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REVIEW ARTICLE

Geological evolution of Mount Etna volcano (Italy) from earliest products until the first central volcanism (between 500 and 100 ka ago) inferred from geochronological and stratigraphic data

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Abstract We present an updated geological evolution of Mount Etna volcano based on new $^{40}Ar/^{39}Ar$ age determinations and stratigraphic data integrating the previous K/Ar ages. Volcanism began at about 500 ka ago through submarine eruptions on the Gela–Catania Foredeep basin. About 300 ka ago fissure-type eruptions occurred on the ancient alluvial plain of the Simeto River forming a lava plateau. From about 220 ka ago the eruptive activity was localised mainly along the Ionian coast where fissure-type eruptions built a shield volcano. Between 129 and 126 ka ago volcanism shifted westward toward the central portion of the present volcano (Val Calanna–Moscarello area). Furthermore, scattered effusive eruptions on the southern periphery of Etna edifice occurred until about 121 ka ago. The stabilization of the plumbing system on the Valle del Bove area is marked by the building of two small polygenic edifices, Tarderia and Rocche volcanoes. Their eruptive activity was rather coeval ending 106 and 102 ka ago, respectively. During the investigated time-span volcanism in Etna region was controlled by a main E–W extensional tectonic related to the reactivation of Malta Escarpment fault system in eastern Sicily.

Keywords Mount Etna · $^{40}Ar/^{39}Ar$ dating · Stratigraphy · Unconformity · Eruptive activity

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Introduction

Eruptive activity of Mount Etna volcano began during the middle Pleistocene in eastern Sicily in a complex geodynamic frame (Fig. 1). The basaltic volcanism of Etna developed on the structural domain of the Gela–Catania Foredeep on the front of the Apenninic–Maghrebian Chain that overlaps the undeformed African continental plate margin, the Hyblean Foreland (Lentini 1982; Ben Avraham and Grasso 1990). Although the earlier volcanism occurred during the final stage of the compressive deformation of the Apenninic–Maghrebian Chain (Bousquet and Lanzafame 2004 and reference therein) the eastern part of Sicily was affected by the extensional tectonic regime of the Malta Escarpment. This lithospheric fault system separates the continental crust of the Hyblean Foreland from the oceanic crust of the Ionian Basin (Scandone et al. 1981; Finetti 1982; Ben-Avraham and Grasso 1990; Hirn et al. 1997). The northern termination of the Malta Escarpment dissects the lower eastern flank of Etna volcano through a set of NNW–SSE normal faults called Timpe fault system (Lo Giudice et al. 1982; Bousquet and Lanzafame 2004), responsible for the active seismicity of the area (Azzaro 1999 and 2004).

Geological investigations performed by several authors (Rittmann 1973; Romano 1982; Chester et al. 1985; Kieffer and Tanguy 1993; Branca et al. 2004a) have furnished different reconstructions of the Etna volcano evolution (see Branca et al. 2004a for com-

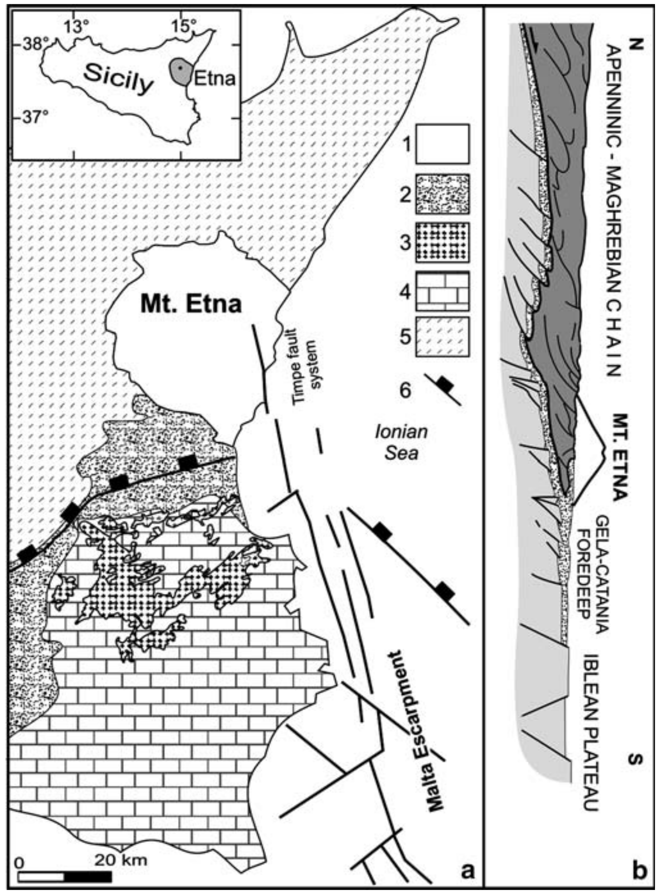


Fig. 1 Geological framework (**a**) and schematic N–S cross-section (**b**) of eastern Sicily (modified after Branca et al. 2004a). *1* Mount Etna volcano; *2* Gela–Catania Foredeep; *3* Late Miocene-early Pleistocene Hyblean volcanics; *4* Hyblean Plateau; *5* Apenninic–Maghrebian Chain; *6* Front of the Apenninic–Maghrebian Chain

parison). The recent geological mapping carried out on Etna's eastern flank for the new geological map of Italy allow revising the geological setting of the volcano using modern stratigraphic concepts (Branca et al. 2004b). Unconformity-bounded units, UBU (Salvador 1987 and 1994), was preliminary applied during the geological study of the Valle del Bove (VdB) area by Calvari et al. (1994) and Coltelli et al. (1994) and then adopted during the field mapping on Etna according to the guidelines suggested for the UBU by International Subcommission on Stratigraphic Classification (Salvador 1994) and by the Italian Geological Survey (Pasquarè et al. 1992).

After the first isotopic ages published by Condomines et al. (1982), a comprehensive scheme of the geochronological evolution of Etna volcano was proposed by Gillot et al. (1994) that temporally constrain the geological reconstruction defined by Romano (1982). Recently, Branca et al. (2004a) presented a revised reconstruction of the geological evolution of Etna volcano on the basis of new stratigraphic data. In particular, the authors defined four different eruptive phases chronologically constrained using the K/Ar age determinations published by Gillot et al. (1994) and Tric et al. (1994).

According to Branca et al. (2004a) the oldest phase, named Basal Tholeiitic (BT), corresponds to a long period of scattered fissure-type volcanism with tholeiitic affinity that began about 500 ka ago in a submarine environmental. During the second phase, named Timpe (TI), starting from about 220 ka ago the volcanism was mainly concentrated on the Ionian coast along the Timpe fault system and produced fissure-type eruptions with Na-alkaline affinity. About 120 ka a stabilization of the volcano feeder system occurred in the VdB area marking the beginning of the third phase, named Valle del Bove centres (VB), during which the earlier polygenic eruptive centres, Tarderia and Rocche volcanoes, formed. Afterward volcanism was mainly concentrated on the SW sector of the VdB with the growth of some nested volcanic centres: Trifoglietto, Giannicola, Salifizio and Cuvigghiuni volcanoes. In the fourth phase, named Stratovolcano (SV), about 60 ka the definitive stabilization of the plumbing system in the Etna region occurred and led to the construction of the large Ellittico volcano which forms the bulk of the present edifice. Ellittico activity ended about 15 ka after four caldera-forming Plinian eruptions (Coltelli et al. 2000). Finally, during the last 15 ka persistent volcanic activity formed the Mongibello volcano, whose products cover at least 85% of the present volcano surface.

Currently, De Beni et al. (2005) successfully applied the $^{40}Ar/^{39}Ar$ technique on Etna volcanics in order to improve the reconstruction of its geochronological evolution defining the temporal hiatus and the significance of one of the main unconformities of the volcanic succession.

