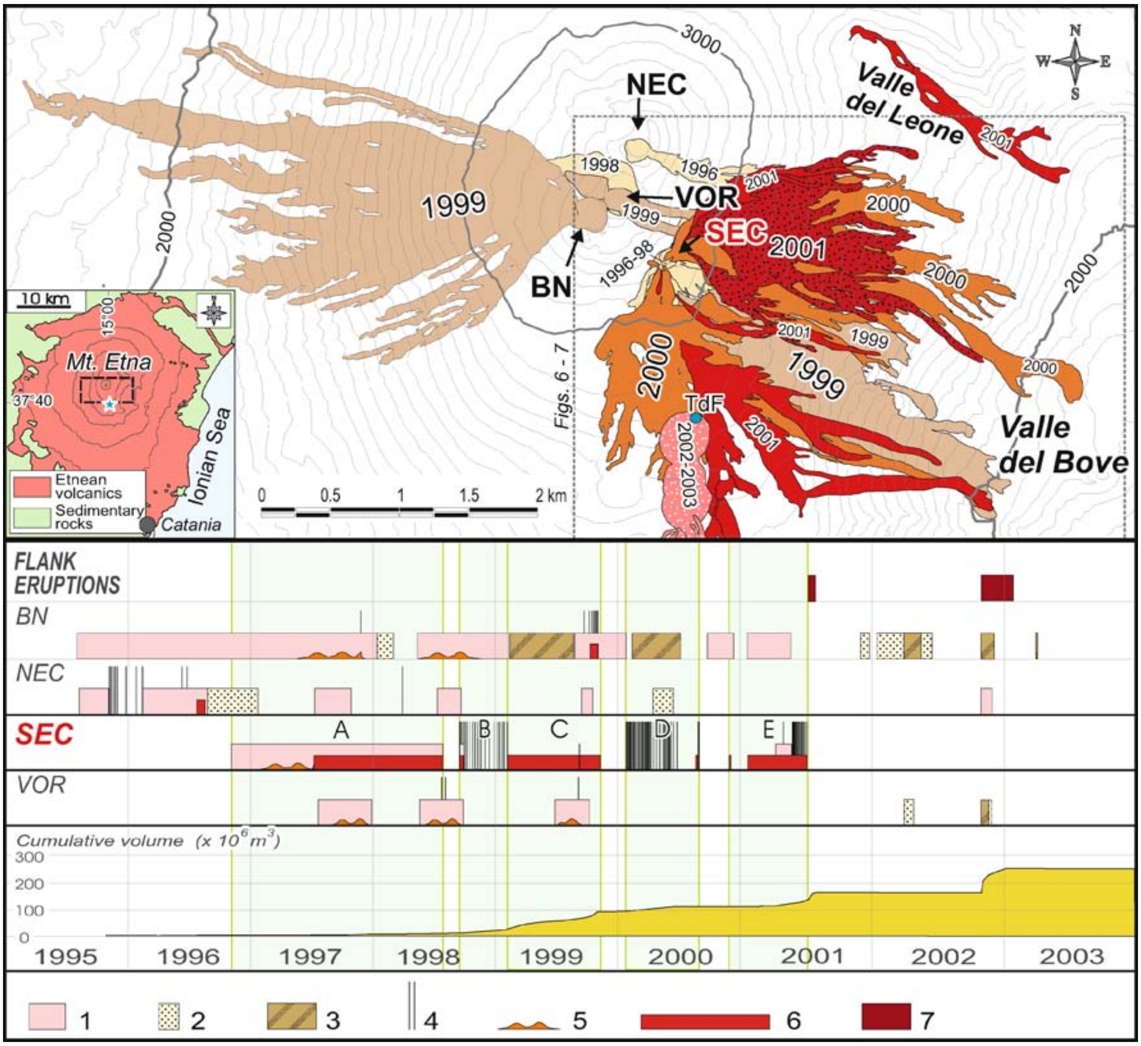

Fig. 1 Map of the summit area of Mount Etna (*inset at left* shows location; the *blue star* indicates the INGV Montagnola monitoring camera), showing the four summit craters of Etna (*NEC* Northeast Crater; *VOR* Voragine; *BN* Bocca Nuova; *SEC* Southeast Crater) and lavas erupted during the activity of 1995–2003. Lower panel is a chronological summary of the eruptive activity for each of the summit craters. Key: *1* more or less continuous mild Strombolian activity; *2* sporadic Strombolian activity and ash emissions; *3* more or less continuous emissions of (mostly lithic) ash; *4* episodes of fountaining and tephra emission, often with fast-moving lava flows; *5* intermittent intracrater lava effusion; *6* lava overflows onto the outer flanks of the crater in question; *7* flank eruption. Hiatuses in the activity as represented by activity gaps are periods of quiet degassing. The lower panel gives the cumulative volume of eruptive products of all summit activity from NEC, VOR, BN and SEC. Figure is updated from Behncke and Neri (2003a)

variations in style and intensity, and the resulting products were emplaced at rates that varied greatly in time and space. The most significant result of this activity was the rapid growth in height and volume of the SEC cone (Fig. 2) to an elevation only about 15 m lower than the highest point on Etna, the Northeast Crater. In addition to the growth of the cone itself, numerous thin lava flows were repeatedly emplaced, extending as far as 3 km from their source, and frequent episodes of violently explosive activity produced tephra falls that in many cases reached distances of many tens of kilometers (Alparone et al. 2003).

Following a description of the methods applied for this study, we present a summary of this exceptional sequence of eruptive events and erupted volumes. We also document the resulting morpho-structural changes at the SEC and focus on the complexities observed especially during a set of eruptive episodes in 2000, comparing them to similar activity at Kīlauea.

Methods and terminology

Morphological and volumetric analysis

Different methods have been used for the evaluation of the main parameters of the 1996–2001 SEC activity, such as the morphological and structural evolution of the cone and the volumes of erupted products. Elevations and geographic coordinates were obtained with a hand-held 12-channel GPS during 1999–2004. During the GPS surveys, we attempted to cover the study area with as many measurement points as possible, especially in areas of more complex morphology. During each survey, only values with vertical errors of less than 5 m were accepted. Digital, georeferenced topographic maps were drawn from these surveys and from existing topographic maps (1967, 1996, 1999, 2004). These were used to visualize and quantify morphological and volumetric changes. Time series of photographs were used to determine changes in cone height and morphology at frequent intervals. Lava flow volumes were calculated from maps produced frequently (daily to weekly) during periods of eruptive activity. These were drawn based on GPS field surveys and aerial photographs (see Calvari et al. 1994b and Harris and Neri 2002 for more detail on this methodology). Field measurements were made with the aid of portable GPS along the boundaries of newly emplaced lava flows. We estimate the volume errors for these maps at 5–20% for any given lava flow. Such errors are estimated from discrepancies between the volumes obtained with the different methods (image analysis, field and aerial surveys, digital topographic analysis).

To correlate the volumes of pyroclastic deposits with those of lava flows, bulk volumes were converted to dense rock equivalent (DRE). This was achieved using a vesicularity of 20% for lava flows (obtained by modal analysis of available samples of lava flows and bombs produced during the study period) and 50% for pyroclastics constituting the cone. This correction takes into account the fact that about half of the cone comprises lava flows and volcanic bombs with vesicularities of 20–25%, the other half comprises inflated scoriae from lava fountains with a coarse mean vesicle volume of 75%.

Image analysis

Image analysis used video footage from the monitoring video camera of the Catania section of the Istituto Nazionale di Geofisica e Vulcanologia (INGV-CT). This was located, until its destruction during the 2001 flank eruption, on the Montagnola (2,612 m, and 3.2 km SSE of the SEC; Fig. 1). These data were also used to derive eruptive typologies and their physical and dynamic properties. They also allowed us to determine the proportion of eruptive activity that contributed to the growth of the cone and approximate mass eruption rates (see Tables 1, 2 and 3). These data were particularly useful during the episodic lava fountaining characteristic of several phases of the activity.

The telecamera, a Sony DXC 3000 IRP cam equipped with a Canon j15x9.5B4 KTS A SX6 zoom lens, recorded in the visible band during daylight hours and in the near IR during the night. The signal was sent to a receiver at Catania, through a 10 GHz microwave transmitter, where it was converted into analogue and digital video and recorded

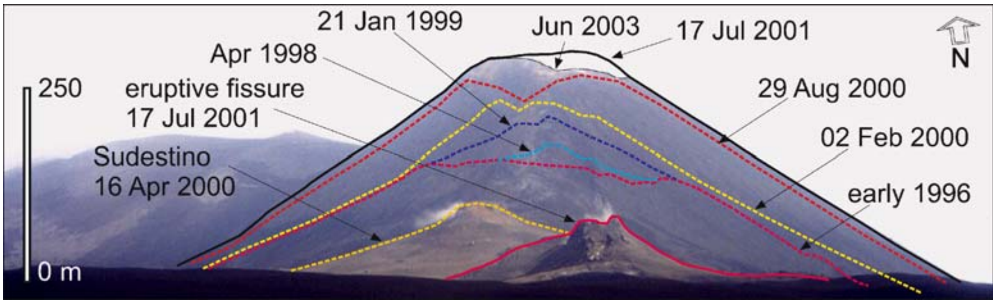

Fig. 2 Annotated photograph (taken 21 October 2002) showing final shape of the Southeast Crater after the final series of eruptive episodes during the 1996–2001 period—those of June-July 2001. Successive outlines of the Southeast Crater cone are shown, based on comparison photographs taken since 1997. These also highlight the development of satellite features at its southern base (Sudestino, formed in 2000, and steep-sided spatter cone formed at uppermost fissure of the 2001 flank eruption). Note that the cone reached its greatest height in late June-early July 2001, immediately before the onset of the 2001 flank eruption that led to collapse of the summit

Table 1 Dates of the first three phases (A, B and C) of the 1996–2001 eruptive activity of the Southeast Crater, and relative volumes and eruption rates for individual eruptive events

Phase	Event	Date (dd/mm/yyyy)	Lava flows			Fountain				Total eruption rate (m^3s^{-1})	Total volume (10^6m^3)	Cumulative volume (10^6m^3)
			Area (10^6 m^2)	Thickness (m)	DRE volume (10^6m^3)	Low-level rate (m^3s^{-1})	Low-level volume (10^3m^3)	Climax rate (m^3s^{-1})	Climax volume (10^3m^3)			
A	1	06/11/1996 – 26/07/1998	0.25	6	1.2					0.02	1.2	1.20
B	1	15/09/1998				3	22	80	72	17	0.16	1.36
	2	18/09/1998				3	16	80	72	12	0.16	1.52
	3	21/09/1998				3	16	80	72	12	0.16	1.67
	4	25/09/1998				3	16	80	72	12	0.16	1.83
	5	30/09/1998				3	16	80	72	12	0.16	1.98
	6	06/10/1998				3	16	110	99	17	0.18	2.17
	7	11/10/1998				3	16	110	99	17	0.18	2.35
	8	18/10/1998				3	16	110	99	17	0.18	2.53
	9	24/10/1998				3	16	110	99	17	0.18	2.72
	10	01/11/1998				3	16	110	99	17	0.18	2.90
	11	07/11/1998				3	16	120	108	18	0.19	3.09
	12	18/11/1998				3	16	120	108	18	0.19	3.28
	13	29/11/1998				3	16	130	117	20	0.20	3.48
	14	14/12/1998				3	16	130	117	20	0.20	3.68
	15	29/12/1998				3	16	140	126	22	0.21	3.89
	16	05/01/1999				3	16	140	126	22	0.21	4.10
	17	10/01/1999				3	16	140	126	22	0.21	4.31
	18	13/01/1999				3	16	150	135	23	0.22	4.53
	19	16/01/1999				3	16	150	135	23	0.22	4.75
	20	18/01/1999				3	11	150	135	30	0.21	4.96
	21	20/01/1999				3	11	150	135	30	0.21	5.18
	22	23/01/1999				3	16	150	135	23	0.22	5.40
	23	04/02/1999				3	16	150	135	30	0.22	5.61
	Phase B total		*0.39*	*5*	*1.55*		*367*		*2493*		*4.41*	
C	1	04/02/1999 – 25/08/1999	1.13	20	22.46					1.29	22.46	28.08
	2	27/08/1999 – 17/09/1999	0.22	3	0.73					0.40	0.73	28.80
	3	18/09/1999 – 14/11/1999	0.31	4	1.18					0.29	1.18	29.99
	Phase C total		*1.45*		*24.37*						*24.37*	

Note that phase C is subdivided into three sub-phases (labeled 1–3). Low-level and climax (lava fountain) eruption rates are based on image analysis of footage of the Montagnola surveillance camera (see Methods and terminology section for details); we estimate a maximum error of 25% for these data

Table 2 Dates of events comprising phase D of the 1996–2001 Southeast Crater activity, which was characterized by 66 episodes of lava fountaining, with relative volumes and eruption rates for individual events

