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Assessing the link between mantle source and sub-volcanic plumbing in the petrology of basalts from the 2001 and 2002/2003 eruptions of Mount Etna, Sicily: Evidence from geochemical and helium isotope data

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ABSTRACT

The 2001 and 2002–2003 flank eruptions of Mt. Etna consisted of near continuous explosive activity and sporadic lava flows. Previous studies have suggested that distinct magmas were simultaneously tapped by fissures in different parts of the volcano, indicating a complex plumbing system. From textural and chemical data it has been suggested that "eccentric" eruptions on the south flank were fed by a deep-seated reservoir that is not related to the central conduit. In contrast, materials erupted above 2600 m and from the northeast flank represent partially degassed, more fractionated magma, typical of that residing within the central vents. A concern is that Etna has entered a new phase of activity, with magma supply from a deep reservoir that is capable of generating recurrent flank eruptions posing significant hazard to populated areas and air travel. We have investigated materials that erupted from different vents during both the 2001 and 2002/3 eruptive episodes by means of petrology, whole-rock chemistry and helium isotopic methods. Here we show from trace element chemistry and the $^{3}He/^{4}He$ isotope record of melt inclusions in olivine that the mantle source for both magma batches is identical. Furthermore, this magmatic source has not changed over the past 0.5 Ma. As such, our data support the premise that the petrological variability exhibited by products that erupted from different parts of the volcano reflects storage, fractionation and degassing at different levels within the crust.

1. Introduction and rationale

Mount Etna is a large stratovolcano located on the Island of Sicily, southern Italy. It has one of the world's longest documented records of historical volcanism, dating back to ~1500 BC (Romano and Sturiale, 1982). It continues to be Europe's most active, with ash eruptions from craters both at the summit and southeast flank of the volcano having occurred as recently as August of 2010 (Istituto Nazionale di Geofisica e Vulcanologia, 2010). The combination of accessibility and near-continuous activity means that Etna provides an excellent natural laboratory to investigate a dynamic magma system (Stirling et al., 1999).

Significant eruptions occurred during 2001 and 2002–2003 that have been shown to tap different levels within the magmatic plumbing system (Clocchiatti et al., 2004; Corsaro et al., 2007). The 2002/3 flank eruption consisted of near continuous explosive activity and intermittent lava eruption (Fig. 1). During a three-month period, eruptive fissures opened on both the northeast and southern flanks of the volcano (see Fig. 1b). In contrast, the fissures that supplied pyroclasts and lava during the 2001 eruption were mainly confined to the southern flank and close to the summit craters (Behncke and Neri, 2003; Lanzafame et al., 2003) (Fig. 1a). A study of these erupted materials, therefore, provides insight into the source and sub-volcanic plumbing for these eruptions and, importantly, can help identify any commonality between products that erupted in close space and time. This data can also facilitate comparison to older episodes of activity and hence the temporal evolution of magmatism at Mt. Etna. As such, this paper presents the results of a study of new geochemical and helium isotopic data from representative samples from the 2001 and 2002/3 eruptive periods to constrain the mantle source(s) and evolution of these eruptions, and investigate the processes related to the transport and storage of the magma batches within the Etna edifice.

2. 2001 and 2002–2003 eruptions of Mount Etna

The 2001 and 2002/3 eruptions were highly explosive and erupted materials concurrently at several sites on the volcano. The 2001 eruption lasted three weeks and took place from seven eruptive fissures (Lanzafame et al., 2003; Neri et al., 2005) on the southern flank, and a minor fissure close to the summit craters on the northeastern side of the volcano (Figs. 1a, 2a–b). The 2002/3 eruption saw fissures opened on