In this paper we present new results based on $^{40}Ar/^{39}Ar$ age determinations and the stratigraphic data derived from 1:10,000 scale geological surveys of Etna, with the aim of defining the uncertain stratigraphic position of some volcanics and clarifying the meaning of the unconformities within the volcanic succession. The geological survey was performed in order to integrate the previous one of the eastern flank (Servizio Geologico d'Italia 2006) for the realization of the new 1:50,000 geological map of Mount Etna (Branca et al. 2004c). The whole data set, integrated with the already available isotopic age, allow us to better constrain chronologically the geological evolution of Etna volcano. In particular, we propose an updated reconstruction of the eruptive activity evolution in the Etnean region from the oldest products until the early stage of the central-type volcanism, defining the relationship between the volcano history and the geodynamics of eastern Sicily.

Geochronology

$^{40}Ar/^{39}Ar$ method and samples preparation

Seven samples were selected from stratigraphically well-defined units to constrain in age the stratigraphy of Etna volcano from the earliest products to about 100 ka ago. ACI sample has been collected from pillow lava that forms the cliff of Acicastello Castle Rock along the Ionian coast. TC sample belongs to a lava flow overlapping the sedimentary basement at Torre Casalotto locality, uphill from Acitrezza village. VS sample has been collected from a massive lava flow forming the top of the Mt. D'Oro morphological scarp, south of Valverde. Three samples (CA, FC and CS) where collected from the southern wall of the Val Calanna at Mt. Fior di Cosimo. Finally, TD sample belongs to a lava flow cropping out at Contrada Passo Cannelli locality, north of Tarderia.

From the methodological point of view we analyzed groundmass particles in the grain size fractions ranging between 250 and 500 μm that may contain phenocryst intergrowths. Each sample was prepared using liquid density and magnetic separation and then handpicked at microscope in order to obtain homogeneous groundmass separates. Samples were then wrapped in Al foil and loaded into a quartz tube together with standards for irradiation (duration: 1 h) with fast neutrons in the Cd-lined RODEO facility of the EU/Petten HFR reactor (The Netherlands). After irradiation ca 20 mg of each sample was spread out evenly in a 13 mm diameter sample holder pan (5 positions on a 60 mm copper tray). The sample tray was loaded in a custom made sample house, and heated overnight at 150°C with a 500 W heating lamp. To extract argon from prepared fractions, a defocused CW argon-ion laser beam (beam diameter ca. 2 mm) was used. The sample house was moved during laser-heating following an x–y raster pattern that ensured even heating of the sample during stepwise heating.

The main features of argon laserprobe extraction line include a low volume vacuum extraction/purification, short heating and clean up times (typically between 5 and 15 min), and no differences in ''cold'' and ''hot'' line blanks. The standard used to calculate the irradiation constant J is DRA1 sanidine with an age of 25.26 ± 0.05 Ma. (Wijbrans et al. 1995). For each groundmass sample we used an incremental heating technique with eight steps for ACI, TC, TD and VS samples, whereas CA, FC and CS samples were analysed in nine steps. The choice of the step number is very important to obtain a homogenous plateau, the laser intensity was increased between 0.3 W and 14 W (total fusion). The purified gas fractions were analyzed with a MAP 215-50 mass spectrometer (Wijbrans et al. 1995). Dedicated data reduction software (ArArCALC of Koppers 2002) provides an easy-to-use graphical interface for the calculation of age plateaus, total fusion ages and isochrons following the regression of $^{40}Ar/^{39}Ar$ mass spectrometry data.

Analytical results

The analytical results of analysed samples are summarized in Table 1 and Fig. 2. All experiments yielded excellent plateaus in agreement with the commonly accepted standards (e.g. Dunai and Wijbrans 2000; De Beni et al. 2005).

ACI sample

This rock was quite weathered, for this reason the weighted plateau age is calculated using only the last four steps of incremental heating, and the uncertain margin is 8.75%. The K/Ca diagram shows a regular pattern of continuously decreasing ratios from 0.158 at the first step to 0.016 at the fusion. This behaviour

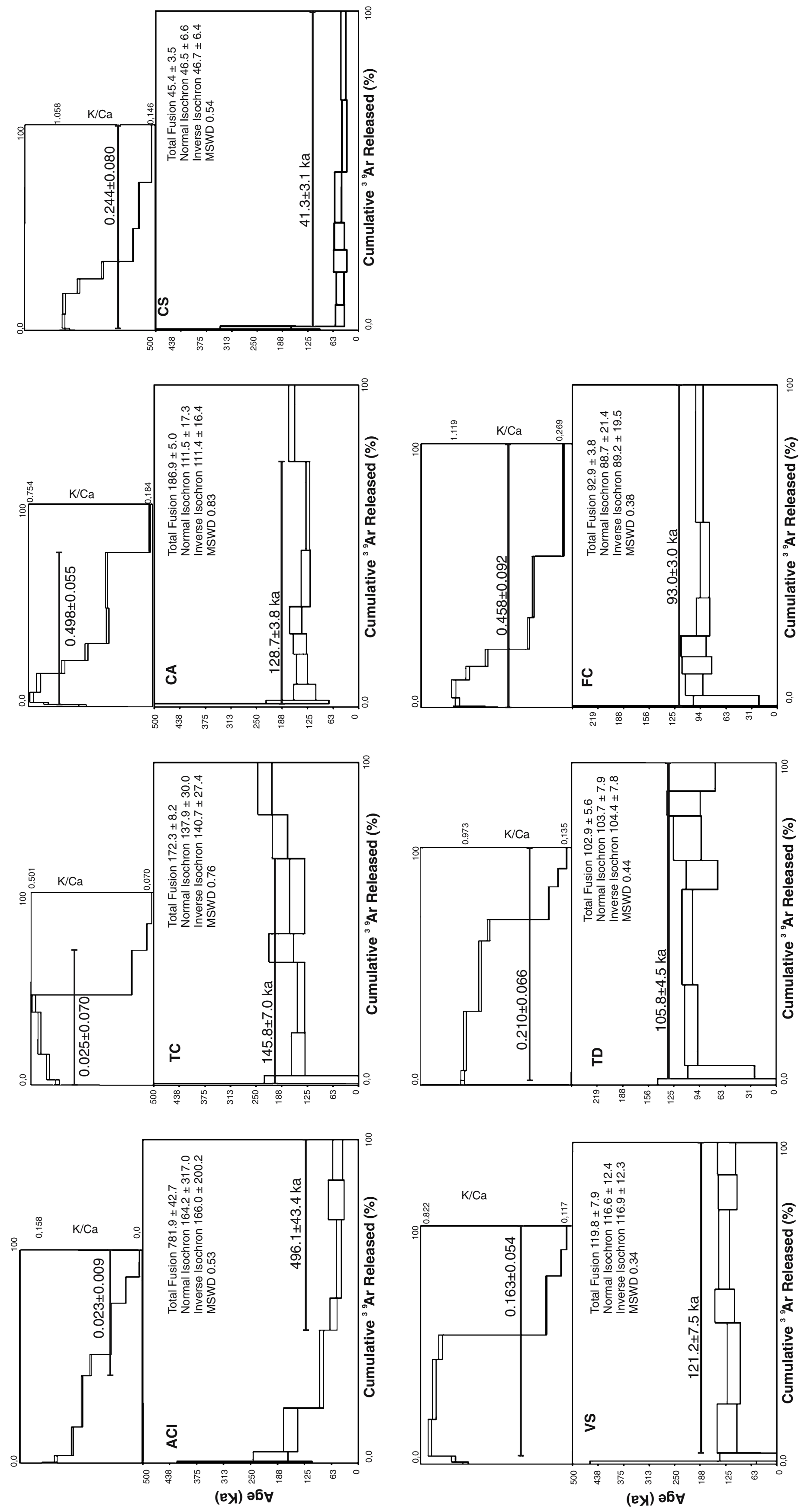
Table 1 Petrography and incremental heating results of the samples