Phase	Event	Date (dd/mm/yyyy)	Lava flows			Fountain				Total eruption rate (m^3s^{-1})	Total volume (10^6 m^3)	Cumulative volume (10^6 m^3)
			Area (10^6 m^2)	Thickness (m)	DRE volume (10^6m^3)	Low-level rate (m^3s^{-1})	Low-level volume (10^3m^3)	Climax rate (m^3s^{-1})	Climax volume (10^3m^3)			
D	1	26/01/2000	0.34	2	0.54	3	72	170	561	38	1.17	31.16
	2	29/01/2000	0.03	2	0.04	3	11	170	153	46	0.20	31.36
	3	01/02/2000				3	14	170	102	65	0.46	31.82
	4	02/02/2000				3	9	170	102	91	0.46	32.27
	5	03/02/2000				3	6	170	102	120	0.45	32.72
	6	04/02/2000				3	7	170	102	74	0.28	33.00
	7	04/02/2000				3	7	170	102	74	0.28	33.29
	8	05/02/2000				3	13	170	102	65	0.46	33.74
	9	06/02/2000				3	5	170	102	90	0.28	34.02
	10	06/02/2000				3	5	170	102	90	0.28	34.30
	11	07/02/2000				3	9	170	102	91	0.46	34.76
	12	08/02/2000				3	10	170	102	57	0.28	35.04
	13	08/02/2000				3	10	170	102	57	0.28	35.33
	14	09/02/2000				3	8	170	102	66	0.28	35.61
	15	09/02/2000				3	8	170	102	66	0.28	35.89
	16	10/02/2000				3	5	170	102	134	0.45	36.34
	17	11/02/2000				3	10	170	102	56	0.28	36.63
	18	11/02/2000				3	10	170	102	56	0.28	36.91
	19	12/02/2000				3	5	170	102	75	0.22	37.13
	20	12/02/2000				3	5	170	102	75	0.22	37.35
	21	12/02/2000				3	5	170	102	75	0.22	37.58
	22	13/02/2000				3	3	170	102	205	0.45	38.02
	23	14/02/2000				3	9	170	102	61	0.28	38.31
	24	14/02/2000				3	9	170	102	61	0.28	38.59
	25	15/02/2000				3	6	170	102	131	0.45	39.04
	D3-D25 total		*0.65*	*10*	*5.16*							
	26	16/02/2000				3	4	170	102	54	0.14	39.18
	27	16/02/2000				3	4	170	102	54	0.14	39.32
	D26-D27 total		*0.04*	*2*	*0.06*							
	28	17/02/2000				3	3	170	102	86	0.15	39.47
	29	17/02/2000				3	3	170	102	86	0.15	39.61

Table 2 (continued)

Phase	Event	Date (dd/mm/yyyy)	Lava flows			Fountain				Total eruption rate (m^3s^{-1})	Total volume (10^6 m^3)	Cumulative volume (10^6 m^3)
			Area (10^6 m^2)	Thickness (m)	DRE volume (10^6m^3)	Low-level rate (m^3s^{-1})	Low-level volume (10^3m^3)	Climax rate (m^3s^{-1})	Climax volume (10^3m^3)			
	30	17/02/2000				3	3	170	102	86	0.15	39.76
	31	18/02/2000				3	3	170	102	104	0.17	39.94
	32	18/02/2000				3	3	170	102	104	0.17	40.11
	33	19/02/2000				3	7	170	102	85	0.24	40.35
	34	20/02/2000				3	11	170	102	41	0.18	40.53
	35	20/02/2000				3	11	170	102	41	0.18	40.70
	36	23/02/2000				3	22	100	270	43	0.42	41.13
	37	27/02/2000				3	23	100	360	45	0.51	41.64
	38	28/02/2000				3	20	100	240	43	0.39	42.03
	D28-D38 total		*0.14*	*8.00*	*0.92*							
	39	04/03/2000	0.08	2	0.12	3	60	170	102	24	0.29	42.32
	40	08/03/2000	0.19	2	0.30	3	15	170	102	76	0.42	42.74
	41	12/03/2000	0.30	2	0.48	3	54	125	338	42	0.87	43.61
	42	14/03/2000				3	11	100	60	154	1.75	45.36
	43	19/03/2000				3	29	100	60	174	1.77	47.13
	D42-D43 total		*1.05*	*4*	*3.36*							
	44	22/03/2000	0.51	2	0.82	3	19	170	306	142	1.14	48.27
	45	24/03/2000	0.20	2	0.32	3	11	170	306	117	0.63	48.90
	46	29/03/2000				3	31	170	306	86	1.04	49.94
	47	01/04/2000				3	22	170	102	103	0.82	50.76
	48	03/04/2000				3	15	170	102	143	0.82	51.58
D	49	06/04/2000				3	14	170	204	155	0.92	52.50
	50	16/04/2000				3	31	170	204	82	0.93	53.44
	51	26/04/2000				3	5	170	102	40	0.81	54.24
	D46-D51 total		*0.88*	*6*	*4.20*							
	52	05/05/2000	0.69	5	2.76	3	15	170	204	99	2.98	57.22
	53	15/05/2000				3	8	170	102	100	1.54	58.77
	54	15/05/2000				3	8	170	102	100	1.54	60.31

Table 2 (continued)

Phase	Event	Date (dd/mm/yyyy)	Lava flows			Fountain				Total eruption rate (m^3s^{-1})	Total volume (10^6 m^3)	Cumulative volume (10^6 m^3)
			Area (10^6 m^2)	Thickness (m)	DRE volume (10^6m^3)	Low-level rate (m^3s^{-1})	Low-level volume (10^3m^3)	Climax rate (m^3s^{-1})	Climax volume (10^3m^3)			
	D53-D54 total		*0.72*	*5*	*2.86*							
	55	17/05/2000	0.70	5	2.81	3	20	170	102	84	2.93	63.24
	56	19/05/2000	0.75	5	2.98	3	10	170	102	126	3.09	66.33
	57	23/05/2000	0.70	5	2.80	3	5	170	102	139	2.91	69.24
	58	27/05/2000	0.69	5	2.76	3	4	170	51	23	2.82	72.06
	59	01/06/2000				3	7	170	77	127	0.36	72.41
	60	01/06/2000				3	7	170	77	127	0.36	72.77
	D59-D60 total		*0.34*	*2*	*0.55*							
	61	05/06/2000	0.47	2	0.75	3	4	170	102	32	0.86	73.63
	62	08/06/2000	0.11	2	0.17	3	19	170	204	54	0.40	74.03
	63	14/06/2000	0.53	2	0.85	3	9	170	102	24	0.96	74.99
	64	24/06/2000	0.45	2	0.72	3	4	170	102	22	0.83	75.82
	65	28/08/2000	0.31	2	0.49	3	16	120	72	15	0.58	76.40
D	66	29/08/2000	0.21	2	0.34	3	33	100	60	15	0.43	76.82
	Phase D total		*2.89*		*37.18*		*864*		*8803*		*46.83*	

Note that lava volumes are sometimes calculated for groups of eruptive episodes because mapping could not be carried out immediately after each of the individual events. Eruption rates during episodes of lava fountaining were calculated from the analysis of video footage taken by the INGV Montagnola monitoring camera

Table 3 Dates of events comprising phase E of the 1996–2001 Southeast Crater activity, which was characterized by two periods of non-explosive lava emission and 16 episodes of lava fountaining, with relative volumes and eruptive rates for individual events

Phase	Event	Date (dd/mm/yyyy)	Lava flows			Fountain				Total eruption rate (m^3s^{-1})	Total volume (10^6 m^3)	Cumulative volume (10^6 m^3)
			Area (10^6 m^2)	Thickness (m)	DRE volume (10^6m^3)	Low-level rate (m^3s^{-1})	Low-level volume (10^3m^3)	Climax rate (m^3s^{-1})	Climax volume (10^3m^3)			
E	1	20/01/2001–06/06/2001								0.1	1.3	78.18
	2[a]	09/05/2001				3	43	30	72	13	0.66	78.84
	3	07/06/2001				3	43	30	36	12	0.62	79.46
	4	09/06/2001				3	43	50	60	13	0.64	80.10
	5	11/06/2001				3	43	60	72	13	0.66	80.76
	6	13/06/2001				3	43	70	84	13	0.67	81.43
	7	15/06/2001				3	43	70	84	13	0.67	82.09
	8	17/06/2001				3	43	70	84	13	0.67	82.76
	9	19/06/2001				3	43	70	84	13	0.67	83.43
	10	22/06/2001				3	16	80	96	13	0.65	84.08
	11	24/06/2001				3	11	80	96	13	0.65	84.73
	12	27/06/2001				3	11	80	96	13	0.65	85.38
	13	30/06/2001				3	11	90	108	13	0.66	86.04
	14	04/07/2001				3	11	100	180	14	0.73	86.77
	15	07/07/2001				3	11	100	180	14	0.73	87.50
	16	13/07/2001				3	11	120	216	15	0.77	88.27
	17	17/07/2001				3	11	120	216	15	0.77	89.04
	Phase E total		*1.15*	*10*	*9.2*		*437*		*1764*		*12.16*	

Lava volume is calculated from field mapping for the entire period only

[a] Event 2 was a fountaining episode that actually occurred during the persistent activity of event 1

on tape. A GPS time-code containing date and time was added to each frame before being recorded. Image sequences were digitized to a resolution of 640×480 pixels. Frames were selected for analysis from footage of significant eruptive events, through dedicated software developed by the IMAQ Vision Builder tool of the LabVIEW software. The procedure applied to these frames is shown in Fig. 3. Semi-automated analysis of fountaining events consisted of opening selected frames in bmp format (Fig. 3a). The image was then resampled and converted to a resolution of 1,024×768 pixels (Fig. 3b), and elements to be excluded from the analysis (such as the incandescent material covering the cone) were masked (Fig. 3c). A color threshold was then applied to eliminate all further elements that were not part of the fountain itself (such as tephra illuminated by the glow of the fountain), as shown in Fig. 3d. The next step, as illustrated in Fig. 3e, consisted of the binarization of the image and filtering of particles outside the main body of the fountain to generate a uniform surface representing the fountain. This allowed calculation of the main physical parameters of the fountain such as height, width, area and perimeter in every image. These data were output to a summary table (Fig. 3f) and exported to a spreadsheet file. Finally, distinctive incandescent lava fragments were chosen to determine the velocity of the eruptive jet and acceleration of individual clasts from particle tracking.

To convert pixel number into a physical dimension, simple trigonometric calculations were performed using data distances to (and between) ground-control features within the scene along with lens aperture. The cumulative error on all spatial measurements, due to different magnifications used during data acquisition and poor quality of some frames, is about 2%. However, we estimate that the error in our calculations of eruption rates and volumes based on the image analysis is much higher, up to 20%. We arrive at this estimate from discrepancies between volumes derived from our video analysis and those based on other methods. The error exists because we had much less control on certain events such as those from eruptive vents not directly visible to the telecamera (i.e., on the north flank of the SEC cone). Furthermore, bad weather conditions and/or unfavorable wind directions hindered about one third of the total visual observations, and recording sometimes failed due to technical problems (black out and/or wrong use of IR filter during the nighttime).

For the events without an available visual image record, we have inferred volumes and eruption rates from subsequent field and aerial surveys or, when this was not possible, from seismic data documenting the duration and

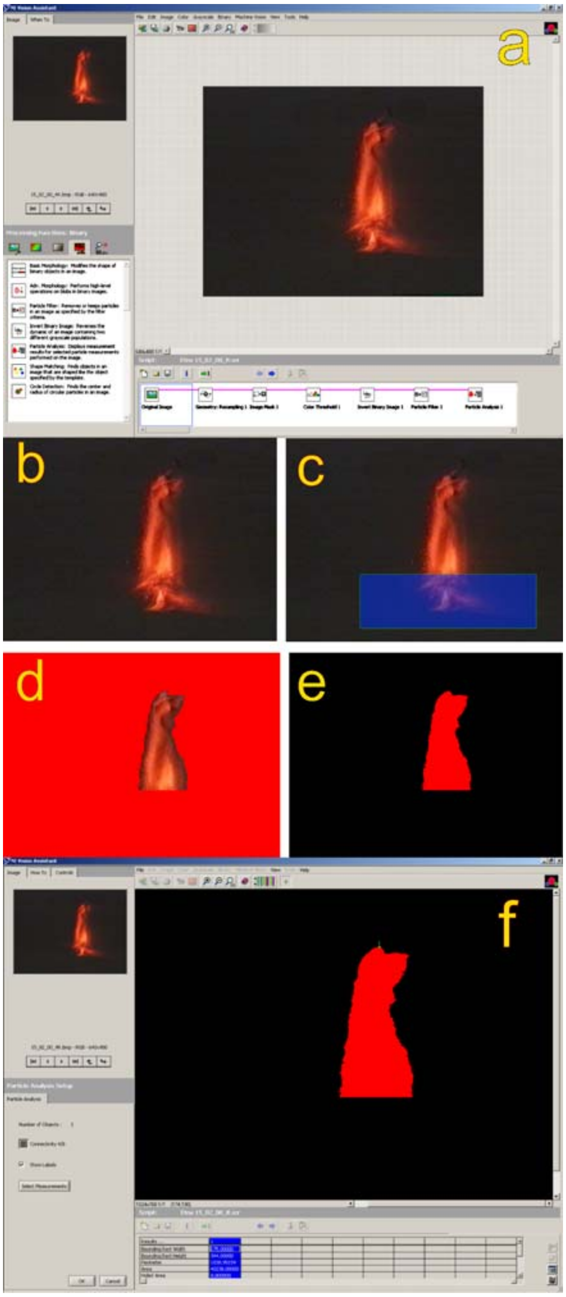

Fig. 3 Example of the procedure applied to extract dimensional characteristics of each fountain using images taken by the monitoring video camera. This example uses data from the fountaining episode on 24 June 2000. **a** Single 640×480 pixel frame captured from original video and opened in the main window of IMAQ Vision Builder software. **b** Resampling and conversion of the image into a 1,024×768 pixel bmp file. **c** Upper portion of the cone covered with incandescent material is removed using an image mask to exclude it from analysis. **d** Color threshold is applied to eliminate any other elements that are not part of the fountain. **e** Binarization and filtering of particles that comprise the fountain to generate a uniform image surface representing the fountain. **f** Final analysis of the selected fountain area to determine the main physical parameters of the fountain. See text for more details

amplitude of volcanic tremor (Alparone et al. 2003). Low-level eruption rates, as in the waxing phases of eruptive episodes, were inferred from direct observation (measurements of the main geometrical parameters of lava flows and flow channels) whenever this was possible and yielded a mean value of 3 m^3 s^{-1} for any given episode (Tables 1, 2 and 3). This is a rather conservative estimate, because in reality such rates showed an exponential increase from the very beginning of an eruptive episode to the onset of its climactic phase.