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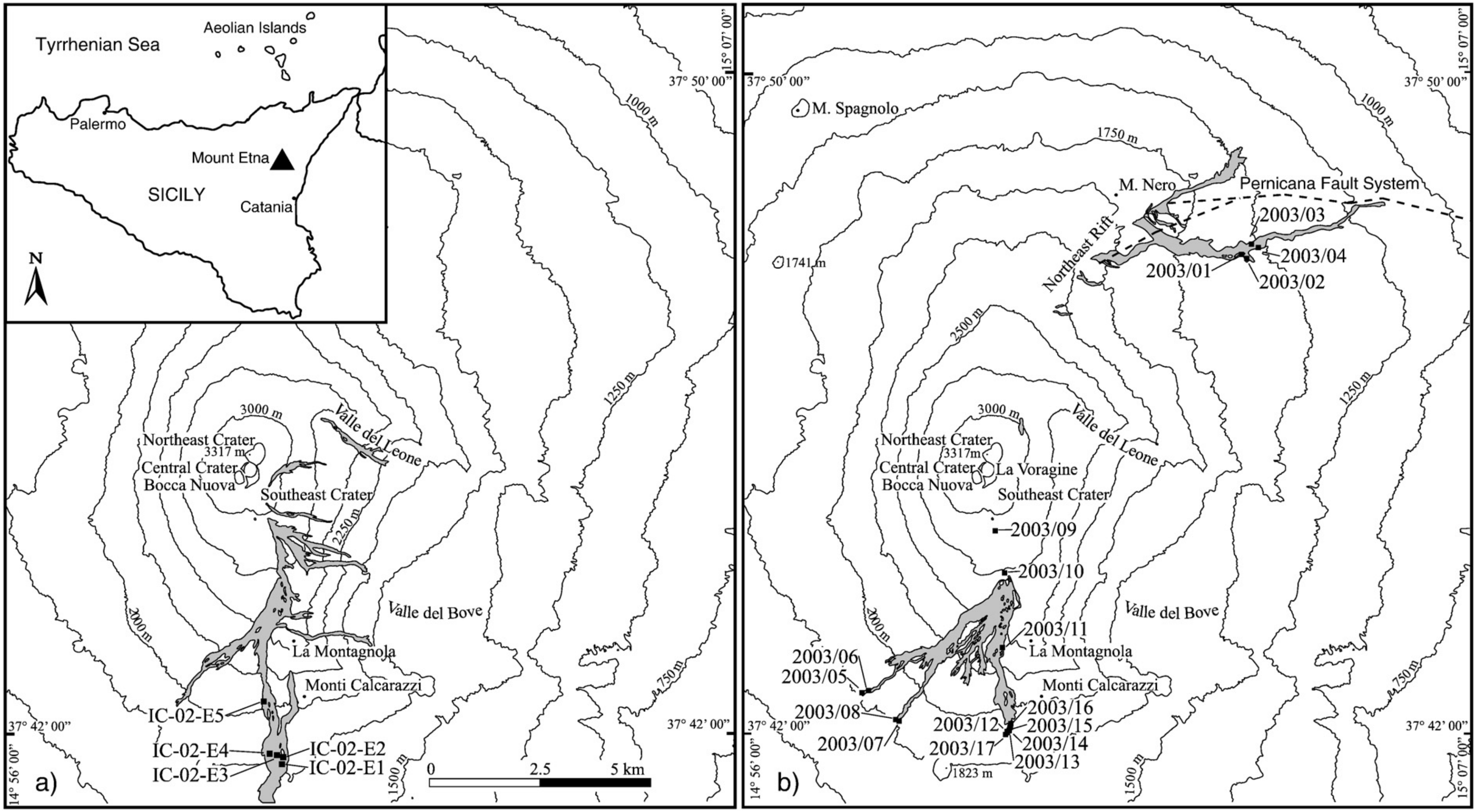

Fig. 1. a) Simplified map of eruptive and non-eruptive fissures, vents and lava flows (grey shading) of the July–August 2001 eruption of Mt. Etna; b) simplified map of the flows and vents related to the October 2002–January 2003 eruption of Mt. Etna. 2001 lava flows were omitted for clarity. Sample locations are indicated with a filled square. Inset map shows the location of Mt. Etna volcano and the nearby Aeolian Islands volcanic-arc (figures redrawn after Andronico et al., 2005; Behncke and Neri, 2003; Neri et al., 2005).

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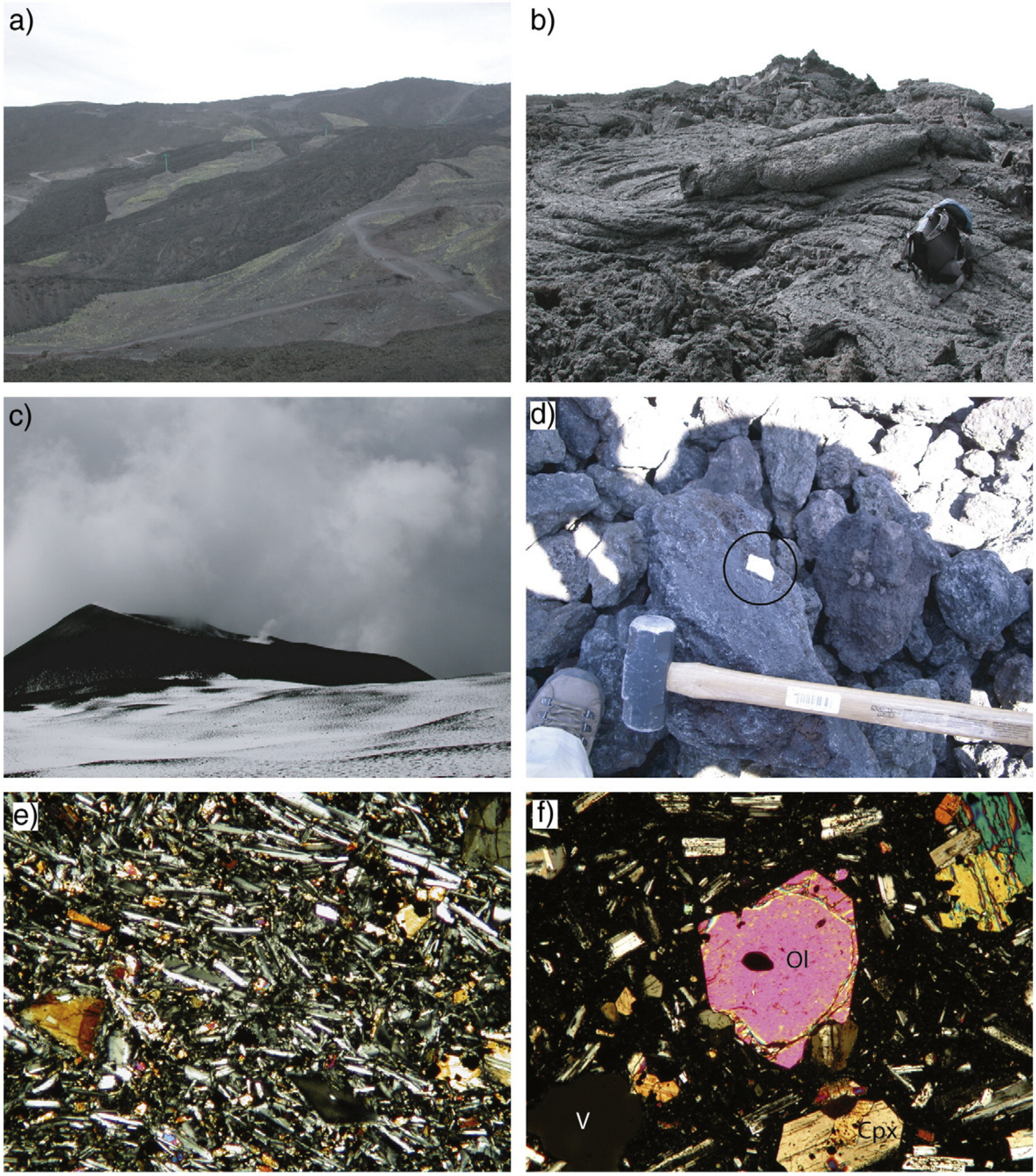