Samples	Location	Latitude longitude	Elevation (m a.s.l.)	Petrography			Age (ka) from the normal isochrons diagram	Age (ka) from the inverse isochrons diagram	$^{39}Ar_{(k)}$ used in plateau calculation (%)	MSWD	Weighted plateau age ka ± 1σ
				P.I. (%)	Most abundant phenocrysts (from the most to the less in mm)	Groundmass texture and mineralogy					
ACI	NE side of the Acicastello Castel Rock	37°33′21″ 15°09′03″	2	5	Ol 0.2 and Px 0.2	Cryptocrystalline	164.2 ± 317.0	166.0 ± 200.2	58.98	0.20	496.1 ± 43.5
TC	Torre Casalotto locality	37°34′29″ 15°09′10″	195	30	Plg 3.5-0.1, Px 4-0.1, Ol less then 0.5 in the same quantity of Px and opaque oxide	Micro-cryptocrystalline: Plg and Px	137.9 ± 30.0	140.7 ± 27.4	69.65	0.87	145.8 ± 7.0
CA	Mt. Fior di Cosimo (Val Calanna)	37°42′43″ 15°04′22″	1,110	15	Plg 3-0.1, Px 1.5-0.1, Ol 0.5 -0.1 and opaque oxide	Micro-cryptocrystalline: Plg, Px and opaque oxides	111.5 ± 17.3	111.4 ± 16.4	75.03	0.88	128.7 ± 3.8
VS	Mt. D'Oro locality	37°34′13″ 15°07′32″	360	15	Px 4–0.1, Ol 0.5, Plg 2.5–0.1 and opaque oxides	Intergranular: Plg, Px and opaque oxides	116.6 ± 12.4	116.9 ± 12.3	96.61	0.34	121.2 ± 7.5
TD	Tarderia locality	37°46′43″ 15°10′22″	1,155	20	Plg 3–0.1, Amph3–0.1, Ol 2.5–0.1, Px 2–0.1	Subophitic: Plg, Ol and opaque oxides	103.7 ± 7.9	104.4 ± 7.8	98.02	0.32	105.8 ± 4.5
FC	Mt. Fior di Cosimo (Val Calanna)	37°42′43″ 15°04′35″	1,100	20	Plg 3.5–0.1, Ol 3–0.1, rare and opaque oxides	Subophitic: Plg, and opaque oxides	88.7 ± 21.4	89.2 ± 19.5	100.00	0.38	93.0 ± 3.0
CS	Mt. Fior di Cosimo (Val Calanna)	37°45′49″ 15°05′37″	1,335	25	Plg 3–0.1, Px 3.5–0.1 rare Ol and opaque oxides	Ophitic: Plg, Px and opaque oxides	46.5 ± 6.6	46.7 ± 6.4	98.78	0.60	41.3 ± 3.1

The original ArArCalc data table are available as Electronic supplementary material. See text for the large difference between normal isochrons and weighted plateau age of the sample ACI

Plg Plagioclase; *Px* pyroxene; *Amph* amphibole; *Ol* olivine

Fig. 2 K/Ca and age spectra obtained with the $^{40}Ar/^{39}Ar$ step heating technique eight steps for samples *ACI*, *TC*, *CA*, *VS*, *TD* and nine steps for samples *FC* and *CS*. K/Ca diagrams have a, more or less regular, stairs path decreasing up to 0.007 in ACI sample. The spectra age diagrams, age (Ka) versus cumulative ^{39}Ar released show which steps are used to calculate the sample age. In the upper part of each diagram there is some information on: weighted plateau age, total fusion age, isochron age and MSWD



suggests that the K-rich components become depleted and Ca-rich phases (andesine and labradorite) dominate the final steps of the experiments because their crystal sizes are generally larger and likely to melt later then K-rich components. K-rich phases are microlite of albite and anorthoclase which are spread in the groundmass as the result of the late (post-eruption) crystallization of the volcanic glass during the cooling of lava flow below the solidus temperature (De Beni et al. 2005). The isochron age is in disagreement with the weighted plateau age probably due to the presence of extraneous argon. The mean squared weighted deviations (MSWD) factor is 0.53 that could be considered valid following the criterion stabilised by Dunai and Wijbrans (2000): a plateau is considered acceptable when MSWD is less then 2.5. The age 496.1 ± 43.4 ka is in agreement with the results obtained by Gillot et al. (1994) with the K–Ar method: 467.0 ± 41.0 ka, 583.0 ± 89.0 ka and 500 ± 87 ka.

TC sample

The K/Ca diagram is characterised by an irregular path with a peak (0,501) at the fifth step which corresponds to a peak within the plateau age spectrum (189.1 ± 30.3 ka), then the K/Ca ratio decreases to 0.070. It is likely that during the fifth heating step the microlites of albite and anorthoclase began to degas. Weighted plateau and isochrons (normal and inverse) ages are perfectly in agreement; their values are, respectively, 145.8 ± 7.0 ka, 137.9 ± 30.0 ka, 140.7 ± 27.4 ka, and MSWD is 0.76.

CA sample

Even if this sample came from a weathered lava flow the obtained results are very good because of the leaching technique applied to the separated fraction that was used to selectively dissolve the weathered portions. K/Ca ratio decreases from 0.754 at the third step to 0.184 at the last step. Normal (111.5 ± 17.3 ka) and inverse isochron age (111.4 ± 16.4 ka) are concordant with the result of the weighted plateau age (128.7 ± 3.8 ka) and are characterized by little uncertain margins; finally MSWD is 0.83.

VS sample

K/Ca and plateau age are regular if we excluded the first two steps during which relatively little radiogenic argon is released. In particular K/Ca ratio strongly decreases from the fifth step 0.767 to value 0.117 at the last step. The weighted plateau age 121.2 ± 7.5 ka has an uncertain margin of 6.22% of the calculated age. Results obtained with the normal (116.6 ± 12.4 ka) and inverse isochrons (116.9 ± 12.3 ka) are comparable with the plateau age; MSWD is 0.34.

TD sample

The K/Ca diagram shows a regular and continuously decreasing ratio from 0.973 at the first step to 0.135 at total fusion. To calculate the weighted plateau age the first step has been excluded, the resulting age of 105.8 ± 4.5 ka has a good uncertain margin of 4.25% and MSWD is 0.44. Normal isochron age (103.7 ± 7.9 ka) and inverse isochron age (104.4 ± 7.8 ka) are in agreement with the weighted plateau age.

FC sample

The first step of the incremental heating has a big error, however, the results are excellent with an uncertain margin of 3.19% of the calculated age. K/Ca ratio has a regular path decreasing form 1.119 at the forth step to 0.269 at total fusion. The plateau age is calculated over 95% of the total gas release. The weighted plateau age (93.0 ± 3.0 ka) is comparable with normal isochron (88.7 ± 21.4 ka) and inverse isochron age (89.2 ± 19.5 ka); MSWD is 0.38. This result is in accordance with the age of 96.0 ± 5.0 ka measured by Gillot et al. (1994) on a sample located at the base of the Mt. Fior di Cosimo with similar stratigraphical position of our FC sample. For verifying the reliability of this result we measured the age of a sample located at the top of the Mt. Fior di Cosimo lava succession (CS sample) which results the youngest volcanic of this data set.

CS sample

K/Ca diagram shows a regular decreasing, from 1.062 to 0.146 at total fusion, excluding the first step. For the weighted plateau age calculation we did not consider the first two steps which release only a small amount of argon and have a large error. The plateau age of 41.3 ± 3.1 ka with an uncertain margin of 7.31% is comparable with, normal (46.5 ± 6.6 ka) and inverse (46.7 ± 6.4 ka) isochron ages; MSWD is 0.54.