Terminology

The activity of the Southeast Crater during the study period showed notable variations in eruptive styles and intensity, as well as in the duration of the respective types of activity. For convenience, we adopt the following terminology for the different eruptive styles:

1. Purely effusive activity: non-explosive lava emission of several weeks-to-months in duration.
2. Spattering: very mild explosive activity with ejection of blobs of molten lava to a few meters above the vents, generally persisting for periods of a few days.
3. Strombolian activity: discrete, relatively modest-sized, brief, and generally ash-free explosions, persisting for periods of up to >1 year.
4. Short-lived (<1 hour to <1 day) eruptive episodes. These have been frequently termed paroxysms (e.g., Alparone et al. 2003; Behncke and Neri 2003a; Dubosclard et al. 2004) but no clear distinction has been made as to whether this term refers to the entire eruptive episode or only to its climactic phase. These events are complex and show transitions from (1) purely effusive or (2) mild Strombolian activity to (3) closely-spaced Strombolian bursts blending into (4) pulsating, (5) sustained Hawaiian (ash-poor) or (6) sustained ash-rich fountaining generating eruption columns up to 6 km in height. We consider that the term microplinian, as proposed by Francis et al. (1990), is appropriate for this latter style of activity.

Activity and products of the Southeast Crater

The history of the SEC began during the second phase of the 1971 eruption (Rittmann et al. 1973), when the crater formed as a degassing pit at the southeast base (~3,070 m) of the central summit cone. The position of this new pit coincided with the intersection of two major systems of eruptive fractures (extending down the ENE and SSE flanks). From 1978, the crater produced frequent eruptions that were often associated with flank eruptions (Calvari et al. 1994a). Frequently, the activity of the SEC was characterized by violent but short-lived episodes of lava fountaining and voluminous lava flow production, most notably in 1989 (Barberi et al. 1990). The most recent activity prior to 1996 occurred in December 1991, during

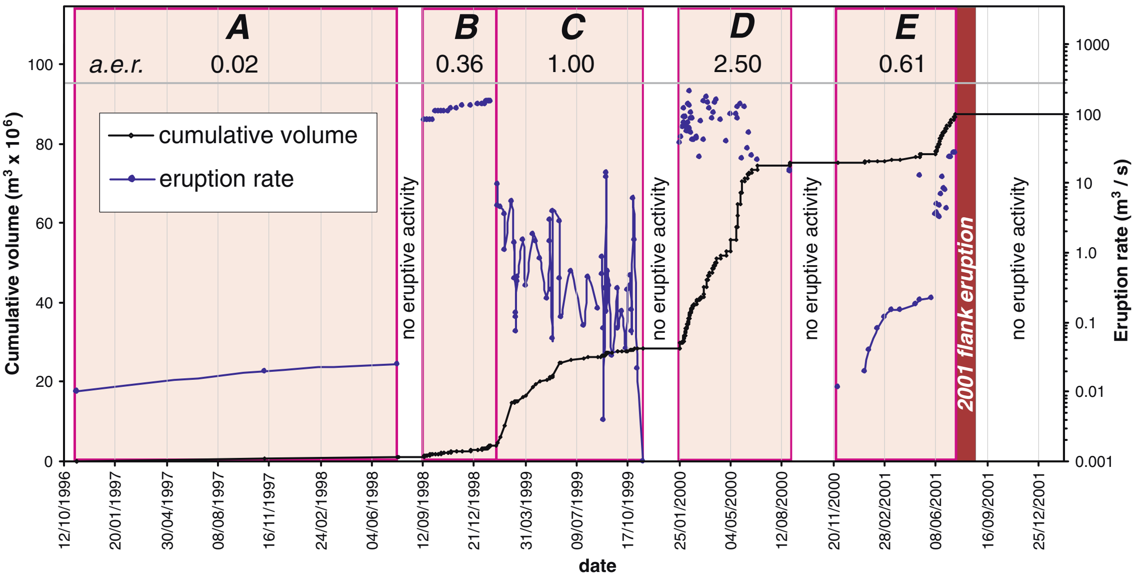

Fig. 4 Eruption rates and cumulative volume (dense-rock equivalent) of the Southeast Crater activity since 1996, divided into five eruptive phases (*A*–*E*). After the July-August 2001 flank eruption, the Southeast Crater remained completely inactive until September 2004; *AER* average eruption rate for each phase in m^{3}s^{-1}

the first phase of the 1991–1993 flank eruption (Calvari et al. 1994b).

Prior to its reactivation in 1996, the SEC was a relatively simple, saucer-shaped depression about 150 m wide with the crater rim being highest on the NW side (3,196 m; Fig. 2). The crater truncated a broad cone that rose about 120 m above its southern base. From early November 1996 to mid-July 2001 eruptive activity occurred at this crater during five distinct phases separated by intervals of relative quiet or significant changes in eruptive styles (Fig. 4). These phases spanned the following periods: (A) November 1996–July 1998, (B) September 1998–February 1999, (C) February-November 1999, (D) January-August 2000, and (E) November 2000-July 2001. The activity occurred within the context of a long period of intense summit activity at Etna, which had begun in July 1995, and involved all four summit craters (e.g., Aloisi et al. 2002; Harris and Neri 2002; Calvari and Pinkerton 2002; Calvari et al. 2002; Alparone et al. 2003; Behncke et al. 2003; Lautze et al. 2004; personal observations). Violently explosive eruptive episodes occurred at the Northeast Crater and at the Voragine in 1995–1996 and 1998–1999, respectively, and Bocca Nuova produced a major effusive eruption in 1999 (Harris and Neri 2002; Behncke et al. 2003). Next, we provide a summary of the activity and morphological changes observed at the SEC during this period, focusing on the complexities and evolutionary trends observed during some of the phases.

Phase A: November 1996-July 1998

Mild eruptive activity began after almost 5 years of repose at the SEC in early November 1996 and continued for 20 months (phase *A*; Table 1; Fig. 4). This period was characterized by the slow growth of a small intracrater pyroclastic cone (Fig. 5a, c) that was built around a cluster of small vents by continuous mild explosive (Strombolian) activity. In addition, lava effusion occurred from various locations on the flanks and base of the intracrater cone. Throughout much of the spring and summer of 1997, the active cone had a peculiar shape, resembling a lava dome, with flanks that were constantly swelling, especially before the opening of new effusive vents. A gently sloping lava platform formed around the intracrater cone, gradually filling the crater. From mid-July 1997 short lava overflows spilled onto the outer flanks of the SEC cone. These flows generally did not extend far beyond the base of the cone (marked in yellow in Fig. 6) and covered all of its flanks except the northwest where the crater rim was highest. Activity stopped abruptly in late July 1998, a few days after a violent explosive eruptive episode at the Voragine (Aloisi et al. 2002). At this time the intracrater cone had attained an elevation of about 3,220 m (estimate based on image analysis) and stood about 20–25 m above the surrounding lava platform.

The total area buried by lava flows in this period was 0.25×10^6 m^2. These had an average thickness of 6 m, giving a volume of 1.2×10^6 m^3 and a time-averaged discharge rate of 0.02 m^3 s^{-1} (Table 1), although the rate underwent some fluctuations in time. The volume of pyroclastics constituting the intracrater cone was negligible.

Phase B: September 1998-February 1999

Following about 6 weeks of quiescence, strong explosions started during the early morning of 15 September 1998. This event was the first in a series of 23 eruptive episodes that continued until 4 February 1999 (see Table 1 as well as La Delfa et al. 2001; Dubosclard et al. 2004; Alparone et al. 2005 for details). The intervals between these events

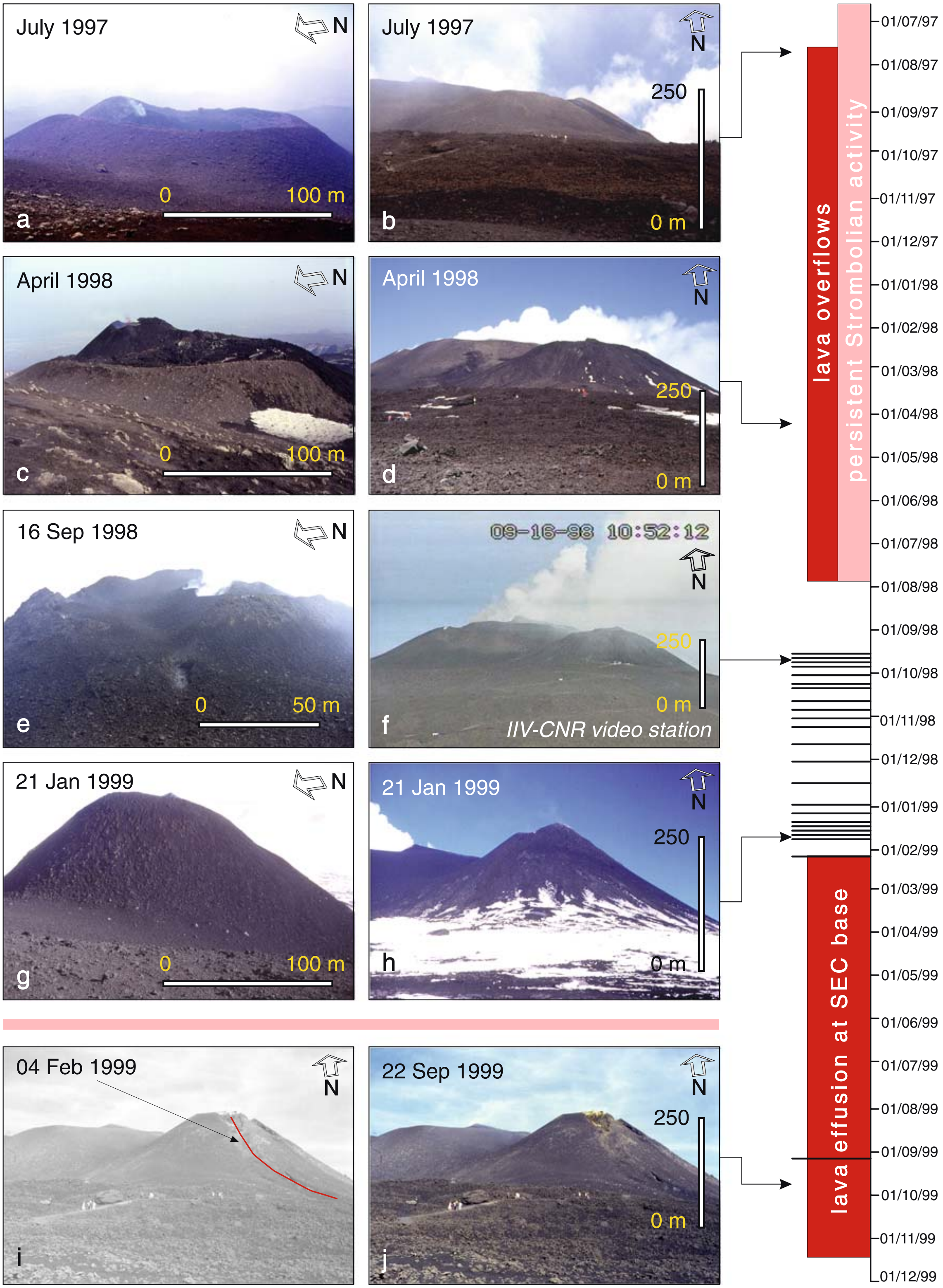

Fig. 5 Activity time line and comparison photographs showing the evolution of the Southeast Crater between July 1997 and September 1999 (phases A, B and C). The first four rows of photographs (**a**–**h**) show view pairs taken at about the same time from different directions (WNW at left and S at right). **i** This is an annotated version of photograph shown in **j**, indicating position of the 4 February 1999 fissure cutting the SE flank of the Southeast Crater cone. Time line of eruptive activity is shown at *right* (*horizontal bars* are paroxysmal eruptive episodes) and *arrows* indicate dates when photographs were taken

