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RESEARCH ARTICLE

Regimes of magma recharge and their control on the eruptive behaviour during the period 2001–2005 at Mt. Etna volcano

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Abstract Mount Etna volcano (Italy) during the period 2001–2005 has undergone a period of intense eruptive activity marked by three large eruptions (2001, 2002–2003 and 2004–2005). These eruptions encompassed diverse eruptive styles and regimes: from intensely explosive, during 2001 and 2002–2003 eruptions, to exclusively effusive in the 2004–2005 event. In this work, we put forward the idea that these three eruptions are the response of the progressive arrival into the uppermost segment of the open-conduit system of a new magma, which was geochemically distinct in terms of trace element and Sr–Nd–Pb isotope signature from the products previously emitted by the Etnean volcano. The magma migrated upwards mainly through a peripheral tectonic system, which can be considered as eccentric in spite of its relative proximity to the main system. The ingress of the new magma and its gradual displacement from the eccentric system into the uppermost sector of the open-conduit gave rise to different eruptive behaviours. At the beginning, the ascent of the undegassed magma, able to exsolve a gas phase at depth, and its interaction with closed-system magma reservoirs less than 10 km deep gave rise to the explosive events of 2001 and 2002–2003. Later, when the same magma entered into the open-conduit system, it took part in the steady-state degassing and partially lost its volatile load, leading to a totally effusive eruption during the 2004–2005 event. One further consideration highlighted here is that in 2001–2005, migration of the feeding axis from an eccentric and peripheral position towards the main open-conduit has led to the development of a new vent (South East Crater 2) located at the eastern base of the South East Crater through which most of the subsequent Etnean activity occurred.

Keywords Magma supply · Ascent dynamics · Mixing · Volatiles · Degassing · Eruptive style

Introduction

Mount Etna volcano (Italy) has an open-conduit system persistently filled with magma, located at the intersection of two main fracture and fault systems oriented NNW–SSE (sometimes switched to N–S directions) and NE–SW (Bousquet and Lanzafame 2004, and references therein). Repeated inputs from depth of undegassed magma into the degassed resident magma makes the entire open-conduit system act as a buffer, where new pulses of magma are diluted and petrochemical diversities are homogenized (e.g., Corsaro and Pompilio 2004). Since distinct magma batches do not keep their original geochemical character, their ascent through the feeding system can normally be tracked only when geophysical effects (ground deformation and shallow earthquakes) are produced. The pristine geochemical signature of new magma pulses can only be preserved if they ascend through a pathway unconnected to the main open-conduit system (i.e., flank eruptions). Interesting examples are the three eruptive events of 2001, 2002–2003 and 2004–2005, which occurred on the upper flanks of Mt. Etna, in which ~115×10^6 m^3 of lavas and tephra were emitted

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(Behncke and Neri 2003; Clocchiatti et al. 2004; Burton et al. 2005). These three eruptions have been the subject of many recent papers, where each single event of this period has been studied in detail, presenting the petrological characterization of the volcanics and a large amount of data on the geophysical signals that preceded and accompanied the events (e.g., Clocchiatti et al. 2004; Métrich et al. 2004; Andronico et al. 2005; Monaco et al. 2005; Spilliaert et al. 2006; Viccaro et al. 2006, 2008; Corsaro et al. 2007, 2009; Nuccio et al. 2008; Collins et al. 2009; Ferlito et al. 2009a). However, no attempts have been made to present a comprehensive model that associates the three events, their varied eruptive behaviours, the feeding dynamics and the geochemical characters of the emitted products. This work is aimed at interpreting the sequence of eruptions occurring on the southern flank of Mt. Etna volcano between 2001 and 2005. Petrochemical and isotopic data from lavas and tephra emitted through the South Rift, along with a reappraisal of published geophysical results, support the interpretation that the volcanic activity was driven by the progressive ascent of a new geochemically distinct and volatile-rich magma (hereafter defined as deep magma [DM]) into the Etnean feeding system through fractures related to regional tectonics. Data and interpretations relative to the short 2002 eruption on the north-eastern flank of the volcano are not discussed here in detail (Clocchiatti et al. 2004; Andronico et al. 2005; Ferlito et al. 2009a). In this regard, Ferlito et al. (2009a) have provided indications that the upper portion of the 2002 eruptive fracture on the north-eastern flank was fed by magmas rather different from those simultaneously emitted by the lower portion of the north-eastern fracture and by the fracture on the southern flank. The geochemical data used in this paper are part of the extensive dataset published in Viccaro and Cristofolini (2008) on historic and recent Etnean volcanic rocks. The same data, used by these authors to evaluate how the partial melting mechanisms of the Etnean mantle source could have had a control on the short-term geochemical changes during the last four decades, are here used to provide an original model of the volcanological development of the events during the 2001–2005 period. We believe that our results contribute to a better understanding of the supply dynamics presently acting within the Etnean feeding system.

Geological and volcanological background

Mount Etna is a large composite stratovolcano, 3,340 m high and covering about 1,250 km^2. It is located on the eastern coast of Sicily at the intersection of two major fault zones trending NNW–SSE (Tindari–Letojanni–Malta) and NNE–SSW (Messina–Giardini). Here, three structural domains merge to constitute a complex geodynamic setting (Cristofolini et al. 1985; Bousquet et al. 1988; Scribano et al. 2009; Schellart 2010).