In our samples $^{38}Ar_{Cl}$ is generally very low; thus we do not expect significant interference of $^{36}Ar_{Cl}$ on the determination of radiogenic argon ($^{40}Ar^{*}$).

Geological data

In this section we briefly describe the stratigraphy of the volcanic successions of the BT and TI phases and of the earlier volcanics of the VB phase.

BT phase

The earliest volcanics found in the Etnean region are related to the BT phase and they are preserved in a restricted area between the villages of Acicastello and

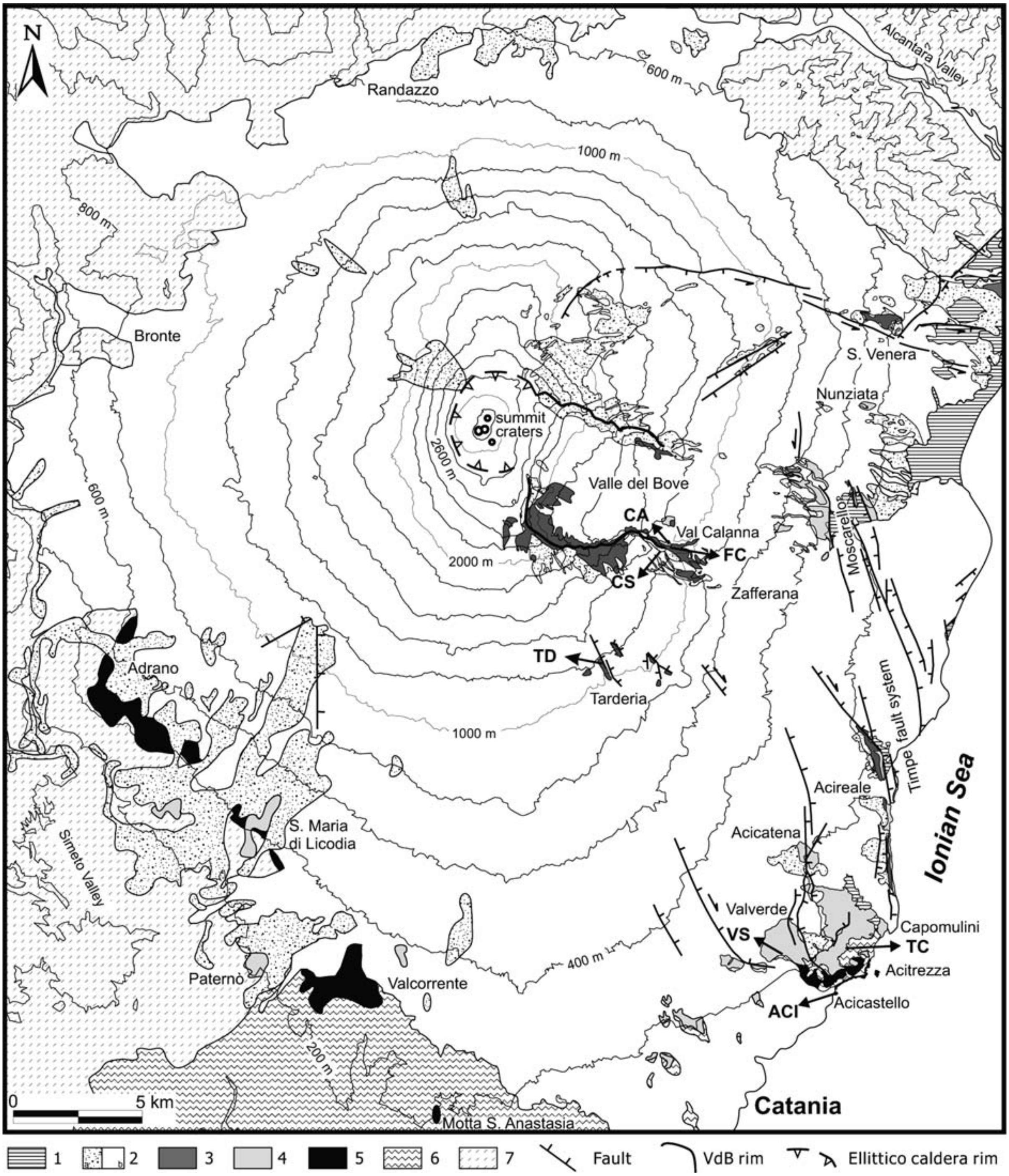


Fig. 3 Geological sketch map of Mount Etna based on the new 1:50,000 geological map of the volcano (Branca et al. 2004b) and location of the analysed samples. *1* Apenninic–Maghrebian Chain, *2* Early-middle Pleistocene sediments; *3* BT phase volcanics; *4* TI phase volcanics; *5* VB phase volcanics; *6* SV phase volcanics, *a* Ellittico volcano and *b* Mongibello volcano; *7* Recent alluvial deposits

Fig. 4 Aerial view from south of the coastal cliff of Acicastello Castle Rock that is formed by the submarine products of the BT phase and location of ACI sample

Acitrezza along the Ionian coast (Fig. 3). They consist of shallow subvolcanic bodies, pillow lavas and hyaloclastic breccias with a tholeiitic affinity (Tanguy et al. 1997; Corsaro and Cristofolini 1997, 2000) that are intercalated in the top of the early-middle Pleistocene marly-clays of the Gela–Catania Foredeep (Di Stefano and Branca 2002). Submarine eruption products are preserved in the isolated coastal cliff of the Acicastello Castle Rock and inland between the villages of Ficarazzi and Acitrezza. At Acicastello Castle Rock they consist of pillow lavas and hyaloclastic pillow-breccia fed by a N–S oriented dyke (Fig. 4). Inland, these volcanics crop out discontinuously within the early-middle Pleistocene marly-clays. They consist of pillow lava and pillow breccia made of sharp-edged pillow fragments dispersed in a hyaloclastic matrix. These deposits were fed by several small subvolcanic bodies having bulb-shapes that are generally characterized by columnar joints radiating from the inner part of the body.

The oldest subaerial lava flows of BT phase are exposed in the lower western flank of the volcano along the left bank of the Simeto River; they have a tholeiitic composition (Tanguy 1978; Corsaro and Pompilio 2004). The lava flows crop out discontinuously between Adrano town at 650 m asl and Paternò town at 300 m asl forming a lava plateau between 5 and 25 m thick. The plateau rests on a sub-flat morphology gently SSE dipping developed on top of Apenninic–Maghrebian Chain terrains and locally, near Paterno, on the Pleistocene infra-littoral sands. The tholeiitic lava extends 8–9 km northward to Adrano town according to subsurface data (Cristofolini et al. 1991). The base of the lava plateau is locally characterized by the presence of pillow lava facies resting on lenses of alluvial deposits between Adrano and S. Maria di Licodia towns as reported by Chester and Duncan (1979). Pillow lava fragments in a hyaloclastic matrix are also present at Valcorrente locality close to the town of Paternò where the sub-aerial lava flow shows marine incrustations of Polycaeta. The tholeiitic lava plateau was generated by fissure-type eruptions whose vents are covered by the younger volcanics with the exception of one located in the south-eastern border of the plateau at Valcorrente. Here, the eruptive fissure is bordered by a pyroclastic deposit consisting of an alternation of densely black scoriaceous lapilli and bombs layers and stratified ashy layers. The juvenile clasts are characterised by a yellowish alteration surface and the bombs show a well-developed bread-crust surface. The pyroclastic deposit also contains sedimentary lithics of Pleistocene marly-clay clasts and polygenetic alluvial pebbles. Attitude and geometrical arrangements of the pyroclastic deposit indicate that the eruptive fissure is oriented about N–S extending for a length of about 650 m.