Fig. 2. Field shots: a) view of the 2001 trachybasalt flows on the S flank of Mt. Etna, close to Rifugio Sapienza, that destroyed the cable car system; b) Pahoehoe flow tops present on some of the S flank upper level trachybasalt flows from the 2001 eruption; c) view of one of the two pyroclastic cones constructed during the 2002/3 eruptions on the S flank; d) blocky trachybasalt flow top from the 2002/3 eruption on the NE flank of Etna. As with the erupted material from the S flanks, sedimentary xenoliths (circled) are clearly evident in some blocks. Photomicrographs (under cross-polarised light): e) and f) highlight some variations in textures and mineralogy of trachybasalt erupted from Etna during 2001 and 2002/3. Field of view in each is 2.5 mm. Key: Ol — olivine; Cpx — clinopyroxene; and dark areas in (f) are volcanic glass and vesicles (V).

both the northeast and southern flanks of the volcano, following a brief period of lava fountaining at the summit. This coincided with the opening of a large fissure on the northeast rift (Fig. 1b) related to slippage along the Pernicana Fault system (Neri et al., 2005). On the southern side of the volcano, explosive eruptions occurred from a fissure and led to the growth of two pyroclastic cones (Fig. 2c).

A significant and notable feature of the 2001 and 2002/3 flank activity is the simultaneous eruption of lavas with different composition and emplacement features (Andronico et al., 2005; Clocchiatti et al., 2004; Corsaro et al., 2007; Viccaro et al., 2006). Magma erupted from the northeast flank, and vents above 2600 m on the southern flank for the 2001 eruption, represent partially-degassed and more fractionated (strongly plagioclase-phyric) magma that is typical of magma residing within the central conduits (Clocchiatti et al., 2004; Ferlito et al., 2008). In contrast, the magma that erupted from the southern flank in both eruptions is relatively undegassed, volatile-rich and more buoyant, and it has been suggested that it originates from a deeper source (Andronico et al., 2005; Corsaro et al., 2007). This latter type of magma eruption has been ascribed as "eccentric" (Rittmann, 1965) and based on petrological features and U-series isotopic disequilibria, it is shown to have ascended rapidly within the volcano prior to eruption, possibly in only a few months (Clocchiatti et al., 2004). This has raised concern that Mt. Etna has entered a new and potentially more dangerous phase of eruptive activity, with magma supply from a deep reservoir that is independent of the central conduit, and potentially capable of generating recurrent flank eruptions that pose a significant hazard to populated areas and air travel (Andronico et al., 2005; Behncke and Neri, 2003).

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Table 1
Whole rock geochemical data for representative basalt and tephra samples of Etna's 2001 and 2002/3 eruptions.