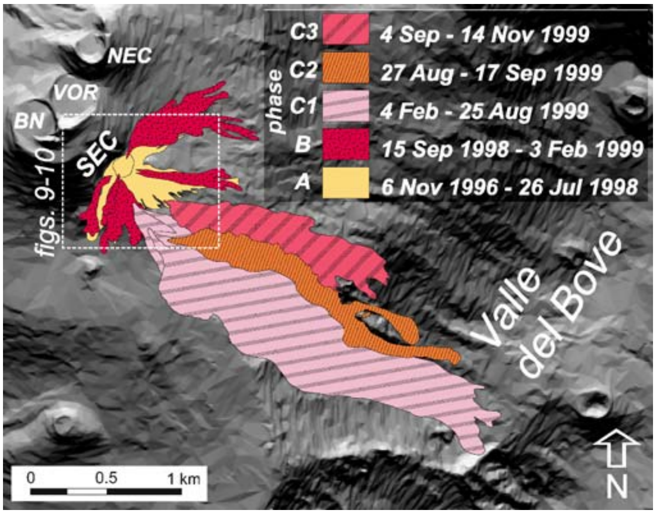

Fig. 6 Map of 1996–1999 (phase *A*, *B* and *C*) lavas of the Southeast Crater superimposed on a digital elevation model (DEM) of the summit area. Box identifies area of detailed topographic analysis shown in Figs. 6 and 7

increased systematically from 3 days to 2 weeks by the end of 1998. However, they shortened again in January 1999 (to as little as 2 days). Many of these events, especially during the earlier part of this phase, culminated with intense Strombolian explosions without blending into continuous fountains. However, sustained fountaining and tephra columns up to 3 km in height were produced during some of the later events. Lava flows extended a few hundred meters beyond the base of the cone, mostly during the earlier eruptive episodes (Fig. 6).

During this phase of activity, the SEC cone underwent rapid growth. Following the destruction of the former intra-crater cone during the first eruptive episode (Fig. 5e,f), a new cone began to grow on the surrounding platform and eventually obliterated any trace of the former intra-crater morphology (Fig. 5g–j). At the end of January 1999, immediately before the last eruptive episode of this phase, the cone was nearly symmetrical and rose to an elevation of 3,242 m, 46 m higher than in 1996 (Fig. 2).

The last and 23rd eruptive episode of this series occurred on the afternoon of 4 February 1999 and differed from its predecessors in that it culminated with the opening of a 700-m-long fracture on the SSE flank of the SEC cone. Lava fountaining occurred from the central portion of this new fracture and ceased after ~30 min. However, lava effusion continued from the lower part of the fissure and nearby vents for 9 months. This activity comprised the beginning of the following phase (C).

The total volume of phase B lavas was about 1.6×10^6 m^3. Flows covered a total area of 0.39×10^6 m^2 with an average thickness of 5 m. In addition, about 2.8×10^6 m^3 of pyroclastics were erupted by the 23 eruptive episodes. The full volume of all phase B products was thus 4.4×10^6 m^3.

Phase C: February-November 1999

Phase C consisted of an effusive eruption from several short eruptive fissures located at the southeast base of the SEC cone. It began on 4 February and lasted until 14 November 1999 and is described in detail by Calvari et al. (2002). During this period, a complex lava flow-field formed on the western rim of the Valle del Bove, with a maximum length of 2.8 km (Table 1; Figs. 1 and 6). The lava flow field can be subdivided into three portions (C1-C3), which were each erupted from separate eruptive fissures and are partially superimposed in space and time.

The SEC itself remained quiet except for a brief episode of Strombolian activity and lava flow emission on the evening

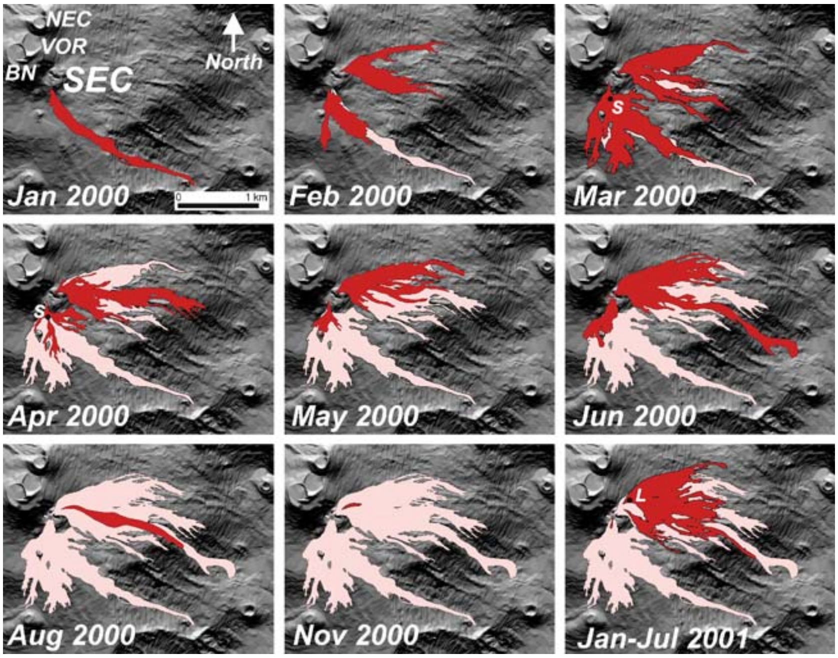

Fig. 7 Maps showing lava flows erupted from the Southeast Crater between January 2000 and July 2001 (phases D and E) and growth of two lava fields to the south and northeast of the crater. Extent of new lavas is shown in *red* at monthly intervals for January-June 2000, when frequent eruptive episodes occurred. Lavas shown in *pink* are from previous phase D and E activity. Maps are also given for August 2000 (two further eruptive episodes), November 2000 (minor lava effusion) and the full January-July 2001 period. Note that the morphology of the Southeast Crater in the DEM pre-dates the activity under review in this paper. The letters *S* and *L* denote the location of the satellite vents Sudestino and Levantino, respectively

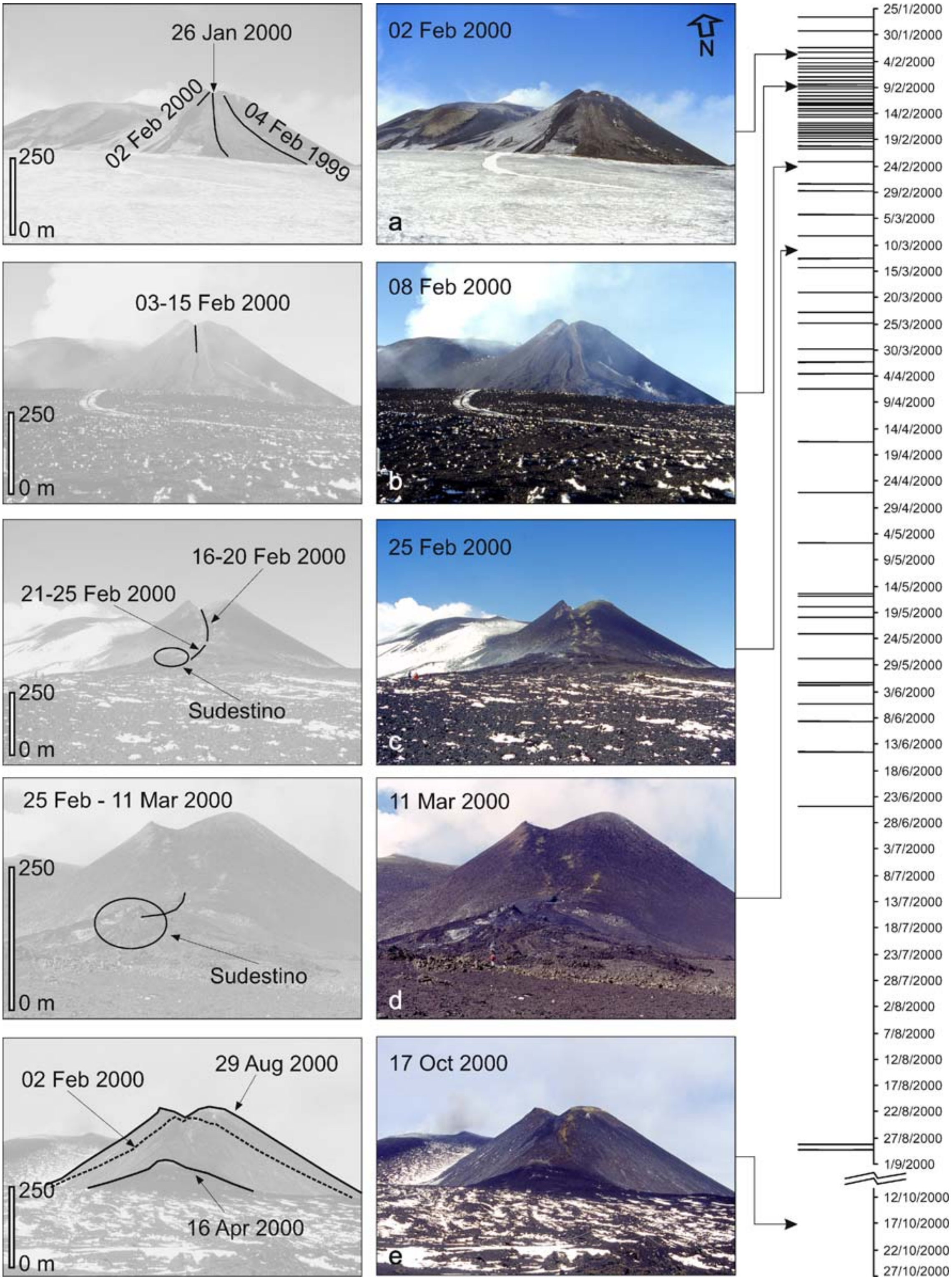

Fig. 8 Activity time line and comparison photographs showing the evolution of the Southeast Crater between early February and mid-October 2000 (Phase D). *Left column* shows annotated versions of the photographs shown in *right column*, indicating fissure segments active during the relative time periods, and including the *scale bar*. Time line at right with *bars* indicating paroxysmal eruptive episodes; arrows indicate dates when photographs were taken. Final annotated frame shows growth of the Southeast Crater during the 2000 activity and outline of the Sudestino cone at its southern base

of 4 September 1999, following a sub-Plinian episode at the Voragine a few hours earlier (Branca and Del Carlo 2004). This event culminated with the reopening of the lower portion of the 4 February fissure and caused the collapse of the east rim of the SEC (Calvari and Pinkerton 2002). A few hours later, eruptive activity shifted to new vents located at the northern margin of the phase C lava flow-field, where activity continued until 14 November 1999.

The phase C activity emplaced a total lava flow volume of ~24×10^6 m^3, most of which was erupted between February and August 1999 (Table 1, phase C1). The total area covered by this lava was 1.45×10^6 m^2, with thicknesses varying from 3 m (C2) to 20 m (C1). This phase produced virtually no tephra.

Phase D: January-August 2000

Phase D, which lasted from late January until late August 2000, consisted of 66 distinct eruptive episodes (Table 2; Alparone et al. 2003). This activity significantly built up the SEC cone, and lava formed two separate flow fields on the south and northeast sides of the cone (Figs. 7 and 8).

The first episode began on the early morning of 26 January, about 2.5 months after the end of phase C (Figs. 1 and 4). A second episode followed 3 days later and, during 1–20 February, eruptive episodes occurred at a rate of 1–3 events per day. During this period, each episode followed the same 5-stage cycle. The episode began with (1) a waxing phase, characterized by gradually increasing lava effusion (emplacing 1.5–2 m thick ‘a‘ā flows) from one or both of the eruptive fractures on the S and NE flanks of the cone and/or Strombolian activity at its summit. This was followed by (2) increasing Strombolian activity at one or more summit vents, sometimes accompanied by spattering or fountaining at the NE fissure, generally lasting 10–25 min. This was terminated abruptly by (3) a very rapid onset of fountaining from the summit vent(s) and rise of a tall tephra column (microplinian activity). The peak of fountaining was marked by (4) the opening or re-opening of the fissure on the S flank of the cone and emission of rapidly moving lava flows. The cycle was terminated by (5) abrupt cessation of summit fountaining, emission of dense ash puffs and a rapid decline in the rate of lava emission from the S and NE flank fissures. Generally, the eruptive episodes lasted no more than 30 min, and the culminating phase rarely exceeded 10 min in duration.