Finally, about 4 km south–east of the lava plateau an isolated neck of tholeiitic lavas (Tanguy 1978) is intruded in the marine Pleistocene sediments at Motta S. Anastasia town. This subvolcanic body showing well-developed columnar joints is about 400 m N–S elongated, 200 m-wide and about 60 m-high. A pyroclastic deposit is locally preserved along the wall of the neck. It is formed by scoriaceous lapilli and bombs, with a bread-crust surface, and occasionally sedimentary lithic fragments made up of heterolithologic alluvial pebbles. A small NNW trending dike is present in the northern side of the subvolcanic body.

TI phase

The volcanic products related to the TI phase are well exposed along the Ionian coast where a thick lava flow succession crops out along the Acireale Timpa and

Moscarello Timpa fault scarps. In particular, the lava flows succession thickens from south to north (10–100 m), forming the basal portion of the Acireale Timpa fault scarp. The succession is made up of the superposition of several massive lava flows, 10–30° dipping SSW and SW, separated by brown-yellowish epiclastic deposits a few meters thick (Fig. 5). The base of the succession is formed by porphyritic lava flows (from tholeiitic to transitional affinity; Tanguy et al. 1997) containing large mafic crystals and nodules. Upward, the succession passes to porphyritic lava flows with Na-alkaline affinity (Corsaro and Pompilio 2004). The relics of some eruptive fissures N–S trending crop out along the fault scarp. They are feeder-dikes constitute of columnar lavas and proximal pyroclastic deposits made up of reddish scoriaceous bombs (Corsaro et al. 2002). The top of the Acireale Timpa lava succession is unconformably covered by a volcaniclastic deposits, up to 60 m thick, mainly formed of debris flows and alluvial deposits (Fig. 5).

A thick lava flow succession forms the Moscarello Timpa fault scarp that is characterised by a basal portion, about 70 m thick, consisting of superposed massive lava flows, 20–30° dipping NNW. The central portion of the scarp is formed by about 150 m of massive lava flows superimposed and interstratified to a spatter rampart, WNW–ESE elongated. On the whole, this portion of the lava succession, gently dipping eastward, overlaps with an angular unconformity the basal portion. North of the Moscarello Timpa fault scarp, thin lava flows discontinuously crop out near of Nunziata and S. Venera villages (Fig. 3). These weathered lava flows are mafic nodules-rich resting on the early-middle Pleistocene marly-clays.

During the TI phase scattered monogenic centres erupted also on the south periphery of Etna. The remnants of these eruptions form limited outcrops of massive lava flows, 5–10 m thick, that are deep-weathered and eroded. They crop out discontinuously along the left bank of the Simeto River, between Adrano and Paternò towns, resting on both the sedimentary basement and the tholeiitic lava plateau. They were generated by fissure-type eruptions whose vents are preserved only at Paternò town where a large proximal scoria deposit N–S oriented, about 800 m-long, 500 m-wide and 100 m-high, crop out. The deposit is made up of welded scoriaceous lapilli and bombs and lithic fragments mainly of alluvial pebbles. The lava flows related to the Paternò fissure are exposed only along its slopes. Furthermore, isolated remnants of thin lava flows rest on the early-middle Pleistocene marly-clays in the northern Catania suburbs and between Acitrezza and Valverde villages (Fig. 3). In this area a lava flow succession is well-exposed along the morphological scarp of Mt. D'Oro and on the Acicatena Timpa fault scarp. Mt. D'Oro succession ranges in thickness from a few meters up to 50 m. It is formed by several massive lava flows resting

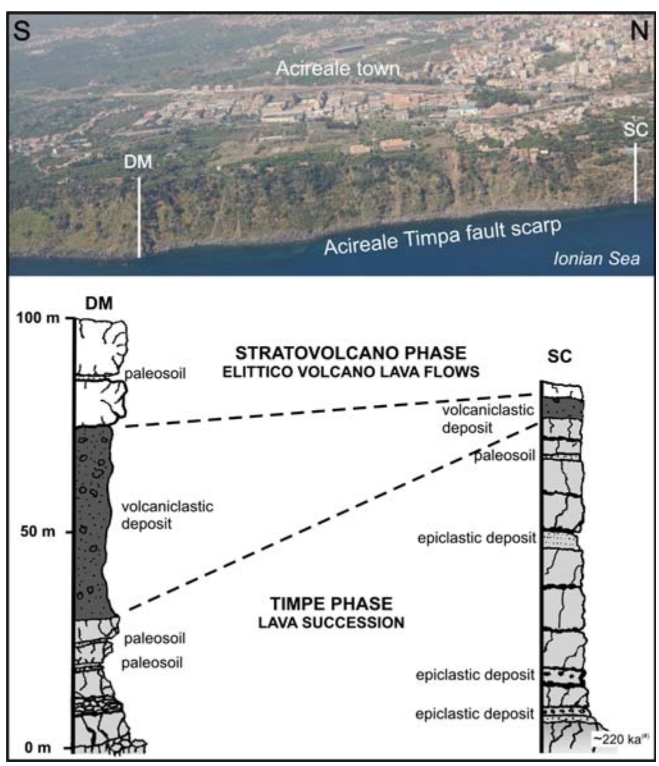


Fig. 5 Aerial view from east of the Acireale Timpa fault scarp and the stratigraphic sections measured at Don Masi (DM) and S. Caterina (SC) localities showing the relationships between the different lithostratigraphic units. Isotopic data: (*hashes*) Gillot et al. 1994

on the early-middle Pleistocene marly-clays. At the Gelso locality, on the sedimentary hill of Acitrezza, the Mt. D'Oro succession is formed by three lava flows separated by a thin paleosoil and a 6 m thick epiclastic deposit (Fig. 6). The succession was generated by fissure-type eruptions whose vents are preserved only on the Acicatena Timpa fault scarp. Here, a proximal deposit made up of densely lapilli and bread-crust bombs alternating with ash layers containing lava lithic and, occasionally, clay fragments crops out. The lava flow related to this fissure extends eastward on the Pleistocene sedimentary basement for more than 4 km reaching the coast at Capo Mulini bay (Fig. 3).

Highly tectonized volcanics crop out in Val Calanna forming the relief of Mt. Calanna, an isolated and highly eroded volcanic body, and the base of Mt. Fior di Cosimo a morphological scarp unconformably covered by the VB phase lava flows (Fig. 7). These volcanics have an uncertain stratigraphic position due to the lack of any basal contact (Branca et al. 2004a). They are highly-weathered cataclastic lava flows with a grey-yellowish clay matrix that are cut by several tectonized dykes. These products are also exposed in a drainage gallery about 1.5 km southward of Mt. Fior di Cosimo, indicating a southward extension for the Calanna volcanics (Branca et al. 2004a).

On the whole, the top of the TI phase volcanics is marked by a main erosional unconformity represented by: (a) a buried morphological scarp in Val Calanna; (b) debris and alluvial deposits along the Ionian coast on the Acireale Timpa fault scarp; (c) isolated lava relicts smoothed on the top and deeply eroded sideways due to the entrenchment of the drainage pattern on the southern border of the volcano.

VB phase

The VB phase products crop out in the central portion of the volcano. They are localised in the Val Calanna area, at Tarderia locality and on the northern wall of the Valle del Bove. In particular, in Val Calanna the earliest lava flows of the VB phase on Mt. Calanna and on Mt. Fior di Cosimo scarp are well-exposed (Fig. 7). On the eastern slope of Mt. Calanna, a 10 m thick, SE dipping, lava flow is fed by a dike that cut the cataclastic volcanics of the TI phase. Along the Mt. Fior di Cosimo scarp, a 180 m-thick lava flow succession rests with an angular unconformity on the TI phase cataclastic volcanics (Fig. 7). This succession is formed by the superposition of massive lava flows, dipping 10–20° toward SE and SSE, which are unconformably covered by the volcanics of the SV phase (Fig. 7).