Sample #	IC-02-E1	IC-02-E5	2003/01	2003/02	2003/03	2003/04	2003/05	2003/07	2003/09	2003/10	2003/11	2003/12	2003/14	2003/15	2003/16	2003/17	1σ st. dev.
Eruption	2001 S	2001 S	2002/3 N	2002/3 N	2002/3 N	2002/3 N	2002/3 S	2002/3 S	2002/3 S	2002/3 S	2002/3 S	2002/3 S	2002/3 S	2002/3 S	2002/3 S	2002/3 S	
SiO_2 (wt.%)	47.94	47.82	48.65	48.40	48.15	48.21	47.83	47.85	47.48	47.83	48.45	47.86	48.29	47.70	47.74	47.71	0.728
Al_2O_3	15.97	15.85	17.09	17.06	16.93	16.82	15.99	16.19	15.58	15.50	16.55	16.18	16.32	16.21	16.20	16.17	0.382
Fe_2O_3	6.06	6.39	7.37	8.33	7.78	7.63	8.17	7.42	7.11	7.16	7.14	9.23	6.97	6.46	6.11	8.83	0.085
FeO	4.83	4.59	3.34	2.64	2.97	3.18	2.84	3.51	3.70	3.82	3.49	1.69	3.88	4.12	4.47	2.17	0.057
MnO	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.17	0.18	0.17	0.17	0.18	0.17	0.17	0.18	0.003
MgO	6.55	6.54	5.20	5.34	5.28	5.45	6.30	6.19	6.62	7.05	5.69	6.08	6.25	5.90	6.02	6.16	0.021
CaO	10.83	10.85	9.91	10.03	9.90	9.96	10.54	10.43	10.73	10.96	10.20	10.42	10.57	10.28	10.43	10.53	0.099
Na_2O	3.39	3.38	3.98	3.82	3.84	3.86	3.37	3.39	3.23	3.10	3.54	3.39	3.43	3.41	3.42	3.44	0.007
K_2O	1.86	1.98	2.22	2.07	2.12	2.06	1.93	1.97	1.93	1.82	2.08	2.00	2.09	1.97	1.98	1.94	0.028
TiO_2	1.64	1.67	1.67	1.69	1.66	1.66	1.66	1.67	1.66	1.68	1.68	1.66	1.68	1.67	1.67	1.67	0.005
P_2O_5	0.53	0.52	0.60	0.57	0.57	0.58	0.52	0.53	0.51	0.48	0.54	0.51	0.52	0.52	0.51	0.52	0.014
L.O.I.	0.18	0.16	0.14	0.03	0.04	0.09	−0.05	0.04	0.21	0.20	0.05	−0.14	0.11	0.17	0.22	0.02	
Total	99.94	99.93	100.34	100.16	99.40	99.67	99.27	99.35	98.93	99.76	99.59	99.04	100.29	98.57	98.95	99.33	
Sc (in ppm)	32	33	24	26	24	25	31	29	33	37	28	30	33	31	31	30	
V	253	262	293	300	287	290	298	303	280	276	270	268	268	263	266	259	
Cr	41	41	21	22	21	21	46	38	53	59	37	42	42	39	41	41	
Co	37	38	37	38	37	38	41	42	40	41	36	37	37	37	37	37	
Ni	30	30	25	27	24	23	36	34	33	40	26	29	31	27	27	30	
Rb	43	45	51	49	47	47	46	47	45	41	47	46	47	46	46	45	
Sr	1,110	1150	1240	1220	1170	1180	1010	1140	1070	1040	1150	1110	1130	1120	1140	1120	
Y	25.2	25.7	27.9	26.9	26.0	26.5	25.1	25.9	25.0	24.3	25.5	25.0	25.4	25.5	25.7	24.8	
Zr	181	188	190	202	203	203	193	192	182	176	194	186	191	191	191	187	
Nb	36.8	41.6	39.6	42.3	43.3	46.0	41.0	43.0	33.9	33.8	39.4	38.6	40.4	41.4	41.8	41.7	
Cs	0.9	0.9	1.3	1.2	1.1	1.0	1.0	1.0	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.9	
Ba	621	635	736	695	690	703	594	608	596	581	657	631	638	627	634	624	
La	47.8	47.3	61.7	60.4	59.2	59.4	51.4	52.5	48.4	46.7	53.0	50.9	49.2	50.3	49.5	49.7	
Ce	97.6	95.0	122	118	117	115	104	105	98.2	94.5	107	103	100.3	101	99.5	101	
Pr	10.9	10.7	12.9	12.7	12.3	12.5	11.3	11.3	10.7	10.4	11.6	11.1	11.0	11.1	10.9	11.0	
Nd	43.8	43.0	51.4	50.0	49.9	48.9	45.3	46.2	43.7	42.3	46.2	44.8	43.9	44.8	44.2	43.9	
Sm	8.56	8.45	9.73	9.38	9.11	9.42	8.86	8.88	8.54	8.43	8.84	8.68	8.54	8.63	8.49	8.52	
Eu	2.54	2.54	2.85	2.77	2.69	2.73	2.61	2.61	2.55	2.51	2.64	2.59	2.56	2.66	2.59	2.58	
Gd	7.41	7.42	8.56	8.24	8.02	7.90	7.58	7.66	7.64	7.44	7.73	7.67	7.50	7.74	7.55	7.60	
Tb	1.03	1.05	1.13	1.10	1.07	1.07	1.04	1.06	1.05	1.02	1.06	1.04	1.02	1.05	1.04	1.04	
Dy	5.24	5.27	5.67	5.45	5.30	5.47	5.25	5.22	5.24	5.09	5.28	5.23	5.23	5.33	5.21	5.26	
Ho	0.89	0.90	0.97	0.94	0.92	0.91	0.90	0.89	0.91	0.87	0.90	0.89	0.90	0.91	0.89	0.90	
Er	2.31	2.34	2.57	2.49	2.40	2.47	2.35	2.37	2.35	2.27	2.43	2.37	2.37	2.40	2.38	2.33	
Tm	0.337	0.340	0.374	0.358	0.354	0.346	0.346	0.335	0.336	0.327	0.339	0.347	0.333	0.347	0.344	0.353	
Yb	2.12	2.08	2.29	2.22	2.19	2.16	2.15	2.16	2.05	2.04	2.09	2.07	2.07	2.15	2.10	2.10	
Lu	0.305	0.298	0.329	0.317	0.310	0.300	0.299	0.301	0.299	0.290	0.302	0.303	0.298	0.302	0.301	0.300	

Note: L.O.I. loss on ignition; analytical uncertainty for major elements is based on duplicate measurements on samples and known standard rock powders.

Table 2
Helium isotope data for phenocrysts from basalt and tephra samples from the 2001 and 2002/3 eruptions of Mt. Etna.