The volcanic activity in the Etnean area began ~500 ka with fissural emission of sub-marine, later sub-aerial, tholeiitic lavas distributed rather discontinuously in the southern sectors of the volcano (Branca et al. 2004). The erupted products gradually changed (~220 ka) to transitional and finally to Na alkaline (Cristofolini and Romano 1982; Branca et al. 2004). The building of alkaline central-conduit edifices started about 122–130 ka and went on with the construction and destruction of several volcanic centers in the present Valle del Bove (cf. Branca et al. 2004; Ferlito and Nicotra 2010, and references therein). Their activity was characterized by cycles of Strombolian eruptions, alternating with violent explosive episodes associated with caldera-forming collapses. The recent activity of "Mongibello" from 14 ka to the present (Branca et al. 2004) displayed a wide range of eruptive styles from effusive and mildly Strombolian to Plinian. However, throughout the rather complete historical record (since 1329 A.D.) and particularly over the last few centuries, the activity was dominated by effusive eruptions from summit craters or parasitic vents on the volcano flanks, often accompanied by Strombolian ejections. After the benchmark represented by the 1971 eruption, a significant increase in eruptions frequency occurred (Branca and Del Carlo 2005). Some of the frequent episodes in the last 40 years of activity were important in terms of emission rates and amounts of erupted magma, such as the 1983 eruption on the southern flank or the 1991–1993 eruption in Valle del Bove.

Summary of the 2001–2005 eruptive activity

In a persistently active volcano such as Mt. Etna, it is not simple to fix the boundaries of an eruptive period. Based on petrographic features and geochemical signatures of the erupted products, we choose to consider the events that took place between 2001 and 2005 as related to the same eruptive period. These events are summarized here. More detailed descriptions for each of the eruptions can be found in works already published (e.g., Behncke and Neri 2003; Andronico et al. 2005; Corsaro et al. 2007, 2009).

The first event, which occurred from July 13 to August 9, 2001, was characterized by two simultaneously active systems of eruptive fissures, located on the upper southern flank of the volcano (Fig. 1a and Table 1; cf. Behncke and Neri 2003). The fissures of the upper system, trending NNW–SSE, developed between the South East (SE) crater and the Piano del Lago area (PL) from an elevation of 3,100 m down to about 2,650 m (SE–PL system). The fissures of the lower system, oriented N–S, developed

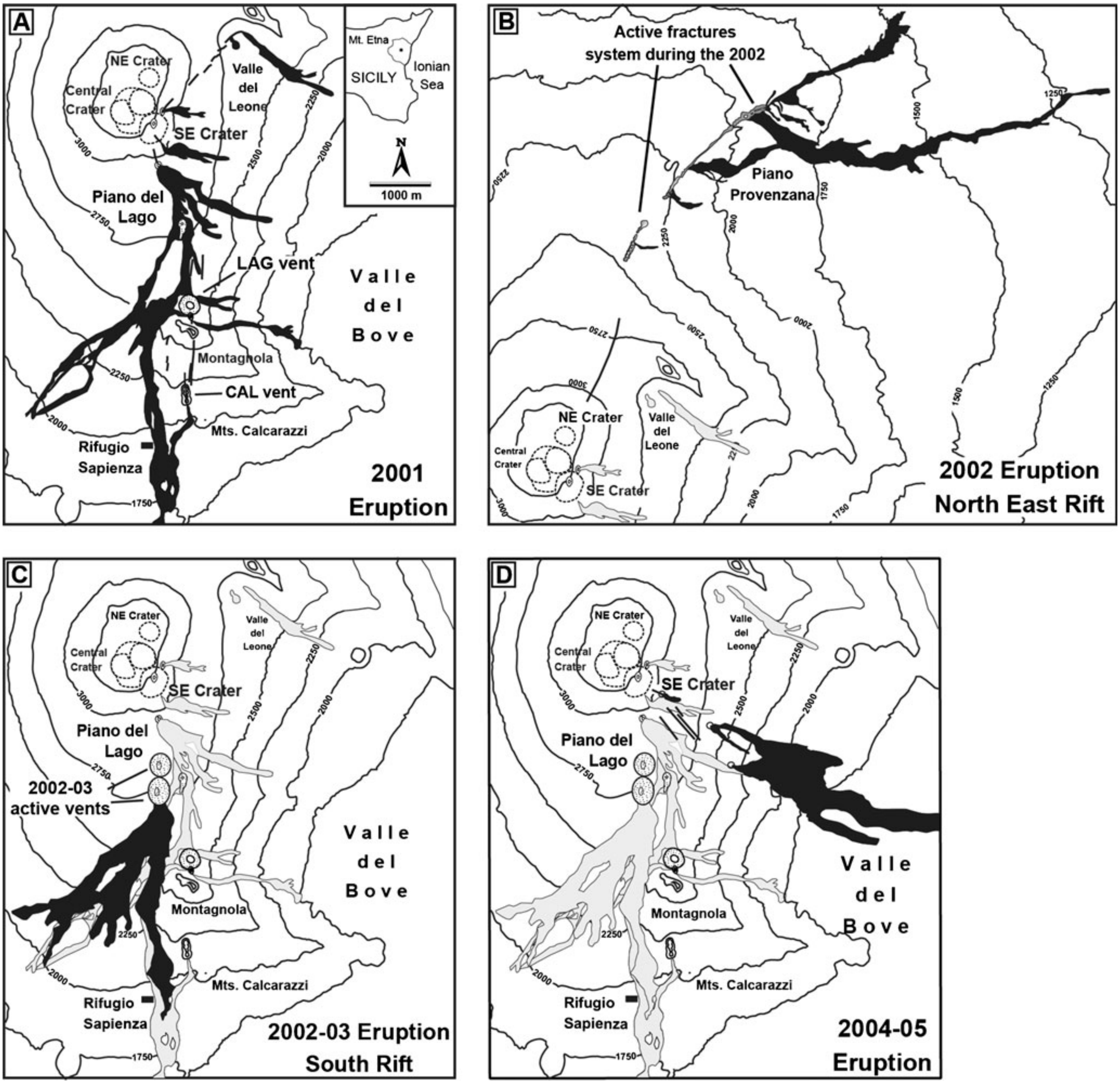

Fig. 1 Sketch maps of scoria cones (*stippled*), eruptive fractures (*black lines*) and lava flow fields of the 2001 (**a**), 2002–2003 (**b** northeast flank; **c** south flank) and 2004–2005 (**d**) eruptions occurred at Mt. Etna (lava fields for each of the eruptive events are *highlighted in black*)

starting from 2,100 m (CAL vents) up to the Laghetto area at 2,550 m, where a distinct vent (LAG) formed, characterized by highly explosive activity that is regarded as one of the most violent in the recent record of Mt. Etna (Branca and Del Carlo 2005). A minor eruptive fissure with a northeast trend opened in the Valle del Leone (Fig. 1).