South of the Val Calanna limited outcrops of a lava flow succession, up to 30 m thick, are exposed along fault scarps of Contrada Passo Cannelli, Tarderia, Mt. Pò and Mt. Cicirello. The succession is formed by the superposition of massive southward dipping lava flows that are unconformably covered by the SV phase vol-

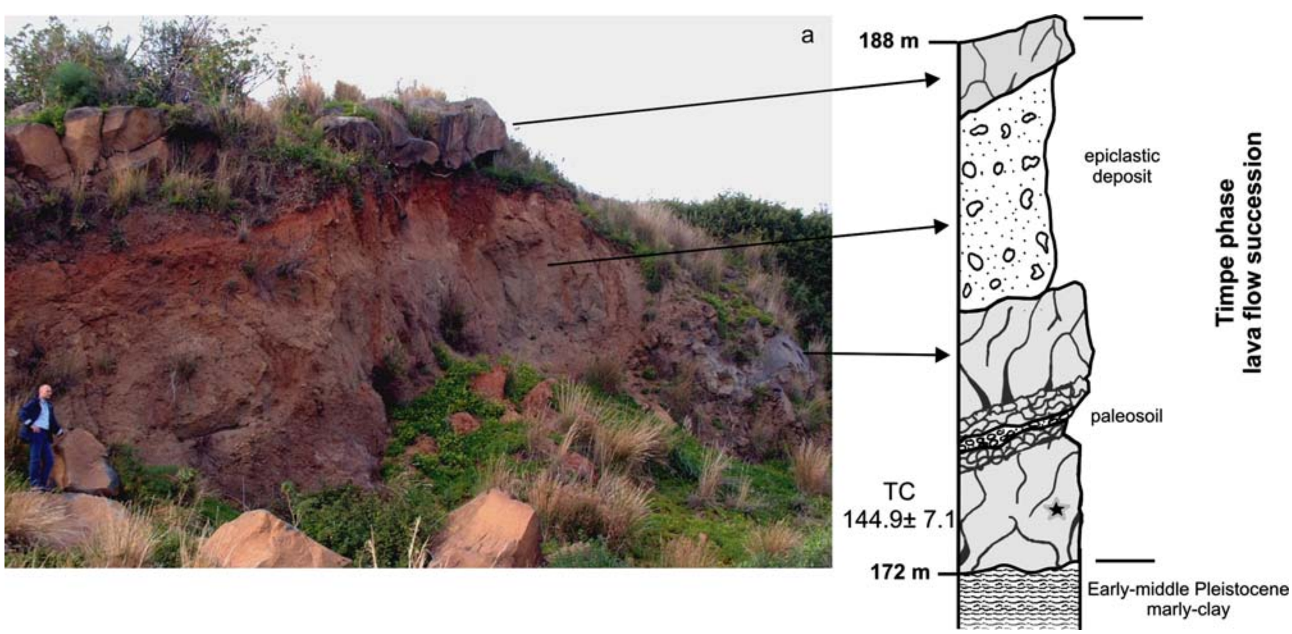


Fig. 6 Image of the top of the Acitrezza sedimentary hill (a) and stratigraphic section measured at Gelso locality. The star indicates the location of the TC sample in the stratigraphic column

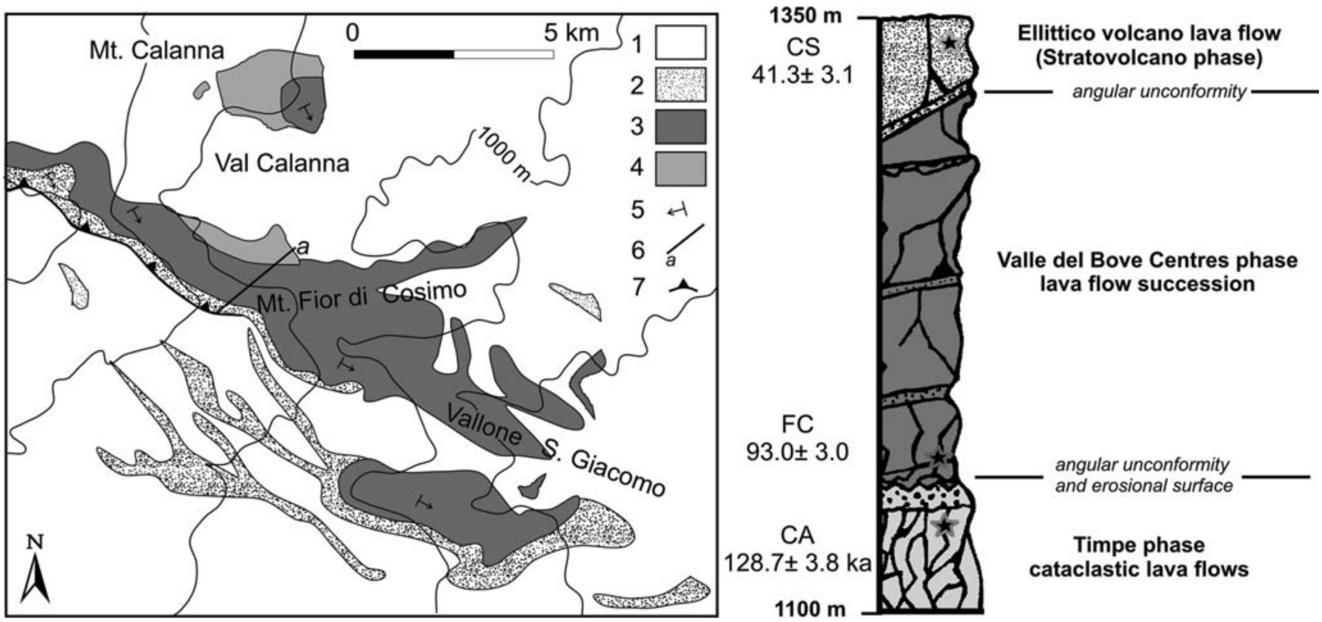


Fig. 7 Geological sketch map of Val Calanna area and the stratigraphic section measured at Mt. Fior di Cosimo. The stars indicate the location of the CA, FC and CS samples in the stratigraphic section. *1* Mongibello volcano products; *2* Ellittico volcano products; *3* VB phase volcanics; *4* TI phase volcanics; *5* bedding attitude; *6* location of the stratigraphic section; *7* VdB rim

canics. The top of this lava succession is highly eroded and is characterised by the presence of thin and confined volcaniclastic deposits.

North of Val Calanna, a complex volcanic succession is exposed at the base of Valle del Bove northern wall at Rocca Capra and Rocca Palombe localities (Fig. 3), representing the relic of a small polygenic eruptive center (Rocche volcano of Branca et al. 2004a). The succession is about 120 m thick, dipping 20–35° from NW to NE. From the base it consists of thin superimposed lava flows passing upward to an alternation of autoclastic lavas with pyroclastic and epiclastic deposits. At Rocca Palombe a 30 m thick reddish pyroclastic flow deposit crop out. The top of this volcanic succession is highly eroded and is unconformably covered by the SV phase volcanics (Fig. 3).

Discussion

$^{40}Ar/^{39}Ar$ age determinations and stratigraphic data allow us to constrain the evolution of the eruptive activity of Etna volcano chronologically from the first submarine products of the BT phase to the formation of the earliest eruptive center of the VB phase. Geochronological and geological data allowed for the first time to define the uncertain stratigraphic position of some volcanics, to understand the meaning and the role of the main unconformities that characterise the complex Etnean volcanic succession and finally to clarify the relationship with the tectonic evolution of eastern Sicily.