After 20 February, the intervals between eruptive episodes grew longer. At the same time the events lasted longer but were somewhat less violent. Furthermore, the main focus of activity shifted from the summit vent to a point on the lower portion of the eruptive fissure on the south flank of the cone at about 3,050 m elevation. Here a low shield began to grow around an ill-defined ~10 m diameter vent (informally named Sudestino; Figs. 2, 7 and 8). In mid-March, the Sudestino became the main focus of activity during eruptive episodes and produced virtually ash-free Hawaiian-style lava fountains on 12, 14 and 19 March. During these episodes, activity at the summit vents of the SEC was limited to ash emission and pulsating fountaining at the climax of the activity.

From 22 March, eruptive episodes became once more focused at the summit vents. Almost all of these events followed the same pattern as the early-to-mid February eruptive episodes. However, they lasted longer, were more voluminous and occurred at longer intervals (up to 10 days; Table 2). Furthermore, only the uppermost portion of the S-flank fracture became active during these events; the Sudestino erupted only once (on 15–16 April) during this period. Small pyroclastic flows were generated on at least two occasions, on 16 April and 8 June 2000. In both cases, the flows were generated when oblique jets from the eruptive vents caused copious tephra fallout onto the steep flanks of the SEC cone; fortunately, they advanced only a few hundred meters beyond the cone's base and away from spectators who were watching the events. Two isolated eruptive episodes occurred on 28 and 29 August, during which the S flank fracture failed to open.

Growth of the SEC cone was vigorous during this phase of activity. At the end of phase D, image analysis revealed that the summit had risen to about 3,280 m, 40 m higher than at the beginning of phase D (Figs. 2 and 8). Furthermore, while a broad spatter cone surrounded by a lava shield and rising about 30 m above the former altitude of the terrain (3,055 m) had developed at the Sudestino, a low spatter ridge had grown in the lower portion of the NE flank fissure. We have calculated a total volume of ~47×10^6 m^3 for the phase D products, of which 37×10^6 m^3 are lava flows, covering a total area of about 2.9×10^6 m^2.

Phase E: November 2000-July 2001

Renewed lava emission began at the lowermost vent of the NE fissure for a brief period in November 2000 and lasted only for a few days (Fig. 7, bottom center). Eruptive activity resumed at the same site around 20 January 2001 and continued at a slowly increasing rate through late April. During the first week of May, Strombolian activity at the summit vent of the SEC and at the effusive vent on the NE fissure gradually increased and culminated in a relatively mild eruptive episode on 9 May. No activity occurred at the S fissure during this time or during any of the following eruptive episodes. After the 9 May eruptive event, lava outflow from the vent on the NE fissure and Strombolian activity at the summit vent continued at fluctuating rates.

After the end of lava emission on 6 June, a series of new eruptive episodes began on 7 June, with Hawaiian-style lava fountaining and voluminous lava effusion from the NE vent and Strombolian activity at the summit. Over the next 6 weeks, 14 further eruptive episodes occurred at irregular intervals ranging from 2 to 6 days. Although, generally, following the same evolutionary scheme, they gradually became stronger, and significant lava volumes were erupted from one or more vents in the lower portion of the NE fissure (Table 3). A steep-sided, elongate cone or spatter rampart built up around the lowermost vent, which was informally named Levantino (Fig. 7). Lava fountaining was generally strongest and ash-free at this vent, while the summit vent displayed strong, closely-spaced Strombolian explosions, sometimes evolving into pulsating, ash-rich fountains. Compared with the eruptive episodes of the previous year, those of 2001 were less energetic and produced less tephra but more voluminous lava flows.

The penultimate eruptive episode of this series, during 13 July, coincided with the beginning of strong seismicity and ground deformation on the S flank of Etna (Bonaccorso et al. 2002; Patanè et al. 2003). This heralded the beginning of a complex flank eruption (Behncke and Neri 2003a; Acocella and Neri 2003; Lanzafame et al. 2003; Billi et al. 2003). Immediately before the flank eruption began, the SEC produced yet another fountaining episode during the early morning of 17 July. At least two weak episodes of increased activity occurred during the flank eruption (on 20 and 23 July).

The total volume of phase D eruptive products was 12×10^6 m^3, including 9×10^6 m^3 of lava flows (with an average thickness of 10 m for the total lava flow-field). This is close to the volume of 13×10^6 m^3 determined from satellite-based methods by Lautze et al. (2004). The total volume of 1996–2001 eruptive products from the SEC thus amounted to 89×10^6 m^3 (Table 3).

The 2001 series of eruptive episodes once more changed the profile of the SEC cone, most notably by completely healing the S-flank notch and building the Levantino, which became a conspicuous feature at 3,175 m elevation. Levantino evolved into a beak-shaped feature with extremely steep (~70°) walls. Its vent area was marked by a deep chasm evolving downslope into a prominent lava channel. The height of the cone increased further and probably surpassed 3,300 m, but collapse of the eastern crater rim during the July-August 2001 eruption lowered the cone somewhat (Fig. 2). By the spring of 2004, the highest point of the cone, on the southern crater rim, was measured at 3,300±5 m, only ~15 m lower than the highest point at Etna's summit (3,314 m). It thus stood about 230 m above the surface that existed before the SEC began to form (in 1971), and about 105 m above the 1996 elevation. The diameter of the crater ranged from 100 m (NNE-SSW) to 125 m (WNW-ESE).

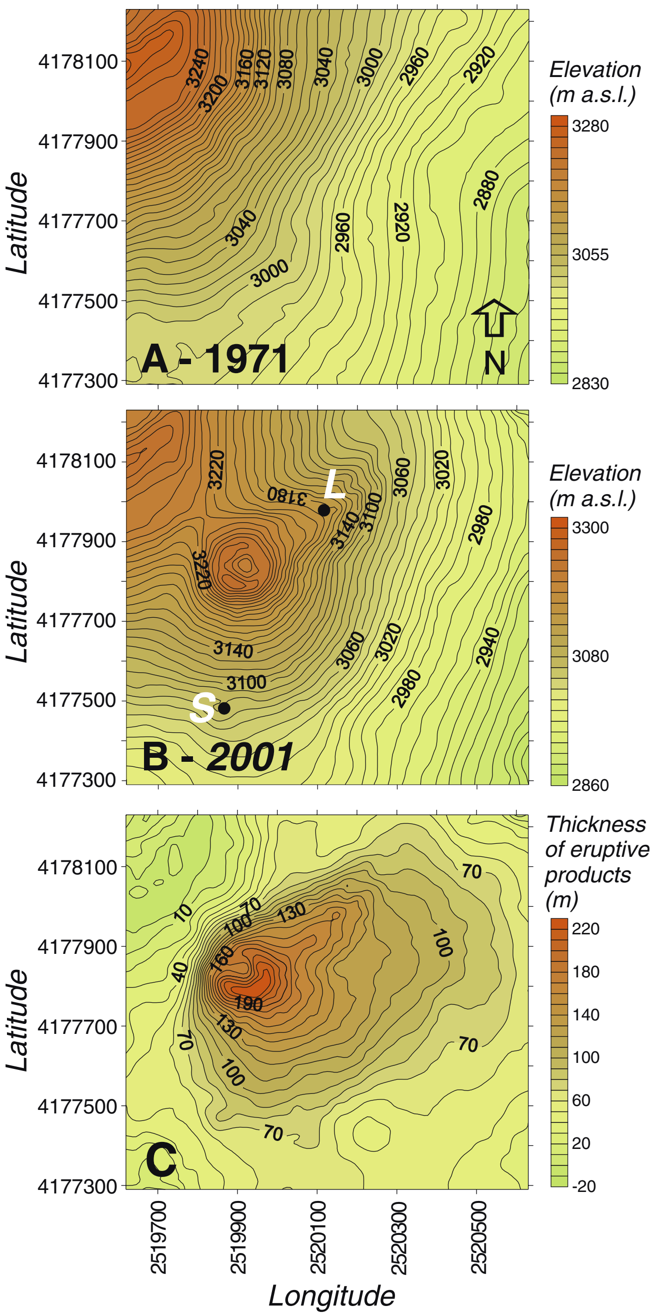

Fig. 9 Morphological evolution of the Southeast Crater cone between 1971 and 2001 (see Fig. 6 for location of map window). Contour map in frame *A* shows the morphology immediately before the formation of the Southeast Crater, unchanged from the 1967 topographic survey on which this map is based. The 2001 morphology of the same area is shown in frame *B*, revealing the topographic changes due to construction of the Southeast Crater cone and its two prominent satellite vents, Sudestino (*S*) and Levantino (*L*). Frame *C* is a difference map created from subtraction of the maps in frames *A* and *B*. Contour interval in all three frames is 10 m. Latitude and Longitude are expressed as UTM coordinates in km

Post-phase E activity: August 2001-January 2006

The last activity observed at the SEC in 2001 was a rather weak emission of ash on 1 August. After that date, no eruptive activity occurred at any of the vents on the cone until 2004. A flank eruption that was closely related to the crater occurred between September 2004 and March 2005 (Burton et al. 2005; Corsaro and Miraglia 2005; Neri and Acocella 2006). This eruption was once more accompanied by a major morphological change at the SEC, but this time a negative one. Between November 2004 and March 2005, a collapse pit with a final diameter of about 200 m opened on the upper southeast flank of the cone. This was the source of copious vapor emissions and it sporadically belched minor volumes of lithic ash.

Table 4 Comparison of volumes emplaced during each phase of the 1996–2001 activity of the Southeast Crater, obtained with different methods

Period	Phase	Date (dd/mm/yyyy)	DRE volume (10^6 m^3)	TOPO volume (10^6 m^3)	TOPO DRE volume (10^6 m^3)	Excess DRE volume (10^6 m^3)
Pre-1996		05/04/1971–05/11/1996	–	36.26	23.57	–
	A	06/11/1996–26/07/1998	1.2	5.2 (A+B)	3.38 (A+B)	2.23 (A+B)
	B	15/09/1998–04/02/1999	4.41			
Post-1996	*C*	04/02/1999–14/11/1999	24.37	31 (C+D+E)	20.15 (C+D+E)	63.21 (C+D+E)
	D	26/01/2000–29/08/2000	46.83			
	E	20/01/2001–17/07/2001	12.16			
	A-E	06/11/1996–17/07/2001	89	36.20	23.53	65.45
Total				72.46	47.10	

DRE volume is the total volume obtained from lava flow maps and image analysis; TOPO volume is calculated from difference maps shown in Figs. 9 and 10 and is not corrected to dense-rock equivalent. TOPO DRE volume is corrected to dense-rock equivalent using an average of 35% vesicles (20% for lava flows and 50% for scoriaceous bombs). Excess volume is obtained from subtraction of the total DRE volume for each phase and TOPO DRE volume; it represents eruptive products (lava and tephra) deposited outside the map window used for the calculation of the TOPO volumes