After a quiet interval of 14 months, eruptive activity resumed on October 27, 2002 (Table 1). This second eruptive event took place from two localities on the volcano. Vents aligned along a fissure located northeast of the summit craters, called North East Rift, produced Strombolian activity and lava flows that lasted for 1 week (Fig. 1b). The fissure system was composed of three segments with different orientations, each fed by a distinct magma (Fig. 1; Ferlito et al. 2009a). Activity from vents located on the southern flank, called the South Rift, lasted for 3 months until the end of January 2003 (Fig. 1c; cf. Andronico et al. 2005). Here, the eruptive vents were located at an elevation of about 2,800 m a.s.l. between the LAG vent of 2001 and the SE crater. The activity was

Table 1 Synoptic table of the eruptive period 2001–2005 at Mt. Etna, including timing and location of vents, styles of eruption, petrographic and some geochemical data

Eruption	Eruption start	Eruption end	Vent location	Type of eruptive activity	Total	Phenocryst content (%)					Average bulk rock			
						Plg	Aug	Ol	Ti–Mt	Amph	FeO_{tot}/MgO	Rb/La	$^{87}Sr/^{86}Sr$	$^{206}Pb/^{204}Pb$
2001	Jul 13	Aug 09	South East crater — 3,100 m (SE) and Piano del Lago — 2,750 m (PL)	Strombolian + Effusive	40	XXX	XX	X	X	Absent	1.96	0.71	0.703573	19.86
	Jul 18	Aug 09	Rifugio Sapienza — 2,100 m (CAL)	Mildly Strombolian + Effusive	15	X	XX	X	X	X	1.56	0.69	0.703536	19.84
	Jul 20	Aug 07	Piano del Lago — 2,550 m (LAG)	Strongly Strombolian + Effusive	15	X	XX	X	X	X	1.70	0.73	0.703619	19.80
2002	Oct 27	Nov 05	North East Rift — 3,010–1,950 m	Mildly Strombolian	20	XXX	XX	X	X	Absent	2.28	0.73	0.703576	19.74
2002–2003	Oct 27	Jan 31	South Rift — 2,800 m	Strongly Strombolian + Effusive	25	XX	XX	X	X	X	1.79	0.81	0.703600	19.77
2004–2005	Sept 07	Mar 08	South East crater — 3,100 m and Valle del Bove	Effusive	35	XXX	XX	X	X	Absent	2.05	0.92	0.703618	19.73

Number of *X* indicates: *X* lower than 10 vol.%, *XX* from 10–15 vol.%, *XXX* more than 15 vol.%

Chemical data for samples of the 2001–2005 eruptions are from Viccaro and Cristofolini (2008), except those for the 2002 eruption on the north-eastern flank that are from Ferlito et al. (2009a)

PI porphyricity index (vol.%)

violently explosive with spectacular lava fountaining. Tephra fall affected human activities over wide sectors of Eastern Sicily and, depending on wind direction, reached as far as Greece (Dellino and Kyriakopoulos 2003) and Libya.

After this eruption, a 20-month lull followed the 2002–2003 eruption, during which the open-conduit system was filled with magma undergoing steady degassing. Activity abruptly started again on September 7, 2004 when a radial fissure opened at the eastern foot (3,000 m a.s.l.) of the SE Crater, without any relevant recorded seismic activity (Table 1; Corsaro et al. 2009, and references therein). During the following days, a NNW–SSE fracture system opened down to the upper slopes of the Valle del Bove, where lava was emitted from two vents at altitudes of 2,650 and 2,350 m, respectively (Fig. 1d). For the next 6 months, until March 8, 2005, these vents erupted lava flows with no explosive activity.

Analytical methods

An extensive sampling was performed on the southern and south-eastern flanks of the volcano during the eruptive events. A total of 50 rock samples were collected from lava flow units of the eruptive period noting their date of emission and field observations. Major and trace element along with Sr–Nd–Pb isotope ratios used in this paper are taken from Viccaro and Cristofolini (2008), where the analytical procedures followed to obtain the data are described in detail.

About 100 thin and polished sections were made for petrographic and SEM-EDS analyses, the results of which are reported as Electronic Supplementary Material (ESM). Major element abundances of mineral phases were obtained at the Dipartimento di Scienze Geologiche of Catania (Italy) using a Tescan Vega-LMU scanning electron microscope equipped with an EDAX Neptune XM4-60 microanalyzer operating by energy dispersive system characterized by an ultra-thin Be window coupled with an EDAX WDS LEXS (wavelength dispersive low energy X-ray spectrometer) calibrated for light elements. Operating conditions were set at 20 kV accelerating voltage and 0.2 nA beam current. Precision of collected data is ~3%.

Petrography and mineral chemistry

Lavas erupted during the period 2001–2005 have a porphyritic index (PI, vol.%) ranging between 10 and 40 (Table 1). Their mineral assemblage is generally made up of euhedral phenocrysts of plagioclase and augite in similar proportions (making up ~80 vol.% of phenocrysts) followed by euhedral to subhedral olivine and Ti magnetite.

Phenocrysts of Mg hastingsite (~2–3 vol.%) have been only observed in some of the 2001 products (CAL and LAG) and in the earliest lavas erupted during the 2002–2003 eruption from the South Rift (Clocchiatti et al. 2004; Viccaro et al. 2007). The groundmass is commonly intersertal with microlites composed of plagioclase and subordinate augite, Ti magnetite and olivine.