The $^{40}Ar/^{39}Ar$ age of 496.1 ± 43.4 ka for the earliest Etnean products (ACI sample) is in agreement with the previous K/Ar age of Gillot et al. (1994), showing that submarine eruptions occurred at about 500 ka ago in the Gela–Catania Foredeep during the deposition of the early-middle Pleistocene marly-clay. After these submarine volcanics no products have been found in the stratigraphic record up to about 300 ka ago as indicate by the isotopic ages of the subaerial tholeiitic lava flow cropping out at Valcorrente (Gillot et al. 1994). This subaerial volcanism is related to fissure-type eruptions that formed a wide plateau, gently SSE dipping, extending for more than 25 km from Bronte to Paternò on the top of the Apenninic–Maghrebian Chain terrains. The alluvial deposits exposed below the lava plateau indicated that these lava flows emplaced on the old alluvial plain of the paleo-Simeto River, characterised by the presence of lacustrine environment as documented by the finding of pillow-lava facies at the base of the plateau. In addition, the pyroclastic deposits of the two eruptive fissures recognised at Valcorrente and Motta S. Anastasia are characterised by phreatomagmatic features indicating

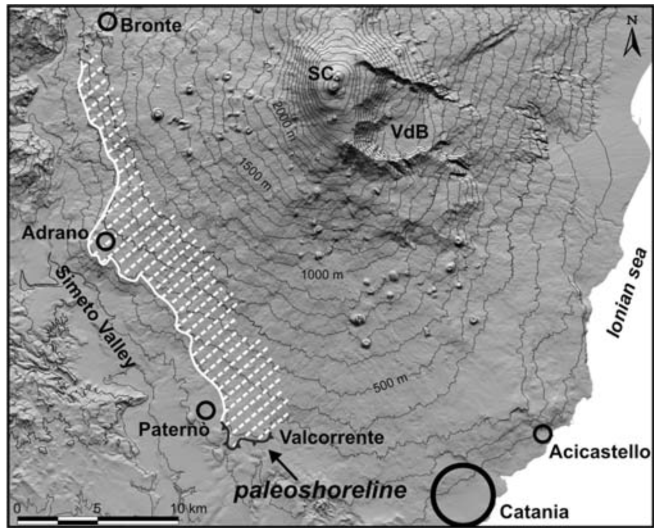


Fig. 8 Extension of the tholeiitic lava plateau inferred by subsurface and geological data and location of the paleo-shoreline of about 300 ka ago. *SC* summit craters; *VdB* Valle del Bove

the interaction between magma and the water located in the sediments of the old alluvial plain. Close to Paternò town the lava plateau rest directly on the middle Pleistocene infra-littoral sands showing a well-developed pillow structures. Furthermore, in this area the presence of marine fauna incrustation within the lava joints suggests a deposition in shallow sea-water condition. These data allow us to identify the location of the paleo-shoreline of about 300 ka ago that is presently located at 260–270 m elevation in the Paternò-Valcorrente area at about 14 km inland from the present coastline (Fig. 8).

A long period of erosion related to the entrenchment of the paleo-Simeto River affected the SW sector of Etna after the emplacement of the tholeiitic lava plateau. As a consequence of the regional uplift that involved the Etnean region (Di Stefano and Branca 2002) the paleo-Simeto drainage patterns eroded both the sedimentary terrains and the lava plateau generating the Terreforti alluvial conglomerates and forming a wide valley. This erosional period separates the BT phase and the TI one. No isotopic and geological data are available yet to establish the duration of the hiatus between the two phases, since the base of the TI phase lava succession, forming the Acireale Timpa scarp, is localized below the sea level.

The oldest products of the TI phase cropping out along the Acireale Timpa scarp have an age of about 220 ka (Gillot et al. 1994). In this period the eruptive activity was mainly concentrated along this NNW-trending regional fault system. Furthermore, a change from subalkaline to Na-alkaline products occurred at the beginning of this phase (Tanguy et al. 1997; Corsaro and Pompilio 2004). The westward general dip of the thick lava flow succession, exposed for at least 15 km between Acireale Timpa and Moscarello Timpa, indicate that the volcanic sources was located east from the present exposures forming a shield-type volcano N–S extended. The absence of major erosional unconformities within the lava succession point out that the eruptive activity was almost continuous in this time span as a consequence of a more efficient magma uprise from the mantle with respect to the volcanism of the BT phase (Branca et al. 2004a). During the TI phase scattered eruptive activity also affected the lower SW and SE sectors of Mount Etna. On the SW sector thin lava flows, ranging in age from about 178 to 136 ka (Gillot et al. 1994; Tric et al. 1994), were erupted from isolate and widely scattered vents covering with an angular unconformity the remnant of the tholeiitic lava plateau. Effusive activity along fissures also affected the SE sector generating a lava flows succession that covers the Pleistocene sedimentary basement between Valverde and Acitrezza towns and on the northern Catania suburb. In particular, the lava flows succession forming the morphological scarp of Mt. D'Oro, has an isotopic age constrained between 145.8 ± 7.0 ka (TC sample) and 121.2 ± 7.5 ka (VS sample). During this time span a thin lava flow cropping out on the northern Catania periphery was emplaced at about 134.2 ± 3.3 ka (De Beni et al. 2005).

The $^{40}Ar/^{39}Ar$ age of 128.7 ± 3.8 ka obtained for the Calanna cataclastic lava (CA sample) allows us to attribute, for the first time, the stratigraphic position of these volcanics to the TI phase. The lava flows forming the base of the Moscarello Timpa succession have an $^{40}Ar/^{39}Ar$ age of 129.9 ± 2.4 ka (De Beni et al. 2005) that is coeval with the age of Calanna volcanics. In particular, De Beni et al. (2005) evidence that the Moscarello lava succession were emplaced in a short time interval between 129.9 ± 2.4 and 126.4 ± 2.4 ka ago ruling out that these volcanics could be related to the younger Trifoglietto s.l. activity as previously inferred by Romano (1982) and Busà and Cristofolini (2001). Consequently, the Moscarello lava succession is the product of an intense effusive activity from fissural type eruptions developed along the northern termination of the Timpe fault system.

All these data suggest that the eruptive activity during the TI phase was localised mainly along the Ionian coast with the growth of a shield volcano from before 220 ka to about 130 ka ago. The eruptive activity moved toward the central portion of the present volcano (Val Calanna–Moscarello area) marking the westward shifting of the main feeder system between about 129 and 126 ka ago. Moreover, scattered eruptions occurred until about 121 ka ago on the SW and SE periphery of Etna. Consequently our geochronological and geological data do not support the presence of lava flows related to the earlier Na-alkaline volcanism (Ancient Alkaline Centres of Romano 1982) in the other sector of the volcano as reported in the geological map of Romano et al. (1979) along the valley floors of the Simeto and Alcantara rivers. Therefore, the hypothesis of Romano (1982) about the formation of a primitive shield volcano extending for about 30 km from Alcantara to Simeto rivers is not supported by our data. Furthermore, Kieffer and Tanguy (1993) inferred the presence of an early central-type volcano named ‘‘Etna Ancient’’ including most of the TI volcanics. It was thought to extend widely from the northern to the southern periphery of Etna during the first stage of the Na-alkaline volcanism. The isotopic and stratigraphic data set here presented does not support the existence of this ancient large stratovolcano.