Sample	Location	Grid reference (WGS 84)	Mineral	$^3He/^4He$ (R/R_a)	^4He (10^{-9} cc STP g^{-1})	$^4He/^{20}Ne^*$
2001						
IC-02-E1	South	N37 41.7405 E015 00.5141	Pyroxene	4.29 ± 0.21	4.6 ± 0.09	0.7 ± 0.1
IC-02-E1	South	N37 41.7405 E015 00.5141	Olivine	6.73 ± 0.18	16.7 ± 0.31	248 ± 12
IC-02-E5	South	N37 42.3195 E014 59.7944	Pyroxene	3.33 ± 1.17	2.0 ± 0.04	0.5 ± 0.1
IC-02-E5	South	N37 42.3195 E014 59.7944	Olivine	6.52 ± 0.18	26.4 ± 0.49	416 ± 21
2002/03						
2003/01	Northeast	N37 47.6882 E015 03.7112	Pyroxene	6.07 ± 0.22	4.2 ± 0.09	35 ± 1.7
2003/01	Northeast	N37 47.6882 E015 03.7112	Olivine	6.66 ± 0.08	14.6 ± 0.27	9.5 ± 0.5
2003/02	Northeast	N37 47.6637 E015 03.7196	Olivine	6.71 ± 0.24	16.2 ± 0.32	1255 ± 63
2003/03	Northeast	N37 47.8636 E015 03.8496	Olivine	6.49 ± 0.15	11.8 ± 0.22	271 ± 14
2003/04	Northeast	N37 47.8408 E015 03.9739	Olivine	6.35 ± 0.28	14.7 ± 0.20	24 ± 1.2
2003/05	South	N37 42.3935 E014 57.8053	Pyroxene	5.56 ± 0.49	2.2 ± 0.04	1.8 ± 0.1
2003/05	South	N37 42.3935 E014 57.8053	Olivine	6.64 ± 0.19	19.2 ± 0.36	151 ± 8
2003/07	South	N37 42.0681 E014 58.3225	Olivine	6.69 ± 0.09	14.0 ± 0.26	291 ± 15
2003/09	South	N37 44.4747 E014 59.8974	Olivine	6.23 ± 0.67	3.0 ± 0.06	695 ± 35
2003/10	South	N37 43.9256 E015 00.2032	Olivine	6.64 ± 0.10	28.9 ± 0.54	683 ± 34
2003/11	South	N37 43.0965 E015 00.0027	Olivine	6.52 ± 0.0.35	8.9 ± 0.19	999 ± 50
2003/12	South	N37 42.0166 E014 59.9921	Olivine	6.83 ± 0.28	18.0 ± 0.15	542 ± 27
2003/14	South	N37 42.0240 E015 00.0233	Olivine	6.73 ± 0.05	27.6 ± 0.52	156 ± 8
2003/15	South	N37 42.0659 E015 00.0378	Olivine	6.12 ± 0.28	4.0 ± 0.08	96 ± 5
2003/16	South	N37 42.0939 E015 00.0471	Olivine	6.19 ± 0.32	8.0 ± 0.16	98 ± 5
2003/17	South	N37 41.9625 E015 00.0757	Olivine	6.36 ± 0.23	6.9 ± 0.13	97 ± 5

Measured $^3He/^4He$ are normalised to the atmospheric ratio ($R_a = 1.39 \times 10^{-6}$) and corrected for blanks. ^4He blanks averaged 4×10^{-11} cc STP g^{-1} and ^3He blanks (5×10^{-15} cc STP g^{-1}) were always less than 5% of the measured ^3He. ^{20}Ne blanks were < 5% of the measured values. Samples IC-02-E1 and IC-02-E4, 2003/05 and 2003/06, 2003/07 and 2003/08, and 2003/13 and 2003/14 were collected in immediate proximity of each other, and mineral separates were combined for isotopic analysis.

3. Experimental methods

Geochemical and isotopic analyses were completed on a suite of representative materials from the 2001 and 2002/3 eruptions of Mt. Etna (Tables 1, 2). Samples were collected shortly after the cessation of the eruptions at locations shown in Fig. 1a–b (see also Table 2). In total, 21 samples were analysed for the whole-rock major, trace and rare earth elements (REE). Helium isotopes were determined in olivine and pyroxene phenocrysts from a subset of these basalts. Sample preparation followed the standard procedures described by Coulson et al. (2002). The analytical precision (quoted in Table 1) was estimated by preparing and analysing several samples and certified standard rock powders in duplicate. The whole-rock analyses were determined by X-ray fluorescence spectrometry at Activation Laboratories in Ancaster, Ontario. A lithium metaborate/tetraborate fusion method was used for major elements, and trace elements were analysed using inductively coupled plasma mass spectrometry.

Helium isotope abundances and isotopic compositions, along with the $^4He/^{20}Ne$ ratios, were measured and determined on pure mineral separates picked under a binocular microscope. The separated olivine and pyroxene grains were ultrasonically cleaned in 5% HNO_3, and then rinsed in distilled water and acetone. Magmatic volatiles were extracted by *in vacuo* crushing of approximately 1 g of mineral. Gas clean-up and helium isotope analysis procedures have been reported previously (Stuart et al., 2000, 2003). Measured $^3He/^4He$ (Table 2) are normalised to the atmospheric ratio ($R_a = 1.39 \times 10^{-6}$) and corrected for blanks. Blank levels never exceeded 5% of the measured ^4He or ^3He. ^{20}Ne blank levels are < 5% of the measured value.