Despite their rather homogeneous petrographic characteristics some systematic differences among the products of 2001–2005 should be outlined. The 2001 SE–PL volcanics are markedly porphyritic (PI ~35–40), amphibole is absent, and the abundant plagioclase phenocrysts are oscillatory zoned. On the contrary, the products from the 2001 CAL and 2001 LAG vents are sparsely porphyritic (PI ~10–20) and are amphibole-bearing with scarce plagioclase as microphenocrysts. Lavas from the 2001 CAL and LAG vents also contain abundant quartz-rich xenoliths. On the whole, plagioclase compositions range between An$_{59}$ and An$_{89}$, Mg# values of augite range between 77 and 90, forsterite contents of olivine are between Fo$_{64}$ and Fo$_{80}$ (see ESM). Lavas from the 2002–2003 event from the South Rift are just slightly more porphyritic (PI ~20–25) than those from the CAL and LAG vents of 2001. Products emitted from the South Rift at the end of this eruption do not show any trace of amphibole, although they are very similar to the CAL and LAG ones in their other petrographic features. Plagioclase compositions range between An$_{68}$ and An$_{88}$, Mg# values of augite range between 79 and 87, and forsterite contents of olivine are between Fo$_{72}$ and Fo$_{77}$. Products erupted from the upper part of the North East Rift are sparsely porphyritic (PI ~10–15), whereas lavas erupted from the lower segments of the same eruptive fissure are porphyritic (PI ~25–30), and no trace of amphibole has been observed (Ferlito et al. 2009a). Plagioclase, augite and olivine compositions are relatively constant at~An$_{89}$, Mg# ~88 and Fo$_{82}$, respectively (ESM). The 2004–2005 products are again porphyritic (PI ~30–40), lack amphibole and contain abundant plagioclase phenocrysts, similar to those of the SE–PL products. Plagioclase compositions range between An$_{73}$ and An$_{87}$, Mg# values of augite range between 79 and 91 and forsterite contents of olivine are between Fo$_{71}$ and Fo$_{81}$ (ESM).

Geochemistry

Major element compositions for all of the 2001–2005 products fall in the K-trachybasalt field of the TAS diagram (not shown). However, a careful analysis of major and trace element abundances reveals the existence of significant differences in the considered rocks: products of the 2001 event both at the CAL and SE–PL vents cluster at SiO$_2$ ~48 wt.%, and are also characterized by TiO$_2$ (~1.4–1.7 wt.

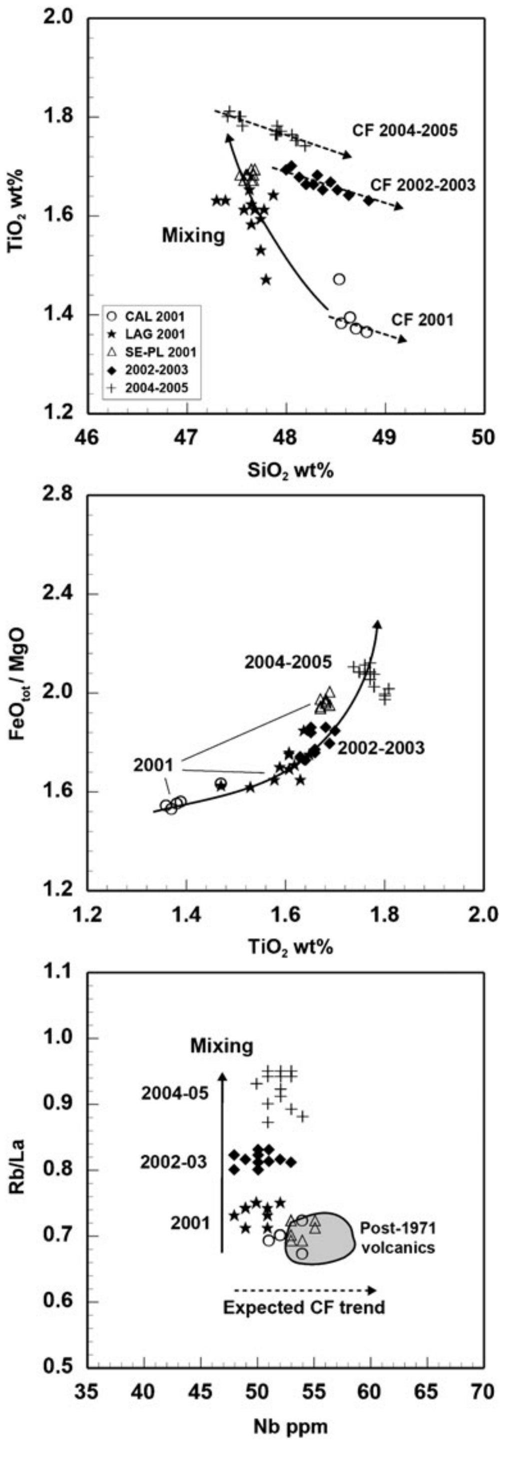

Fig. 2 SiO$_2$ vs. TiO$_2$, TiO$_2$ vs. FeO$_{tot}$/MgO and Nb vs. Rb/La variation diagrams for lavas of the 2001–2005 period. *Solid line arrows* indicate a progressive mixing trend from the 2001 CAL products towards an inferred DM composition. The compositional field (*stippled*) for post-1971 volcanics is shown in Nb vs. Rb/La diagram (data from Viccaro and Cristofolini 2008 and references therein). Shifts from the mixing tie-line (*dashed-line arrows*) are consistent with crystal fractionation trends (*CF*)