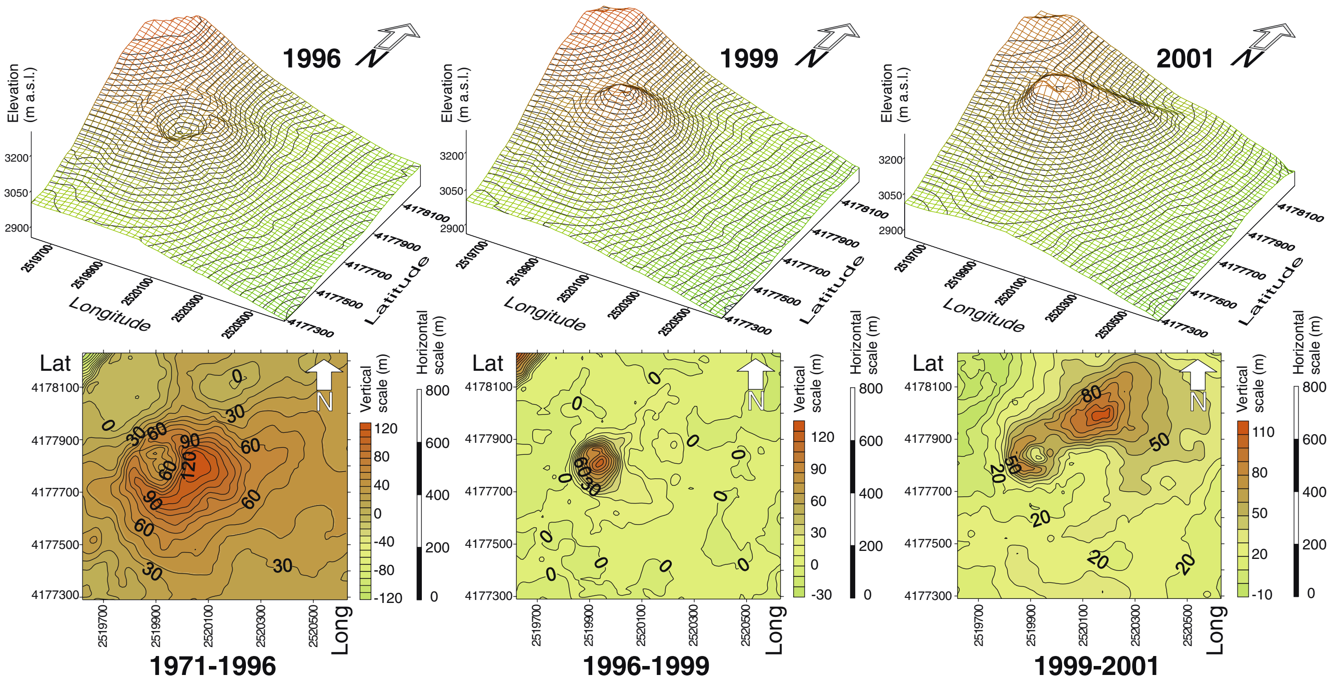

Fig. 10 Comparative gridded relief maps and topographic difference maps illustrating the growth of the Southeast Crater cone. Contour interval is 10 m in all maps; Latitude (*Lat*) and Longitude (*Long*) are expressed as UTM coordinates in km. *Top left*: 1996 grid relief and topography (northwestward projection), based on 1995 survey and showing morphology at the beginning of the 1996–2001 eruptive period. *Bottom left*: Difference map calculated from 1971 and 1996 topographic maps, showing accumulation of up to 120 m of new material. *Top Center*: 1999 grid relief and topography, following the first series of eruptive episodes (phase B) and before the onset of phase C. The previously broad crater has been replaced by a steep cone with a small summit crater. *Bottom center*: Difference map calculated from 1996 and 1999 topographic maps, showing that cone growth was limited mainly to the area of the 1971–1996 crater. *Top right*: 2001 grid relief and topography (based on March 2004 survey) revealing the 2001 shape of the Southeast Crater, following its rapid growth between 1996 and 2001. *Bottom right*: Difference map produced from the superposition of 1999 and 2004 topography. The most conspicuous area of accumulation (on the northeast side of the Southeast Crater cone) coincides with the growth of the Levantino edifice; minor accumulation at the south base marks the Sudestino

Cone evolution from three-dimensional reconstruction and volume difference maps

From the digitization of existing topographic maps (1967, 1995, 1999) and/or maps generated by surveys with hand-held GPS (in the period 1999–2004), we have developed three-dimensional models and volume difference maps that have permitted us to calculate the differential volumes of eruptive products accumulated in the SEC area. Frame A of Fig. 9 shows the topography as it appeared before the birth of the SEC in 1971, based on the topographic map edited by the Istituto Geografico Militare in 1967 (the morphology of the area had undergone no changes between the 1967 survey and the birth of the crater in 1971). Frame B shows the topography of the SEC after the end of the 1996–2001 eruptive activity, as revealed by the topographic survey carried out in the spring of 2004 (only minor collapse has affected the eastern rim of the crater between 2001 and 2004; Fig. 2).

The difference map shown in frame C of Fig. 9 shows the growth the SEC cone between 1971 and 2001, which by 2001 was about 230 m in height and slightly asymmetrical due to its location on an inclined slope and due to the repeated eruptive activity focused on its northeast flank. Here the prominent morphologic ridge of the Levantino vent is also evident. Less clearly expressed but nonetheless important, is the satellite vent of the Sudestino at the southern base of the cone. The calculated bulk volume of the eruptive products deposited during the map window (i.e., between 1971 and 2004) amounts to ~72×10^6 m^3 (Table 4).

Figure 10 shows the results obtained from a three-dimensional reconstruction and from the respective volume difference maps for the period 1996–2001. The left panel

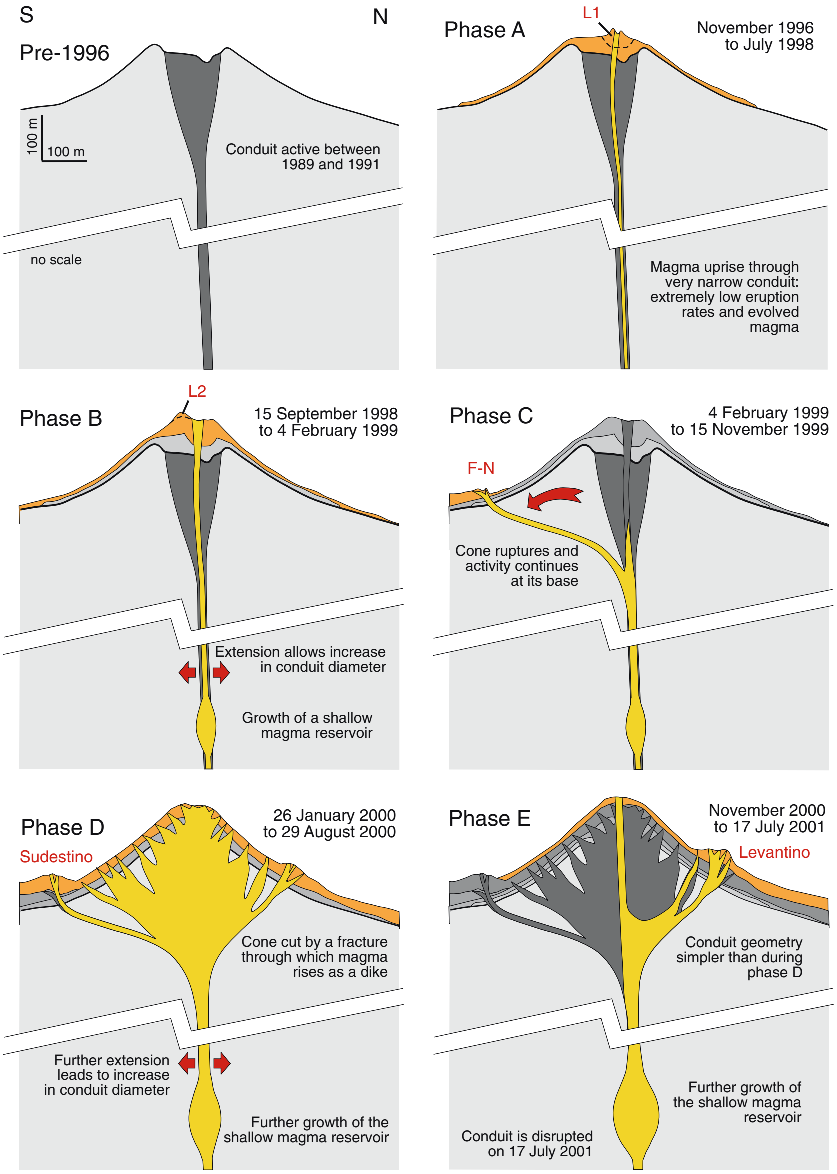

Fig. 11 Hypothetical north–south profiles through the Southeast Crater showing growth of its cone and evolution of its conduit between 1996 and 2001. Upper portion of each profile is to scale, whereas the lower portion is without scale and represents a situation at an unknown depth below the crater. Configuration of active conduit (s) and eruptive deposits for each phase are shown in *yellow* and *orange*, respectively. Older deposits are shown in different *shades of gray*, and inactive portions of conduit in *dark gray*. *L1* and *L2* (phases A and B) correspond to portions of the cone lost after the end of each respective phase of growth. *Red arrows* in phase B and D frames denote extension leading to increase in conduit diameter; *red arrow* in phase C frame represents shift of activity from main (summit) conduit to a vent cluster at the base of the cone. F-N in Phase C frame indicates vents active between February and November 1999. Locations of the prominent satellite vents Sudestino and Levantino are shown in frames for phases D and E. See text for further discussion

indicates the morphology of the SEC as it appeared in 1996 (based on the 1995 topography), when the cone had reached a height of about 120 m above the pre-1971 surface. The associated difference map reveals a bulk volume of eruptive products for the 1971–1996 period of ~36×10^6 m^3 (Table 4). This volume includes both the cone itself and a part of the lavas erupted from the crater, as is evident from the extension of the isopachs to the east of the cone.

The central panel of Fig. 10 represents the SEC cone as it was in 1999, when it had become much more symmetrical and pointed as compared to its 1996 morphology. The related volume difference map shows that the eruptive products of the 1996–1999 period accumulated prevalently within the former crater rim which, as a result, was completely filled and obliterated. The bulk volume of 1996–1999 eruptive products, as derived from this volume difference map, is ~5×10^6 m^3 (Table 4).

The right panel of Fig. 10 shows the morphology of the SEC cone in 2001, following the numerous episodes of lava emission and fountaining during 2000–2001. The 1999–2001 volume difference map reveals that the most significant growth (more than 100 m of vertical construction) occurred on the northeastern flank of the cone, coincident with the Levantino. However, isopachs indicate thicknesses of up to 50 m of newly accumulated products also to the east of the cone, especially in those areas covered by lavas during phases C, D and E. The bulk volume of 1999–2001 eruptive products derived from this map is about 31×10^6 m^3.

Table 4 shows a comparison between volumes computed with the various methods described in section 2, including those derived from volume difference maps (topo volume), which cover all of the SEC cone but only a small portion of the associated lava fields. The total 1996–2001 volume increase (~23×10^6 m^3 DRE) derived from the difference maps is seen to be significantly lower than the DRE volume increase obtained with the other methods. This is mainly due to the fact that much of the lavas was emplaced outside the map window, and Tables 1, 2 and 3 clearly show that the volume of lava produced during the entire period was about 5 times that of pyroclastics. Much of the topographic volume is therefore related to the growth of the SEC cone, whose summit rose from an elevation of 3,196 m in 1996 to about 3,300 m in 2001. This volume includes the prominent satellite vents Sudestino and Levantino on the southern and northeastern flanks of the cone, respectively (Fig. 9b).

A certain fraction of the excess volume (i.e., the volume difference between the topographic and erupted DRE volumes; Table 4) is due to airborne tephra deposited beyond the base of the SEC cone and outside the difference map window. Unfortunately, the methods applied for the present study do not allow us to determine with any appreciable precision the volume of this tephra, because no isopach maps are available for the deposits, and the time intervals between topographic maps contain more than one of the eruptive phases.

Discussion

Slow start of the activity (phase A, 1996–1998)

Compared to its later stages (and earlier phases of activity, as in 1989 and 1990), the activity at the SEC started in a rather subdued manner and persisted rather weakly for its first 20 months (phase A). The effusion rate was very low (0.02 m^3 s^{-1}; Fig. 4) and Strombolian bursts rarely exceeded 50 m in height. Corsaro and Pompilio (2004) note that the products erupted at the SEC during this period were slightly more evolved and alkalic than those erupted from the other three summit craters at the same time. These authors furthermore found that the lava temperature was about 20–30°C lower at the SEC than at the other three craters. This might explain the somewhat higher viscosity of the magma during phase A, which led to the slow intrusion of magma into the intracrater cone, deforming it to obtain a dome-like shape. Furthermore, the SEC conduit had been thoroughly sealed during the 5 years of eruptive quiescence preceding the onset of phase A in late 1996, whereas the other three summit craters had maintained open, degassing conduits during the period of quiescence following the 1991–1993 flank eruption. Corsaro and Pompilio (2004) argue that the SEC conduit diameter during this initial activity may have been small, allowing only a slow uprise of magma and thus facilitating its cooling and more evolved composition. This scenario is summarized in the first two frames of Fig. 11.

Changes in the eruptive dynamics

The transitions from one eruptive phase to the next during the 1996–2001 SEC activity were in most cases marked by distinct changes in the character of the activity (Figs. 1 and 4). Effusive and/or mild Strombolian activity alternated with episodic fountaining, and such changes occurred repeatedly throughout the 5 years of activity. The first change, from persistent Strombolian activity and slow lava effusion (phase A) to episodic fountaining (phase B), occurred between late July and mid-September 1998 (Table 1). This change may have occurred in response to a pressure change in the central conduit system caused by the violent 22 July 1998 paroxysm at the Voragine (Aloisi et al. 2002). This was accompanied by the formation of an extensive fracture system extending from the east rim of the Northeast Crater toward the SEC (Neri and Acocella 2006). Both the paroxysm and the opening of the fractures may have been due to extension caused by displacement of the unstable east and southeast flank of Etna, which also led to a change in the geometry of the SEC conduit (Fig. 11). Furthermore, the magma erupted during phase B showed a compositional change during some of the latter eruptive episodes (starting on 13 January 1999; Corsaro and Pompilio 2004) and became essentially undistinguishable from the products erupted from the other summit craters.

This points to a more rapid ascent of fresh magma within the SEC conduit, a factor that, along with a suspected increase in conduit diameter, permitted an 18-fold increase in the average output between phase A and phase B (Fig. 4) and much more vigorous eruptive activity.