4. Results

4.1. Basalt petrology

The powerful, and at times explosive, eruptions of Mt. Etna volcano in 2001 and 2002/3 resulted in the emplacement of numerous, porphyritic trachybasalt lava flows and abundant tephra in the form of scoriaceous blocks, bombs, lapilli, and ash (Fig. 2a–d; Ferlito et al., 2008). Lava textures are predominantly seriate-porphyritic, with clinopyroxene (diopside), plagioclase, olivine and titano-magnetite as phenocrysts in a fine-grained, often glassy, groundmass (Fig. 2e–f; MacLean, 2006).

The petrological study of the products that erupted during 2001 and 2002/3 reveals specific characteristic features. For example, the trachybasalts that erupted from the NE vent in 2002/3 share similarities with lavas that erupted in previous decades from the summit craters (e.g., Clocchiatti et al., 2004; Stirling et al., 1999). These include being strongly porphyritic (plagioclase, clinopyroxene, olivine, and Fe/Ti-oxide) and the compositions that are relatively K_2O-rich with MgO contents of 5–5.5% (Table 1, Fig. 3a,b). This contrasts with the materials that erupted from the southern flank of Etna in both 2001 and 2002/3, that are atypical in the recent history of Etna (Michaud, 1995). These "eccentric" flank eruptions (Rittmann, 1965) have a more mafic mineralogy and composition (e.g., MgO contents of >6%, Fig. 3a,b), are highly vesicular, contain rare occurrences of amphibole and remnant orthopyroxene, and abundant country-rock xenoliths (Fig. 2d–f, Behncke and Neri, 2003; Clocchiatti et al., 2004; MacLean, 2006). As such, these are some of the most primitive magmas that erupted over the past few hundred years from Mt. Etna.

The petrology and textural evidence show that the N and S flank basalts are distinct, and it has been suggested that the S basalts originated at greater depths within the feeder system than the magma that erupted from the summit vents and 2002/3 NE rift zone (Andronico et al., 2005; Corsaro et al., 2007). However, it is also possible that the petrological dissimilarity reflects evolutionary differences related to the transport and storage of similar magmas within the volcano. For example, the greater phenocryst content and lack of evident xenoliths in the N flank basalts might indicate protracted storage, fractionation and more effective mixing with a crustal-contaminant while this magma degassed. In an attempt to further elucidate the origin and evolution of the Etna magma(s), we turn to the evidence from the whole-rock chemistry and data from the helium isotope compositions of olivine and pyroxene phenocrysts.

4.2. Basalt chemistry

The major and trace element composition of representative materials are plotted in Fig. 3 to illustrate the main compositional

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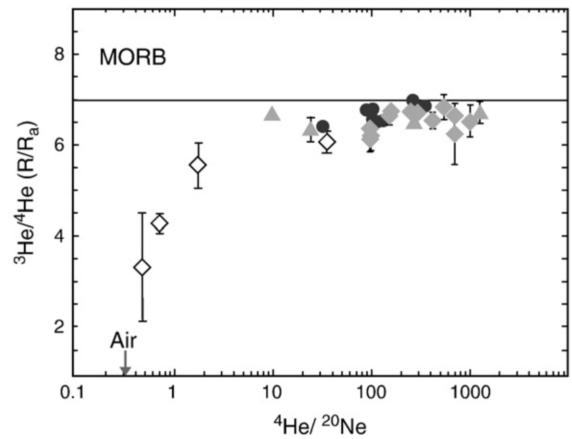

Fig. 4. Plot of olivine $^3He/^4He$ versus $^4He/^{20}Ne$ for 2001 and 2002/3 eruptions of Mt. Etna samples. Key: filled grey diamonds — southern flank samples; filled grey triangles — 2002/3 NE flank. For comparison, are plotted helium ratios for pyroxene separates from the S flank (open diamonds) and helium isotopic data for olivine in Mt. Etna 2001–2005 eruptive products from the study of Nuccio et al. (2008) (filled circles). Air is also shown ($^3He/^4He = 1$, $^4He/^{20}Ne = 0.31$).

characteristics of the 2001 and 2002/3 eruptions and highlight the differences between the N and S flank volcanic products. The "eccentric" S flank samples from both eruptions have higher MgO and lower total alkali contents, and exhibit less extreme enrichment in incompatible elements than the 2002/3 N flank basalts, suggesting they are slightly less differentiated, and is consistent with the earlier studies of Andronico et al. (2005) and Clocchiatti et al. (2004). This observation is further supported by our new trace element data. For example, a plot of La/Yb versus Gd/Yb illustrates that La/Yb ratios for the N flank samples are distinctly higher than the S flank basalts despite having indistinguishable Gd/Yb (Fig. 3d). The elevated La/Yb ratios (>22 for all Etna basalts analysed in this study) are comparable to those from an enriched mantle source and/or suggest that their parental magmas were in equilibrium with garnet at their mantle source or at lower crustal levels (cf. Parada et al., 2007). An alternative explanation is that this reflects contamination with the upper crust (Condie, 1997 and references therein). Perhaps, therefore, the elevated La/Yb ratios for the N flank samples reflect more efficient contamination with the upper crust; a feature that is consistent with the petrology of these basalt samples. As outlined above, the products erupted in 2002/3 along the NE rift zone of Mt. Etna display similar petrological and chemical characteristics to the materials that erupted from the summit craters over the period 1995–2001 (see Fig. 3a).