%) and average FeO_{tot}/MgO ratios ~1.6 and ~2, respectively (Fig. 2; data from Viccaro and Cristofolini 2008). Trace element abundances for these products (e.g., Nb, Rb, La) are on the whole similar to those displayed by the post-1971 volcanics (Fig. 2; data from Viccaro and Cristofolini 2008). Lavas erupted during the 2001 eruption at the LAG vent have SiO_2 contents similar to SE–PL and CAL products, and TiO_2 (~1.6 wt.%) and FeO_{tot}/MgO (average=1.7) intermediate between the SE–PL and CAL ones (Fig. 2). However, their trace element signature is rather distinct with respect to the other lavas of the 2001 event; in particular, Nb and La are noticeably lower and Rb is higher (Fig. 2). Concerning major elements, lavas of the 2002–2003 eruption on the South Rift are quite similar to the LAG and SE–PL ones, with SiO_2=48–48.5 wt.%, TiO_2 ~1.7 wt.%, and FeO_{tot}/MgO ~1.8 (Fig. 2). On the other hand, their trace element concentrations indicate a markedly distinct signature, characterized by higher Rb (Rb/La ~0.8) at relatively constant Nb concentrations with respect to all of the 2001 products (Fig. 2). In addition, LREE, Th and U contents (not plotted) decrease from the 2001 to the 2002–2003 eruptions, whereas other elements are fairly constant. Some data for lavas of the 2002 eruption from the North East Rift have been reported in the synoptic Table 1 for comparison with products simultaneously emitted from the South Rift (data from Ferlito et al. 2009a). Lavas of the 2004–2005 event display SiO_2 ~47.5 wt.%, with values for TiO_2 ~1.8 wt.% and FeO_{tot}/MgO >2 (Fig. 2). They also exhibit the most distinct trace element signature of the whole 2001–2005 eruptive period, being characterized, for example, by the highest Rb/La ratio (higher Rb at markedly lower La; Fig. 2) and by lower Th and Y concentrations.

The Sr–Nd–Pb isotopic compositions of selected samples provide valuable information to further characterize lavas of this period (data from Viccaro and Cristofolini 2008). The $^{87}Sr/^{86}Sr$ ratios display an overall increase with time, ranging between 0.703538 and 0.703624. The $^{143}Nd/^{144}Nd$ ratios vary between 0.512852 and 0.512873, with a slightly negative correlation with $^{87}Sr/^{86}Sr$, although the 2σ of each data point is close to the overall distribution (Fig. 3). Pb isotope ratios decrease with time and vary significantly during the eruptive period: $^{206}Pb/^{204}Pb$ values range between 19.73 and 19.85, $^{207}Pb/^{204}Pb$ ratios between 15.64 and 15.68, and $^{208}Pb/^{204}Pb$ ratios between 39.44 and 39.58 (Fig. 3).

Discussion

Magma evolution in the feeding system

The isotopic changes observed in the products erupted during the 2001 event from the LAG vent may indicate that a new magma (DM), with a distinct isotopic signature, entered into the feeding system (Fig. 5). In particular, the 2001 SE–PL and CAL products follow the main trend of the post-1971 volcanics. Starting from the 2001 LAG lavas, Sr–Nd–Pb isotopic compositions progressively shift away from the previously recognized trend, reaching the extreme value in the 2004–2005 products (Fig. 3).

The summer 2001 eruptive event may therefore be considered as a benchmark for the recent geochemical evolution of the Etnean magmas. In fact, SE–PL and CAL products have geochemical and isotopic signatures resembling those of the products emitted after 1971 (Figs. 2 and 3). Their different petrographic features are due to evolution under diverse physical conditions before the eruption. In particular, crystallization in the steadily degassing open-conduit system would generate the porphyritic textures with abundant plagioclase phenocrysts (cf. Métrich and Rutherford 1998; Viccaro et al. 2010) and the absence of amphibole observed in SE–PL lavas. On the other hand, nucleation and

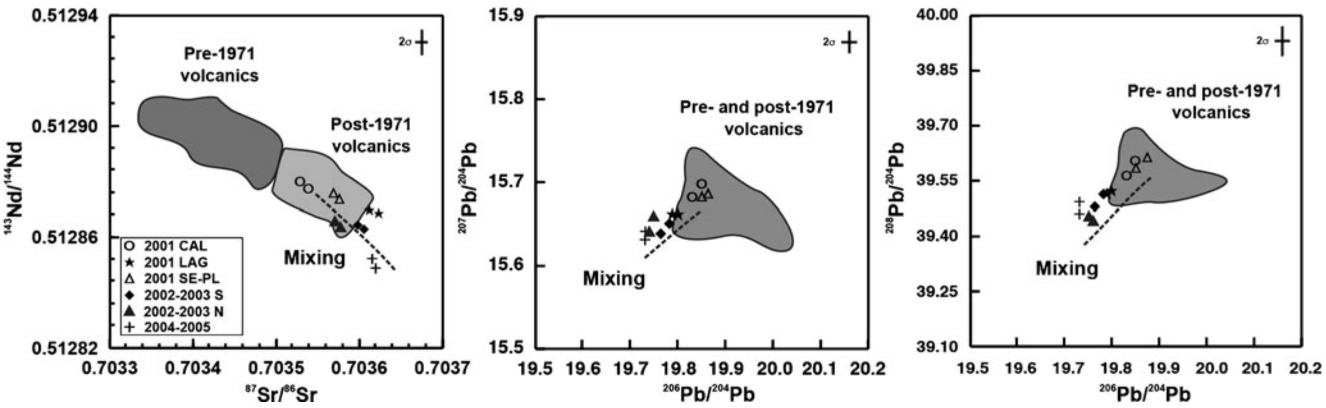

Fig. 3 Variations of Sr–Nd–Pb isotope ratios for lavas of the 2001–2005 eruptive period. Compositional fields for pre- and post-1971 volcanics are shown for comparison (data from Viccaro and Cristofolini 2008 and references therein)

growth in a closed-system would produce sparsely porphyritic textures with amphibole and scarce plagioclase shown by CAL lavas. During the course of the 2001 event, the geochemical frame changed significantly, since the LAG magma differs in its trace element and isotopic signature from SE–PL and even from CAL, all erupted at the same time (Figs. 2 and 3). In this regard, plagioclase and augite phenocrysts found in LAG products are rimmed by envelopes significantly depleted in REE and other trace elements, suggesting modified equilibrium conditions during their growth (Viccaro et al. 2006). These features provide evidence that geochemically distinct magma entered into the CAL reservoir, and support the model of its mixing with the residing CAL magma (Viccaro et al. 2006; 2008; Ferlito et al. 2008).