The transition from phase B to phase C, on 4 February 1999, was marked by a shift from episodic fountaining to continuous, largely non-explosive lava emission. The transition occurred with the fracturing of the southeast side of the SEC cone at the height of the 23rd paroxysm of phase B. The fracturing of the cone may have been caused by (1) the uprise of a more voluminous batch of fresh magma through the SEC conduit; (2) an increase in hydrostatic pressure on the conduit walls due to the rapid growth of the SEC cone during phase B; and/or (3) the opening of fractures at the base of the cone facilitated by the growth of a minor shallow magma reservoir below the SEC. Hypothesis 1 can be discarded because fresh magma rising through the conduit would likely have been more gas-rich, which is inconsistent with the very low levels of explosivity associated with the effusive activity that began on 4 February 1999. Hypothesis 2 might have been valid if the SEC had not returned to vigorous fountaining one year later, in spite of continued growth of the cone through the last of the 66 eruptive episodes of phase D. In contrast, there is some reason to assume that scenario 3 is more realistic. Conspicuous increases in soil radon (^{222}Rn) emissions measured at a monitoring station at Torre del Filosofo (Alparone et al. 2005), 1 km south of the SEC (TdF in Fig. 1), began before the phase B eruptive episodes (around episode #6; Table 1). These were interpreted by Alparone et al. (2005) as indicators of increased gas leaking from the SEC conduit, facilitated by fracturing that occurred in response to the growth of a shallow magma reservoir below the crater as shown in Fig. 11. Such a reservoir was envisaged by La Delfa et al. (2001), Alparone et al. (2003) and Allard et al. (2005). The fracturing may eventually have destabilized the conduit to the point that the southeast flank of the SEC cone ruptured.

There are some analogies between the 4 February 1999 change in the eruptive activity at the SEC and a similar transition during the ongoing Puʻu ʻŌʻō-Kūpaianaha eruption of Kīlauea volcano, Hawaiʻi, in July 1986 (Heliker and Mattox 2003; Heliker et al. 2003). The first phase of that eruption (January 1983–July 1986) was characterized by 47 episodes of lava fountaining, which led to the growth of a substantial pyroclastic cone, Puʻu ʻŌʻō. During the 48th episode, new eruptive fissures opened at the base of that cone and the activity soon concentrated at a vent located 3 km from Puʻu ʻŌʻō, which was named Kūpaianaha. At the same time, the activity changed to quiet lava effusion from a lava lake, while gas continued to escape from Puʻu ʻŌʻō. In that case, Parfitt and Wilson (1994) and Parfitt (2004) attribute the change in eruptive character to a change in the geometry and thermal regime of the conduit feeding the eruption, and to a decrease in the magma supply and ascent rate. According to the rise speed dependent (RSD) model of Parfitt (2004), the lower ascent rate allowed gas bubbles to rise more rapidly than the magma itself, preventing lava fountaining. At Etna in 1999, based on the evidence discussed above, a change in the conduit geometry is likely to have occurred to cause the change in eruption style and location. On the other hand, the eruption rate (averaged for phases B and C) showed a nearly threefold increase (Fig. 4), so that the RSD model does not seem to apply in the case of the SEC.

Phase D marked a shift in the eruptive activity back to the SEC cone and to a style dominated by fountaining. However, the conduit system of the SEC had become more complex than previously (Fig. 11), and so too became the activity. The eruption rate (averaged for the whole of phase D) once more increased by a factor of 2.5 from the preceding phase (Fig. 4). It is possible that the powerful eruptive events of the second half of 1999, including the 4 September paroxysm from the Voragine as well as a major crater-filling eruption and lava overflows from the Bocca Nuova in October-November, was accompanied by further extension in the summit area, as in July 1998. This may have facilitated the return to fountaining activity in 2000. We assume that this activity change was also triggered by the arrival of a fresh batch of gas-rich magma. Lava fountaining ended after 66 episodes, simply because of a temporary reduction in magma supply, so that the continuation of fountaining could no longer be supported. We will discuss the dynamics of the phase D activity in more detail in the following section.

Following the rather minor lava effusion of late November 2000, the SEC once more became active in early 2001, but for more than 3 months it emitted lava at a rather low rate, fluctuating between 0.01 and 1.2 $m^3 s^{-1}$ (Fig. 4; Lautze et al. 2004). The transition to more vigorous activity in April-May 2001 and eventually to the fountaining activity of June-July 2001 was quite gradual, indicating that some mixing of the gas-poor residual and gas-rich new magma occurred in the conduit or within the hypothetical magma reservoir below the SEC (Fig. 11). This may have been due to slow magma ascent and/or the increased size of the magma reservoir, which had continued to grow throughout phase D in 2000 (Alparone et al. 2003; Allard et al. 2005). This phase of the SEC activity fell into the period of buildup toward the 2001 flank eruption, a buildup which is believed to have initiated sometime between September 2000 and April 2001 (Bonaccorso et al. 2004). Interestingly, the SEC continued to maintain its episodic eruptive behavior (albeit at much reduced strength) through part of the 2001 flank eruption, although its conduit was effectively disrupted at the start of that eruption (Behncke and Neri 2003a). Evidence that a significant volume of magma remained stored after the 2001 eruption in the assumed reservoir below the crater came 3 years later, when the reservoir was intersected by flank instability-induced fractures and ~40×10^6 m^3 of degassed, crystal-rich magma were emitted over a period of 6 months (Behncke et al. 2005; Burton et al. 2005; Corsaro and Miraglia 2005; Neri and Acocella 2006).

Episodic lava emission and fountaining: comparison with Pu‘u ‘Ō‘ō and potential mechanisms

The most striking feature of the behavior of the SEC during 1996–2001 was the episodic lava fountaining activity observed during phases B, D, and E, which climaxed with the 66 eruptive episodes of 2000 (Fig. 4). Similar episodic behavior has been observed during other basaltic eruptions, especially at Kīlauea volcano, Hawai‘i, whose Pu‘u ‘Ō‘ō-Kūpaianaha eruption stands as a standard example of this type of activity (e.g., Wolfe et al. 1988; Parfitt and Wilson 1994; Parfitt 2004). We thus make a comparison between these two eruptions even though the physical and chemical characteristics of the magmas (H_2O content, temperature, viscosity, and composition: tholeiites at Kīlauea versus K-enriched alkali basalt at Etna) as well as the respective geodynamic settings of the two volcanoes are not alike (e.g., Burton et al. 2005; Corsaro and Pompilio 2004; Eaton and Murata 1960; Garcia et al. 2000; Greenland 1987).

Both the SEC in 2000–2001 and Pu’u ‘O’ō in 1983–1986 showed a similar evolution of their activity during the buildup (or waxing) stages of episodes of high fountaining, in that degassed magma was extruded first. This had remained in the conduit after the previous episode. At Pu‘u ‘Ō‘ō, Greenland et al. (1988) suggested that degassed magma was pushed toward the surface by ascending gas-rich magma. This is also a plausible mechanism in the case of the SEC. It is likely that the residual gas-poor magma formed a cap below which gas-rich magma foam accumulated until a critical threshold was reached. Allard et al. (2005) envisaged the separate uprise of a “gas layer” from a relatively shallow depth as the main triggering mechanism of eruptive episodes at the SEC, thus substantially supporting the foam collapse model for lava fountaining of Jaupart and Vergniolle (1988).

The transition from the emission of partially degassed residual magma to sustained fountaining was often gradual at the SEC, but in some cases occurred instantaneously, pointing to variations in the location, size, and evolution of the foam layer and to differences in its degree of mixing with the degassed magma filling the uppermost portion of the conduit. Similarly, the buildup to full-scale lava fountaining at Pu‘u ‘Ō‘ō often occurred gradually but sometimes more abruptly (Wolfe et al. 1988). Likewise, fountaining at the SEC often ended quite suddenly and was followed by a violent gas jet (at times containing ash) that

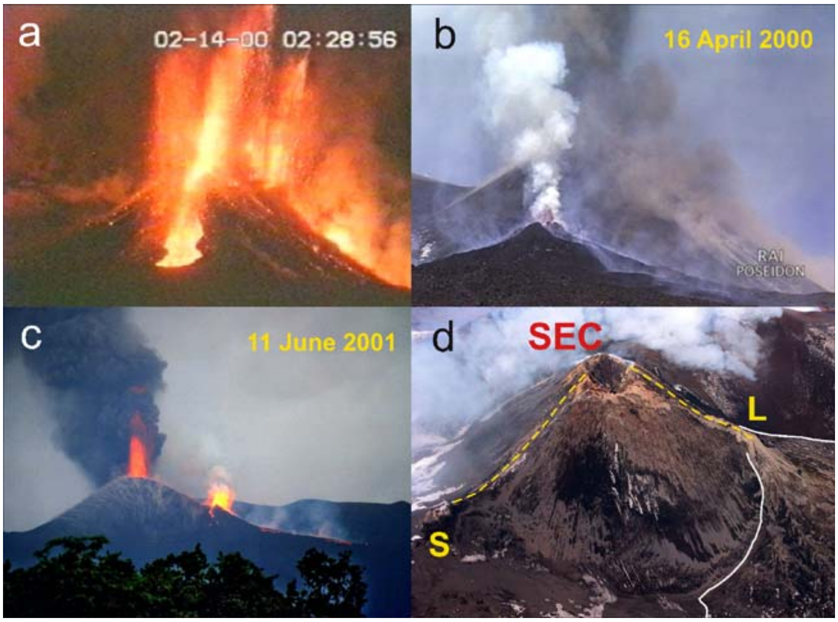

Fig. 12 Photographs of eruptive activity and vents during phases D and E in 2000–2001. **a** Multiple fountains rising from vents at the summit and on the southern and northeastern flanks of the Southeast Crater cone, and short lava flow descending southern (near) flank, as viewed by the monitoring video camera (3.2 km SSE of the crater) early on 14 February 2000. Visible portion of main fountain (in the *center* of the frame) is about 300 m. **b** Ash–free lava fountaining to about 20 m height at Sudestino (in *left foreground*) and ash column rising from summit vents of the Southeast Crater on 16 April 2000, shortly before the culmination of the activity. Light-brown plumes of ash caused by heavy tephra fallout rise from the eastern (*right*) flank of the Southeast Crater cone. The Sudestino appears as a steep spatter cone sitting on top of a low lava shield. View is from south. Photo captured from video courtesy of Giovanni Tomarchio. **c** Typical scene of phase E eruptive episode on 11 June 2001, with ash-rich fountaining from one single vent at the summit of the Southeast Crater, and ash-free lava fountaining at Levantino (at *right*), which is also the source of a lava flow extending to the right (northeast). Height of the cone (from left base to summit) is about 230 m. View is from east, courtesy of Thorsten Boeckel. **d** Oblique aerial photograph (from approximately south-east) of the Southeast Crater after the cessation of the activity in July 2001, showing the satellite vents Sudestino (*S*) and Levantino (*L*) as well as the larger summit vent of the Southeast Crater (*SEC*). *Broken yellow line* indicates the fissure system cutting across the cone that was active in 2000; in 2001 only the summit vent and Levantino were active. Note the fan-shaped lava field (or half–shield), outlined by *white lines*, extending from the Levantino at *right*. Approximate horizontal extent of area (*left to right*) is about 1 km. Photo from the digital image archive of the Unità Funzionale Vulcanologia e Geochimica of the Catania Section of the Istituto Nazionale di Geofisica e Vulcanologia

exited the conduit at around supersonic velocity and would last for up to 10 min. This gas jet can be interpreted to have been released during the foam collapse phase (Allard et al. 2005). Also at Pu‘u ‘Ō‘ō, some lava fountains stopped quite instantaneously (Wolfe et al. 1988), but in contrast to the SEC there are no descriptions of a post-fountain gas jet.

In the case of Pu‘u ‘Ō‘ō, the foam model has been challenged by Parfitt (2004), who attributes the occurrence of lava fountaining to homogeneous magma-gas (two-phase) flow, whereas no sustained fountaining will occur once the magma ascends more slowly than its gas phase. At the SEC, the rise speed dependent model advocated by Parfitt (2004) does not seem to be a plausible mechanism, for reasons already discussed. Furthermore, a more general examination of Etna's eruptions (both summit and flank) shows that vigorous fountaining (or explosive activity) is restricted to some of the summit activity and flank eruptions fed by gas-rich magmas, even when the latter are characterized by low mass eruption rates (such as the 1974 flank eruption; Guest et al. 1974; Tanguy and Kieffer 1977). Conversely, some high-rate effusive eruptions at Etna (such as in 1981; Guest et al. 1987) lacked high fountains or significant explosive activity.