While the chemical differences outlined above have provided some constraints relating to the storage, transport and evolutionary processes affecting the Etna magmas, they do not readily distinguish between a deep and shallow magma source. To test the hypothesis that the N and S flanks were fed by independent magmas that have tapped different levels within the Etna edifice, as has been suggested by other workers, we utilise the data from the helium isotopes.

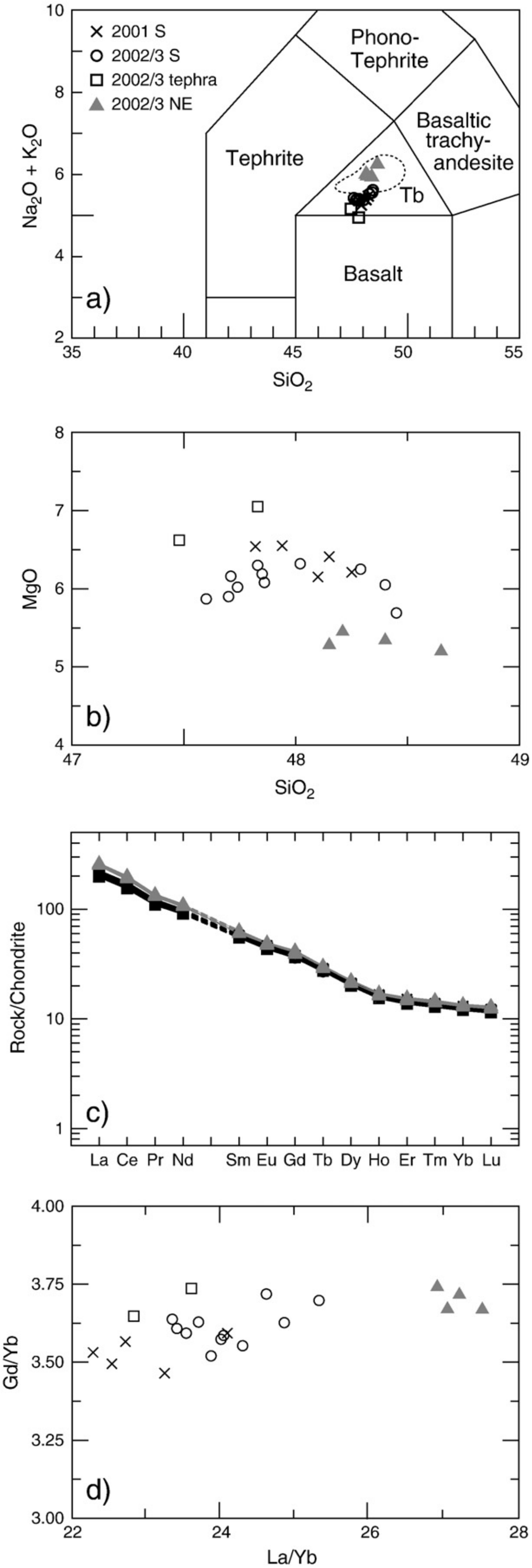

Fig. 3. Plots of: a) total alkali versus SiO_2; b) MgO versus SiO_2, c) chondrite normalised rare earth element (REE) patterns, and d) plot of La/Yb versus Gd/Yb, for representative samples from the 2001 S and 2002/3 S and NE flank eruptions of Mt. Etna. Note that in (a) Tb is the field for trachybasalt (Le Bas et al., 1986) in which all lava and one of the tephra samples reside. The dashed line represents the field for materials erupted from the summit craters and upper vents of Etna during the period 1995–2001 for comparison (data derive from Andronico et al., 2005; Corsaro and Pompilio, 2004; Corsaro et al., 2007). While all investigated samples have near identical, parallel trends, highlighting strong light-REE enrichment (c), those from the 2002/3 NE eruptions show the most evolved patterns of all the Etna samples in terms of La/Yb versus Gd/Yb (d). Key: black crosses — 2001 S; open circles — 2002/3 S; open squares — 2002/3 S tephra; and filled grey triangles — 2002/3 NE. Whole rock compositional data derive from MacLean (2006). Normalisation factors are from Nakamura (1974).

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4.3. Helium isotopes

Helium isotopes are widely used to distinguish between mantle sources. The asthenospheric mantle sampled by mid-ocean ridge basalt (e.g., Graham et al., 1998) and continental lithosphere (e.g., Graham et al., 2009), are characterised by a rather narrow range of ^{3}He/^{4}He (R/R_a = 6–9, where R_a is the atmospheric ratio (1.39×10^{-6})). Basalt erupted by mantle plumes that sample deep asthenosphere, typically ocean island basalt and continental flood basalt provinces, are characterised by high ^{3}He/^{4}He that may reach up to 50 R_a (Ellam and Stuart, 2000; Stuart et al., 2003). A high ^{3}He/^{4}He signal would be expected if the mantle plume contribution proposed by Condomines et al. (1982) and Tanguy et al. (1997), on the basis of the general dome-shaped basement and the compositions of erupted products, were to make up a significant proportion of the sub-Etna mantle. Extensive studies of the Italian arc basalts demonstrate that modification of the overlying mantle wedge by subduction-derived fluids has lowered ^{3}He/^{4}He ratios (Martelli et al., 2004, 2008).