During the 2002–2003 eruptive event, the lavas emitted along the South Rift (Fig. 1) were geochemically similar to the 2001 LAG products (e.g., TiO_2, FeO/MgO ratio), but with some distinctive differences, such as noticeably higher Rb/La values (Fig. 2), that indicate the involvement of a higher proportion of the DM. The DM mixed with the remnants of the amphibole-bearing magma probably still residing beneath the South Rift system. At the North-East Rift, during the short 2002 event, distinct magmas were emitted along the eruptive system, differing in turn by those simultaneously emitted from the South Rift (Ferlito et al. 2009a).

The magma of the 2004–2005 event was erupted through structures directly connected to the steadily degassing open-conduit system, as evidenced by the effusive eruption style and by the SO_2 flux measured in the summit area, which did not increase at the eruption onset (cf. Burton et al. 2005), thus indicating the degassed condition of this magma. These products display the highest TiO_2, FeO/MgO and Rb/La values among the products emitted on the southern flank during the whole period 2001–2005 (Fig. 2). Lavas of the 2004–2005 event may therefore be considered as most closely resembling the DM end-member involved in the progressive mixing. This assumption implies that, after mixing with the amphibole-bearing magmas residing in closed reservoirs, this new magma finally reached the open-conduit system of the summit craters. Evidence that the contribution of the DM increased with time during the 2001–2005 period is offered in Fig. 2, where the 2001 CAL lavas and the 2004–2005 lavas may be considered as end-members of a mixing process. Shifts from the theoretical mixing tie-line can be consistent with effects of crystal fractionation occurring within the evolving feeding system during the time span of about 5 years. In order to evaluate the contribution of crystal fractionation, simulations were performed using the MELTS code (Ghiorso and Sack 1995; Asimow and Ghiorso 1998). Differentiation for the 2002–2003 products was simulated taking into account the most basic 2002–2003 whole rock composition at T=1,100°C, P=250 MPa and fO_2 at the QFM buffer. The H_2O content was assumed as 3.4 wt.% on the basis of data given by Spilliaert et al. (2006) for magmas of this eruption. Under these conditions, the stable mineral assemblage calculated by MELTS is constituted of ~3 vol.% of olivine, ~15 vol.% of augite and 2 vol.% of magnetite. Plagioclase is not stable at 250 MPa and these high volatile contents, and starts to crystallize only when pressure decreases. Differentiation within the open-conduit for the 2004–2005 products was simulated considering the most basic 2004–2005 whole rock composition at T=1,100°C, P=50 MPa and fO_2 at the QFM buffer. If we assume that the Etnean magmas crystallizing within the open-conduit system have an average H_2O content ~2.5 wt.% (cf. Métrich and Rutherford 1998), then we should admit that the original water content of the DM (3.4 wt.%; cf. Métrich et al. 2004 and Spilliaert et al. 2006) decreased due to degassing in the open-conduit system. Results show that, after crystallization of olivine (~3 vol.%) and augite (~11 vol.%) at depth, the crystal fractionation trend at shallower depth (~1.5 km) is mainly controlled by plagioclase (~20 vol.%) plus magnetite (~3 vol.%), leading to a final total volume of ~37% of fractionated phases. This differentiation accounts for petrochemical diversities observed among rocks of the same eruptive event, whose major and trace element compositions plot along trends that, according to MELTS simulations, represent liquid lines of descent (Fig. 2). Due to the compositional variations occurring with time to one or both the end-members, the hypothesized mixing can be simulated by a curved tie-line. Changes in geochemistry observed during the 2001–2005 period are therefore consistent with a first input of the DM into the portion of the feeding system occupied by the amphibole-bearing CAL type magma (2001). This gradually replaced the amphibole-bearing magma (2002–2003), and finally reached the open-conduit system taking part in the steady-state degassing (2004–2005).

Evidence that volatile-rich Etnean magmas can exsolve a gas phase at depth is confirmed by data on primitive glass inclusions in olivine erupted at the LAG vent (Métrich et al. 2004). These data indicate that a gas phase, mostly composed of CO_2, can exsolve under pressures higher than 250 MPa and that the H_2O content in the gas phase increases during magma ascent. In Fig. 4, simulations by VolatileCalc (Newman and Lowenstern 2002) were performed using an average composition at SiO_2=47 wt.% of primitive olivine-hosted melt inclusions from lavas of the 2001 and 2002–2003 eruptions (South Rift) and their calculated volatile concentrations (H_2O=3.4 wt.% and CO_2=1,100 ppm) from Métrich et al. (2004) and Spilliaert et al. (2006). This melt may be regarded as the closest in composition to the above inferred DM and similar to the