In an alternative model, Harris and Neri (2002) proposed that episodic fountaining at Etna may be fed by pulses in magma supply and applied this model to the 1-month-long 1999 Bocca Nuova eruption. They stated that in the Bocca Nuova case the dimensions of the shallow portions of the central conduit system were insufficient to host the volume of magma foam necessary to trigger the fountaining episodes. At the SEC, the conditions were different from the Bocca Nuova eruption in that the activity extended over a much longer period and showed drastic changes in eruptive styles and eruption rates. Also, the volumes produced by the fountaining episodes consistently increased through each of phases B, D and E (Tables 1, 2 and 3), which suggests that the conduit geometry changed in time (Fig. 11). The assumption of La Delfa et al. (2001), Alparone et al. (2003) and Allard et al. (2005) that magma accumulated in a growing shallow reservoir thus seems plausible. Such a reservoir may have been capable of accommodating the volume of magma foam required to produce the fountaining observed during these phases of activity. The actual holding capacity of this reservoir was revealed when some 40×10^6 m^3 of residual magma were drained from it during the peculiar 2004–2005 flank eruption, a volume that is larger by an order of magnitude than that emitted during the most voluminous of the fountaining episodes several years earlier. A cylindrical reservoir with a diameter of 300 m and a vertical extent of 500–600 m would have been sufficient to host such a volume, although in reality its shape is likely to have been less simple.

While some similarities can be drawn between SEC and Pu‘u ‘Ō‘ō, the activity at the SEC and Pu‘u ‘Ō‘ō was also quite dissimilar in many respects. The most important differences between the two eruptions are the respective locations of the eruption sites and the geometries of the conduits. While Pu‘u ‘Ō‘ō is a flank vent of Kīlauea, lying about 16 km east of the summit caldera, the SEC is one of Etna's four summit craters and thus directly fed from the central conduit system. Although the Pu‘u ‘Ō‘ō-Kūpaianaha system has been the hub of eruptive activity at Kīlauea since 1983, magma is believed to be delivered to it from a summit magma reservoir through an extensive and long-lived dike, or dike-like reservoir (Hoffmann et al. 1990; Cervelli and Miklius 2003). We do note, though, that some authors (e.g., Garcia et al. 1996, 2000) also see evidence that Kilauea's summit reservoir is actually bypassed and magma rises directly into a reservoir below Pu‘u ‘Ō‘ō. In this case, the situation would not be all that unlike that at Etna's SEC.

After the first 3 eruptive episodes in early 1983, which occurred at a number of fissure vents (Wolfe et al. 1988), most of the lava fountaining occurred from one single vent at Pu‘u ‘Ō‘ō (although a few episodes involved minor activity from vents and fissures at the base of the Pu‘u ‘Ō‘ō cone; Heliker and Mattox 2003). The conduit diameter was calculated by Greenland et al. (1988) at about 50 m. In contrast, at the SEC all eruptive episodes in 2000 and 2001 involved multiple vents located on two fracture systems extending south and northeast from the summit of the SEC cone, with a total length of 0.6 km (Fig. 12). Close to the surface, the SEC conduit thus had the form of a dike. At the height of the paroxysms, the strongest explosive activity was focused at the summit vent(s), which therefore acted as the principal pressure valve, whereas the lower vents released most of the lava and produced ash-free, Hawaiian-style lava fountains. This is well illustrated in the photographs of Fig. 12b,c. It was also at these lower vents, especially Levantino at the lower end of the NE fissure, where the degassed lava was extruded before the onset of each lava fountain. In many events the fissure cutting through the SEC cone would open in a zipper-like fashion from its northern to its southern ends (that is, upslope first at northeast and then downslope at south), usually the southern section would open at the height of the fountaining. Such complexities are not reported from the period of episodic lava fountaining at Pu‘u ‘Ō‘ō.

Eruptive episodes at the SEC were generally shorter (typically lasting just a few tens of minutes) than at Pu‘u ‘Ō‘ō (hours to days; Wolfe et al. 1988) and consequently the erupted volumes were smaller (10^5–10^6 m^3 compared to 10^6–10^7 m^3). However, eruption rates were similar: at Pu‘u ‘Ō‘ō, Greenland et al. (1988) give rates between 87 and 198 m^3 s^{-1} for episodes #15 to #24; our SEC data yield rates between 24 and 174 m^3 s^{-1} for the eruptive episodes in 2000. Many of the fountains at the SEC in 2000 were much taller (up to 1,200 m) than the highest lava fountains of Pu‘u ‘Ô‘ô (470 m; Heliker and Mattox 2003), and largely surpassed even the tallest lava fountain ever observed in Hawai‘i (580 m in 1959; Richter et al. 1970).

Growth of the Southeast Crater cone and lava shield complex

The morphological evolution of the SEC cone represents one of the two well-documented examples of the growth of a persistently active vent on a basaltic volcano, the other being the evolution of the Pu'u 'Ō'ō-Kūpaianaha cone and shield complex as described by Heliker et al. (2003). Our documentation allows an accurate correlation between different eruptive styles, eruptive volumes, and the rate and mode of cone growth. From our analysis it is evident that most of the post-1996 SEC cone growth occurred during the numerous fountaining episodes during phases B, D, and E (Figs. 2, 5 and 11). In reality, the morphology resulting from the different styles of activity is rather complex, leading not only to cone growth by the accumulation of pyroclastics but also to the accumulation of significant volumes of lava on the slopes and around the base of the cone (Fig. 10). The most prominent effusive vents, Sudestino and Levantino, created minor edifices around themselves (Fig. 12d). The former has a shield morphology with a crowning low spatter cone about 20 m higher than the pre-1996 surface. In contrast, the Levantino is a rather steep rampart cut on its northeast side by a deep lava channel and sits atop a fan-shaped lava ridge or apron. The thickness of this apron exceeds 50 m at the northeast base of the SEC cone (Fig. 10). In addition, lavas emplaced at the southeastern base of the cone in 1999 (phase C) resulted in the construction of a broad ridge which was buried under thick tephra deposits in 2000 and is therefore now less conspicuous. Thus a much larger area than the SEC cone itself underwent significant vertical growth during the long-lived activity. Had this cone and lava buildup occurred on a relatively flat surface, the resulting morphology would have probably much resembled that of the Pu'u 'Ō'ō-Kūpaianaha cone and shield complex (Heliker et al. 2003).

Structural role of the Southeast Crater

From its inception in 1971 until its temporary demise in 1991, the activity of the SEC was closely related to 10 of the 12 flank eruptions of that period (Behncke and Neri 2003a; Acocella and Neri 2003; Calvari et al. 1994a). In most of these cases, vigorous activity at the SEC preceded flank eruptions or was coincident with their beginning, most notably in 1978, 1979, 1986, and 1989 (Behncke et al. 2005 and references therein). On a few occasions, it was even possible to monitor the propagation of a dike from the crater to the site of a flank outbreak (Murray and Pullen 1984; McGuire et al. 1997). It is thus evident that most of those flank eruptions were fed from the SEC conduit. Furthermore, the birth of the crater coincides with a sharp increase in the frequency of flank eruptions: more than half of the flank eruptions of the past century have occurred since that date, and the overall output rate of Etna has increased at the same time (Behncke and Neri 2003b). The appearance of the SEC therefore seems to be an expression of a significant change in the dynamics of the volcano.

Compared to the 1971–1991 period, the 1996–2001 activity of the SEC was different in two fundamental aspects. Firstly, it lasted longer than any previous eruptive period at this crater without being interrupted by flank eruptions. Secondly, it ended with the 2001 flank eruption. This did not result from magma rise through the SEC conduit, as was the case during previous flank eruptions, but was triggered by the emplacement of an eccentric dike (Behncke and Neri 2003a; Acocella and Neri 2003; Lanzafame et al. 2003; Billi et al. 2003). In 2002–2003, a second flank eruption (Acocella et al. 2003; Neri et al. 2004; Andronico et al. 2005), affected almost the same zones of the volcano as the 2001 event, without being accompanied by any SEC activity.

The close relationship between the SEC and most of the flank eruptions between 1971 and 1991 may be a direct consequence of flank instability, as expressed by numerous episodes of flank displacement in the 1980s (Neri et al. 2005b). During these episodes, large areas of the eastern and southeastern flank of Etna showed displacements of tens of centimeters to meters. Based on detailed observations of the flank slip events, which began in coincidence with the 2002–2003 flank eruption (Acocella and Neri 2005; Neri et al. 2004, 2005a; Rust et al. 2005; Walter et al. 2005), we suspect that many of Etna's flank eruptions may be more or less directly triggered or facilitated by flank displacement, as suggested by Acocella and Neri (2003). However, there are some indications that this interplay between structural instability and flank eruptions has not always been the same as it is now. The farther back in time we go, the less evidence we find for flank displacement and possible links with flank eruptions, which can only partly be attributed to the less complete data available for the past. On the other hand, the SEC appeared on the scene just at the time when Etna entered into a phase of significantly increased flank activity (both in terms of eruptions and instability). Thus one of the most intriguing questions to resolve during future studies is whether this link is true or only apparent. If the former is the case, the SEC represents the very pulse of the volcano and an indicator of its dynamic state.

Conclusions

Between 1996 and 2001, near-continuous but extremely varied eruptive activity occurred at the Southeast Crater at the summit of Mount Etna. This activity consisted of: (1) 105 powerful eruptive (fountaining) episodes (23 in 1998–99; 66 in 2000; 16 in 2001); (2) an effusive eruption lasting for 9 months (in 1999); (3) a 20-month period of mild Strombolian and effusive activity (1996–1998); (4) a low effusion rate period during the first months of 2001. Although population centers were not directly threatened by this activity, frequent tephra falls resulting from fountaining damaged crops, fruit gardens and vineyards and occasionally disrupted ground and air traffic. Furthermore, the episodes of violent explosive activity represented a hazard to visitors to the summit area even at distances of several kilometers from the SEC.

The total DRE volume of eruptive products of the SEC during 1996–2001 is nearly 90×10^6 m^3 (Tables 1, 2, 3). This is more than 75% of the total volume of eruptive products of the 1995–2001 summit eruptions, strongly underlining the role of the SEC as the most active of Etna's four summit craters. At the same time, the production rate was four times as high as during the previous 25 years of its life.

During the 4.5 years of activity (1996–2001), the morphology of the crater and its cone changed significantly and its summit rose from an elevation of 3,196 m (in 1996) to about 3,300 m (in 2001). The bulk volume growth of the cone computed from difference maps was about 36×10^6 m^3 (23×10^6 m^3 DRE). The addition of an irregular lava apron or shield around the base and on the flanks of the cone led to a rather complex morphology resembling to some degree that of the Puʻu ʻŌʻō-Kūpaianaha cone and shield complex at Kīlauea described by Heliker et al. (2003).

At SEC we believe that fountaining was triggered by the uprise of a foam (following Allard et al. 2005) that accumulated in a shallow reservoir below the SEC, which eventually grew to a holding capacity of several tens of millions of cubic meters. However, between different eruptive phases, there were changes in both magma volume fluxes and eruptive styles that can be best explained by changes in the conduit geometry and in the rate at which magma was supplied to the shallow conduit system. Some of these changes seem to be related to flank instability-induced extension in the summit area. We thus propose that the SEC plays an important role in reflecting changes in the recent dynamics of Etna, which has been characterized by unusually high levels of activity as well as increased structural instability of the eastern to southeastern flanks (Neri et al. 2005a and references therein).

Both the erupted volumes and intensity of the SEC's 1996–2001 eruptions are exceptional in the historical context of Etna's activity, where summit activity has been traditionally associated with low effusion rates (Chester et al. 1985). Episodic fountaining has been observed on earlier occasions at Etna (Behncke et al. 2004; Branca and Del Carlo 2005), but has never comprised so many events within such a short time period. When considered together with the activity at the other summit craters during 1995–2001, the SEC eruptions represent a striking manifestation of the current high-level dynamics of the volcano. In fact, this period of summit activity was followed by a series of flank eruptions, which occurred in rapid succession (three flank eruptions occurred between July 2001 and March 2005), showing that the levels of Etna's activity were higher than during any time since the second half of the seventeenth century (e.g., Behncke and Neri 2003b; Behncke et al. 2005; Branca and Del Carlo 2005; Clocchiatti et al. 2004; Métrich et al. 2004).

Our work also gives an overall impression of what can be learned from closely documenting this period of activity from Etna's (currently) most active eruptive center. It has yielded insights into the changing dynamics of the central conduit complex and into the mechanisms that govern the episodic fountaining. Moreover, it has offered an opportunity to test various methods for the calculation of eruption rates and volumes, without which it would be difficult to appreciate the full significance of the activity and the quantities of its products. However, the data and interpretations discussed here are far from conclusive. Many questions remain unanswered or, at best, partially answered, such as those regarding the dynamics of lava fountaining. It is probable that the Southeast Crater itself, with future eruptions, will help to increase our understanding of such processes.

Acknowledgements This work was partially funded by grants from the Istituto Nazionale di Geofisica e Vulcanologia (INGV) and from the Dipartimento per la Protezione Civile (Italy). Financial support was received by V.Z. and B.B. in the form of INGV Catania research grants. The pilots and technicians of the Civil Defence helicopters are acknowledged for helping in obtaining photography of lava flows during their emplacement. Particular thanks goes to P. Allard for discussion and D. Bryant, G. Scarpinati, G. Sturiale, G. Tomarchio and R. Velardita, who contributed to the acquisition of data used for this study. We are thankful for the helpful reviews by John Guest and two anonymous reviewers.

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