The ^{3}He/^{4}He ratios of trachybasalts from the 2001 and 2002/3 eruptions are reported in Table 2 and displayed in Fig. 4. Olivine ^{3}He/^{4}He range from 6.12 to 6.83 R_a, with a weighted mean value of 6.61 ± 0.15 R_a (n = 14). This is comparable to the mean value of older Etna basalts (6.7 ± 0.4 R_a) (Marty et al., 1994) and basalts that erupted during the period 2001–2005 (Nuccio et al., 2008). It similarly overlaps the range in peripheral gas emissions at the time of the 2001 and 2002–2003 eruptions (Rizzo et al., 2006) that are fed directly by magmatic degassing within the Etna edifice (Nuccio et al., 2008). Pyroxene ^{3}He/^{4}He (3.3–6.07 R_a, n = 4) are lower and more variable than the olivine data. The olivine and pyroxene data define a trend of increasing ^{3}He/^{4}He with ^{4}He/^{20}Ne (Fig. 4). These data overlap those of the olivine and pyroxene in a recent study of Etna eruptions from 2001 to 2005 by Nuccio et al. (2008) who similarly observed disequilibrium between pairs of co-genetic olivine and pyroxene. This data trend is consistent with the more effective retention of original magmatic helium in olivine, whereas pyroxene has a crystal structure that is more susceptible to helium diffusion and isotopic exchange (Martelli et al., 2004; Nuccio et al., 2008; Shaw et al., 2006). It has also been shown that slight changes to the ^{3}He/^{4}He isotope signature can occur due to volatile degassing. Consequently, we restrict the following discussion of the helium isotope data for olivine from both our study and those of Nuccio et al. (2008).

5. Discussion: source constraints for the eruptions

There are no obvious differences in the ^{3}He/^{4}He ratios of olivine from the N and S flank flows, or between the 2001 and 2002/3 S flank eruptions (Table 2, Fig. 4). ^{3}He/^{4}He ratios of olivine from the 2002/3 N flank (6.63 ± 0.17 R_a; n = 6) are indistinguishable within uncertainty from both the 2001 (6.74 ± 0.15 R_a; n = 4) and 2002/3 S flank (6.49 ± 0.23 R_a; n = 12) samples. These data are also identical to the published helium isotopic data for olivine in Mt. Etna basalts that erupted during the period 2001–2005 (see Fig. 4; Nuccio et al., 2008), and the last 0.5 Ma (Marty et al., 1994). The lack of variation in helium isotopic values, found in rocks that are petrographically and geochemically distinct, implies that the difference in depth of crystallisation, degree of degassing, ascent rate and magmatic differentiation does not correspond to significant variability in the mantle source as traced by inert volatile elements.

Moreover, the constancy of the olivine ^{3}He/^{4}He ratios over the last 0.5 Ma (Marty et al., 1994; Nuccio et al., 2008) and in the last decade, where eruptive activity has strongly increased (Corsaro et al., 2007), implies that the helium isotope composition of the mantle source of Mt. Etna over the last 0.5 million years has remained rather constant, despite major petrological changes and significant variation in the crustal xenolith load. In relation to this, in their recent study of the noble isotope chemistry of Etna basalts that erupted during the period 2001–2005, Nuccio et al. (2008) demonstrated a significant lowering of ^{3}He/^{4}He (by ~0.4 R_a) in 2004/5 eruption products. Nuccio et al. (2008) attributed the changes in helium abundance and isotope ratios to protracted degassing of the identical magma that fed the earlier 2001 S-flank eruptions, and residing within the volcano.

With respect to the characterisation of the source of magmas at Etna, the near constancy of the isotopic compositions are taken as evidence for a single magmatic source for magmas erupted from both the N and S flanks, and that the petrological differences instead relate to distinct evolutionary changes during storage within the volcano. Moreover, a rather uniform helium isotope composition for the Etna mantle source is significant based on observations made over the last 10,000 years of activity at Mt. Etna; i.e., that its mantle source is undergoing fluid-related contamination related to the subduction of Ionian plate (e.g., Schiano et al., 2001, 2004; Tonarini et al., 2001). If this is correct, it is clear that the effect of mantle-metasomatism on helium isotope signature is minimal (cf. Nuccio et al., 2008).

6. Conclusions

Mt. Etna, the most active volcano in Europe, displayed unusual characteristics during the 2001 and 2002/3 powerful eruptive episodes, which resulted in the simultaneous eruption of petrologically distinct magmas from different vents across the edifice. We have investigated the whole-rock composition and the ratios of the helium isotopes in inclusions entrapped within olivine and pyroxene in the materials that erupted during both episodes. Our data has shown that for the 2001 and the 2002/3 eruptions, regardless of vent location, the products are geochemically similar, and likely derive from a common-parent magma. This data also suggests that the petrological distinctions between basalts that erupted from the N and S flanks of Etna relates to the differences in the fractionation, degassing and storage processes within the volcano. At the same time, our data for the helium isotopes fall within a narrow isotopic range typical of volcanism at Mt. Etna (for olivine: 6.61 ± 0.15 R_a; n = 14). The He abundances and ^{3}He/^{4}He ratios in pyroxene are uniformly lower than those found in olivine within the same samples (Table 1, Fig. 4). As recognised by other workers, this can be attributed to a lower closure temperature in pyroxene that caused a higher loss of magmatic volatiles, coupled with more evident effects of air-contamination. Importantly, the helium isotope signature as recorded in olivine confirm that there is no variation in the mantle source for Etna's magmas and that a single mantle source is parental to its eruptive products, despite distinct petrological changes.

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