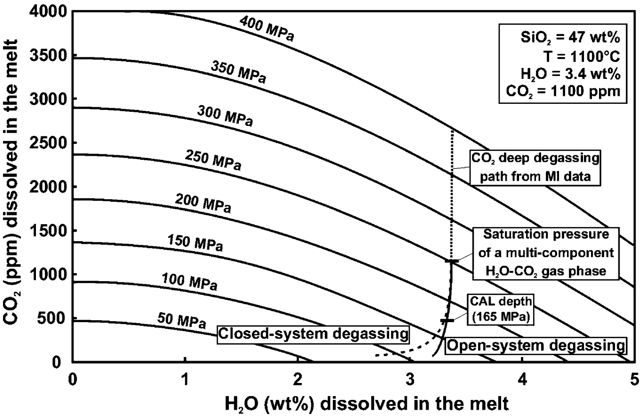

Fig. 4 Isobars with open- and closed-system degassing paths obtained with VolatileCalc (Newman and Lowenstern 2002). Simulations were performed using the average compositions of primitive melt inclusions found in 2001 and 2002–2003 products (Métrich et al. 2004; Spilliaert et al. 2006). Starting conditions were set at T=1,100°C; the volatile content (H_2O=3.4 wt.%, CO_2=1100 ppm) was taken on the basis of melt inclusions (*MI*) data from Métrich et al. (2004). A gas phase (chiefly CO_2) exsolves at pressures higher than 250 MPa (Métrich et al. 2004). Simulations show that H_2O starts to exsolve at ~250 MPa as a multi-component (H_2O–CO_2) phase. During magma ascent, H_2O content in the volatile phase increases very little along either open- or closed-system degassing paths, up to 165 MPa (~6 km b.s.l., where CAL magma was residing). The new magma was then still H_2O-rich and able to supply large amounts of exsolvable volatiles when it mixed with the residing CAL magma. Before the 2002–2003 eruption, similar dynamics could have acted when a new magma input from depth occurred. The two degassing paths strongly differ at $P<$ 165 MPa. This means that when the new magma reached the open-conduit system, after the 2002–2003 eruption, it lost most of its H_2O during degassing at shallow depth (50–75 MPa)

lavas erupted during the 2004–2005 event (Fig. 2). Calculations show that an exsolved gas, composed of H_2O ~75% + CO_2 ~25%, could be present in the CAL magma reservoir at pressure of ~165 MPa (corresponding to ~6 km of depth; Fig. 4; cf. Monaco et al. 2005; Viccaro et al. 2006; Corsaro et al. 2007; Ferlito et al. 2009b). Consistent with our results, Caracausi et al. (2003) and Rizzo et al. (2006) observed an increased emission of CO_2 (exsolved at depth of ~10 km) at the periphery of the volcanic edifice just before the 2001 eruption. This means that, due to gas exsolution, overpressure conditions can be reached even at greater depth (~10 km). If the magma is not connected with the open and steadily degassing conduit, the retained gas raises the overpressure within the melt, which can attain a compressible state (Huppert and Woods 2002). Data on the seismic strain indicate that above 10 km of depth, strain could be driven by magma overpressure acting on the seismogenic structures (Cocina et al. 1998; Barberi et al. 2000, 2004). Under such conditions, even relatively small perturbations (e.g., low magnitude earthquakes) can generate a massive gas exsolution, potentially triggering highly explosive eruptions.

Tracking the ascent of the new magma

The activation of NNW–SSE oriented fractures during a seismic swarm in April 2001 (cf. Alparone et al. 2004; Bonaccorso et al. 2004) has driven the ascent of the DM at a depth <10 km. This magma was characterized by very high volatile contents ($\sum H_2O+CO_2+Cl+F$ ~4 wt.%), as shown by olivine-hosted glass inclusions in LAG vent lavas (Métrich et al. 2004), and was therefore ready to feed strongly explosive eruptions if triggered by perturbation of the system (Fig. 4). The event that might have prompted a significant magma migration into the upper portion of the feeding system probably occurred when the amphibole-bearing magma erupted in July 2001. The seismic swarm, immediately preceding this eruption (Monaco et al. 2005), and the rapid extrusion of significant amounts of lava in the first 3 days of eruption (4–8 × 10^6 m^3; cf. Behncke and Neri 2003) could have produced a pressure drop at the top of the fresh ascending magma. The consequent sudden expansion boosted its fast ascent through the NNW–SSE fracture system (South Rift), which intersected the amphibole-bearing magma reservoir (Monaco et al. 2005; Viccaro et al. 2006; Ferlito et al. 2008). The two magmas mixed and the resulting products were erupted at the LAG vent, where activity was highly explosive due to large amounts of exsolvable as well as exsolved volatiles in the magma. Meanwhile, the lower CAL vent (450 m below the LAG vent) continued undisturbed and erupted the original amphibole-bearing magma (Fig. 5).

Before the 2002–2003 event, a new input of the volatile-rich DM must have recharged the NNW–SSE system, and therefore supplied the resident magma with an amount of volatiles large enough to restart the eruption (Fig. 5). The magma recharge, here proposed on the grounds of geochemical data, is consistent with the geophysical evidence provided by Patanè et al. (2005), who noticed after the end of the 2001 event, ground deflation (going on for about 6 months) followed by a period of inflation. This was interpreted as due to magma migration from deep to shallow portions of the feeding system (cf. also Aloisi et al. 2003, 2006; Barberi et al. 2004). Moreover, the ascent of a volatile-rich magma, shortly before the onset of the 2002–2003 eruption, was recognized on the grounds of changes of He isotope ratios in gas emanations at the periphery of the volcano (Rizzo et al. 2006). Other evidence that the magma involved in the 2002–2003 eruption was volatile-rich is also provided by the high volatile contents found in primitive melt inclusions (~4 wt.%; cf. Spilliaert et al. 2006) and by the intense explosive activity that in a few weeks constructed two large cinder cones and during the entire eruption dispersed about 40 × 10^6 m^3 of ash in the atmosphere.

After the 2002–2003 event, the DM finally reached the upper part of the open-conduit system, where it took part

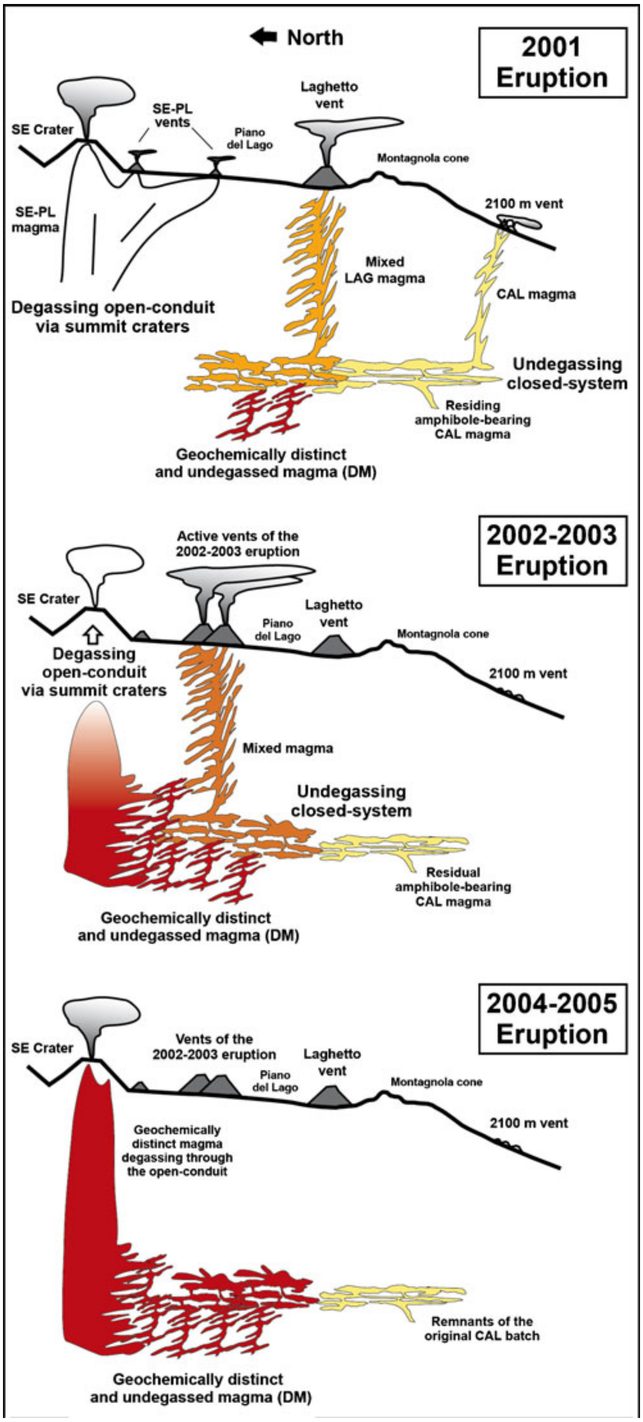

Fig. 5 Schematic representation of the 2001, 2002–2003 and 2004–2005 eruptions. During the first event, three magmas were erupted: (1) the amphibole-bearing CAL magma at the 2,100 m vent, coming from an undegassing closed system; (2) the amphibole-bearing LAG magma from the Laghetto vent, which resulted from the mixing between CAL and DM that intersected the undegassing closed system; (3) the amphibole-free magma from the South East crater and Piano del Lago vents (*SE–PL* vents), connected with the degassing open-conduit system. During the 2002–2003 eruption, a magma that resulted from the mixing between the CAL and a higher proportion of the DM than in 2001 was erupted from two vents located in the Piano del Lago area, unconnected with the open-conduit system. During the late stages of the 2002–2003 event, the DM entered into the open-conduit and started to degas from the summit craters. During the 2004–2005 event, the DM was erupted through fractures connected with the open-conduit system from the base of the South East crater and from vents located in the Valle del Bove (not on plane of the schematic representation)

into the steady-state degassing and acquired in turn the textural features typical of the magmas erupted by the open-conduit system. The recharging phase of the DM into the open-conduit system lasted from June 2003 to August 2004 (cf. Patanè et al. 2005) and was accompanied by quiet degassing from the summit vents. As a consequence, the wholly effusive 2004–2005 eruption, which occurred through fracture systems connected with the SE Crater, emitted degassed lavas for 6 months (Fig. 5).

Conclusions

The systematic sampling and analysis of the products emitted during the period 2001–2005 has revealed the progressive ingress within the uppermost segment of the plumbing system of a volatile-rich magma, geochemically distinct from the products previously erupted by the Etnean volcano. For the first time on Mount Etna, it was recognized that deeply rooted fresh magma fed the eruptive activity through fractures whose opening migrated, in a given period, from the periphery of the volcano to the area of summit craters, with a pattern of migration of the eruptive vents opposite to that observed in the past activity. The erupted rocks record gradual changes in their geochemical signature, but even more significant are the diverse eruptive behaviors that characterized the emission of this new magma. In the first phase, the interaction with magmas residing in shallow reservoirs supplied the activity with large amount of volatiles leading to strong explosive activity, in particular during the 2001 and 2002–2003 eruptions. With time, the new magma reached the axis of the open-conduit where it was involved in the steady-state degassing through the summit craters, which led to the prevailingly effusive eruption of the 2004–2005. Moreover, this work outlines the chief role of the feeding system in controlling the eruptive behaviour (mainly explosive or effusive) more than the compositional character of the emitted products. The activity, in the years following the studied period up to the present, is the result of the new arrangement of the sub-volcanic fracture system, which has produced a new vent (South East Crater 2) located at the base of the South East Crater. This structure has been the site of explosive activity during the last years and can be considered as the new main site of the persistent activity at

Mt. Etna. The model of magma supply, proposed here for the period 2001–2005, could be applied to understanding past eruptive cycles at Mt. Etna which were characterized by strong explosive events followed by long periods of exclusively effusive activity, or to other persistently active basaltic volcanoes characterized by alternating styles of eruptions similar to those of Mt. Etna.

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