At the beginning of the VB phase an earlier central-type eruptive center, Rocche volcano, grew on the VdB area. Rocche volcano is a small polygenic center whose eruptive axis was located less than 1 km south of the Rocca Capra–Rocca Palombe reliefs on the NE sector of the VdB. Rocche volcano activity was mainly characterised by lava effusion even if the presence of some thick pyroclastic flow deposits indicate the occurrence of relevant explosive eruptions. The $^{40}Ar/^{39}Ar$ age of the lava flow forming the top of this volcanic succession indicates that its activity ended about 101.9 ± 3.8 ka (De Beni et al. 2005). On the basis of morphological evidence some authors (Cristofolini et al. 1978, 1982; Romano and Sturiale 1981; Lo Giudice et al. 1982; Chester et al. 1985) inferred the presence of another central-type eruptive center localised south of the VdB that formed a morphological belt from Tarderia to Zafferana town (Fig. 9a). Recently, Branca et al. (2004a) attributed the lava flows succession cropping out at Contrada Passo Cannelli, Tarderia, Mt. Pò and Mt. Cicirello, along the morphological belt, to the products forming the top of

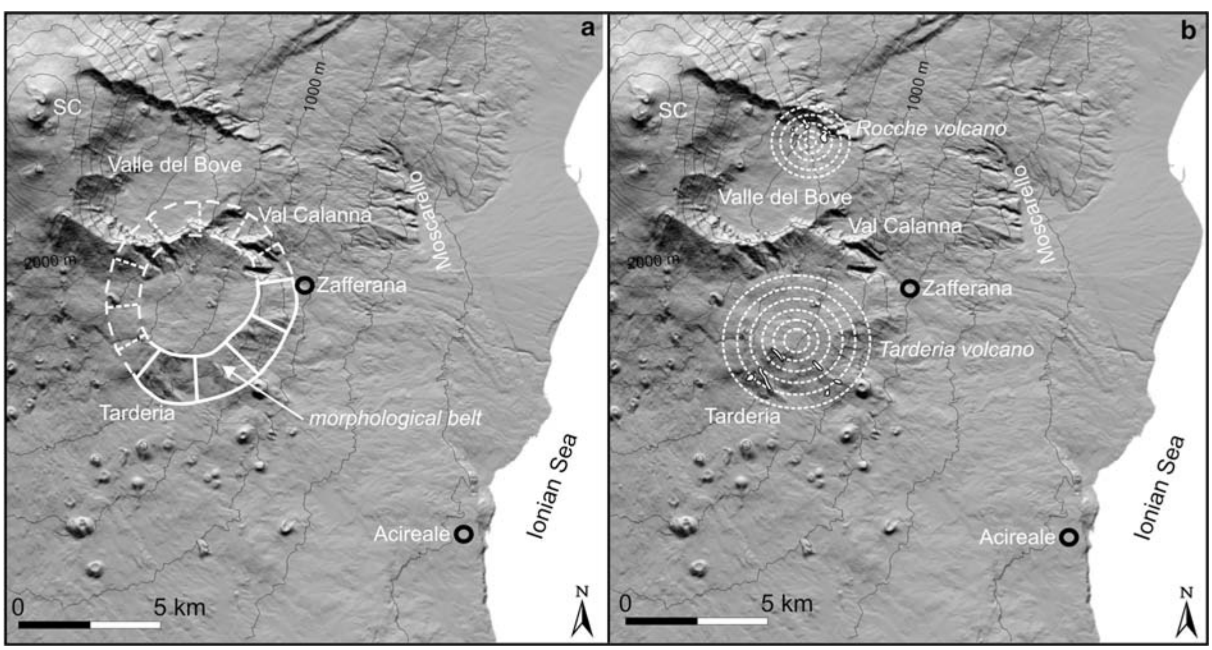


Fig. 9 Reconstruction of the Tarderia eruptive center on the basis of the morphological evidence according previous authors (**a**). Location and extension of Rocche and Tarderia volcanoes based on the geological data (**b**); the white areas are the outcrops of Rocche and Tarderia products

this eruptive center, named Tarderia volcano. The $^{40}Ar/^{39}Ar$ age of 105.8 ± 4.5 ka (TD sample) measured for the Contrada Passo Cannelli lava flow reveal that the two volcanic centres (Rocche and Tarderia) appear almost coeval since their final products have similar isotopic ages. Geological data of the Val Calanna area allows us to define the extension of the Tarderia volcano. From Zafferana the northward extension of the morphological belt intersects the Val Calanna area that should represent, in the hypothesis of the previous authors (Cristofolini et al. 1982; Romano 1982), the NE flank of the Tarderia volcano (Fig. 9a). On the contrary, the lava flows forming the thick succession of Mt. Fior di Cosimo and Vallone S. Giacomo (Val Calanna area) are characterised by a homogeneous SE–SSE dipping (Fig. 7) forming conversely the SE flank of the eruptive centres localized in the W portion of the VdB (Branca et al. 2004a). In addition, the 93.0 ± 3.0 ka age determination (FC sample) obtained for the base of Mt. Fior di Cosimo lava flows succession, resting on the TI phase volcanics (CA sample, 128.7 ± 3.8 ka), evidences that during the time-span of the Tarderia volcano building only erosional processes were reordered in the Val Calanna area. In brief the Tarderia volcano seems to be similar in age and size to the Rocche volcano, and it is aligned with it along a N–S direction (Fig. 9b). Volcanic activity resumed in Val Calanna area about 93 ka ago with the emplacement of lava flows belonging to the Valle del Bove centres phase and continued during the Stratovolcano phase as indicate by the $^{40}Ar/^{39}Ar$ age of 41.3 ± 3.1 ka obtained for the lava flow (CS sample) at the top of the succession of Mt. Fior di Cosimo (Fig. 7).

From a geodynamics point of view the volcanism in the Etnean region started in concomitance of a major tectonic reorganization in the south-central Mediterranean that occurred 800–500 ka ago (Goes et al. 2004). In particular, eastern Sicily was affected by a huge extensional deformation resulting from the divergence of the Ionian basin from the continental crust of the Hyblean Foreland that reactivated the structures of the Malta Escarpment. According to several authors (Adam et al. 2000; Cifelli et al. 2004; Argnani and Bonazzi 2005) a huge ESE–WNW extensional tectonic off- and on-shore affected eastern Sicily from Middle Pleistocene. Geological data clearly evidence that this major reorganization in the tectonic setting of eastern Sicily influenced the change from the Plio-Pleistocene volcanism of the Hyblean foreland to the Etnean region volcanism. In fact, the Plio-Pleistocene Hyblean volcanism is related to a NE–SW extensional tectonic that produced the settlement of the Hyblean foreland margin (Carveni et al. 1991; Schmincke et al. 1997). This tectonic regime of the northern margin of the Hyblean Plateau ended during Late Pliocene–Early Pleistocene times (Torelli et al. 1998). In the Etnean region, we observe that during the BT phase the eruptive fissures trend is characterised by the same N–S orientation of the following TI phase indicating a general E–W extensional tectonic that controls the magma intrusion in agreement with the reactivation of the Malta Escarpment fault system. In particular, the extensional tectonic of the Timpe fault system superimposed the compressive regime of the final stage of the chain shortening that affected the Quaternary sediments of the Gela–Catania Foredeep (Labaume et al. 1990; Lanzafame et al. 1997) favouring the volcanism of the BT phase. During the BT phase the eruptive activity changes from submarine to subaerial as a consequence of the regional uplift affecting the Etnean region (Di Stefano and Branca 2002). The recognition of a paleo-shoreline on the tholeiitic lava plateau at 260–270 m elevation allows us to calculate an uplift rate of about 1.0 mm/year for the past 300 ka using as reference the eustatic curve of Chappel and Shackleton (1986). This value is in agreement with the time-average Holocene Etnean shoreline uplift rate of 0.8–1.4 mm/year obtained by Firth et al. (1996) confirming the occurrence of an active deformation in the Etnean region since the BT phase.

Starting from about 220 ka ago the volcanism appears mainly concentrated in a narrow belt along the present Ionian coast where the Timpe master fault segments developed. The huge WNW–ESE oriented regional-scale extension of the Timpe faults allowed a more efficient magma uprise from the mantle. In particular, during the TI phase the increase of the eruption rate produced the growth of a shield volcano, roughly N–S elongated, according to the orientation of the fault system. During the late stage of the TI phase, between about 129 and 126 ka, the volcanism concentrated on the northern tip of the fault system. In this time span, we observe the westward shifting of the main plumbing system due to the NW migration of the extensional regime of the Timpe fault system toward the central portion of Etna edifice (Val Calanna–Moscarello area). Finally, during the earlier stage of VB phase the passage from fissure to central eruptive style occurred, still controlled by an E–W extensive tectonics as suggested by the N–S alignment of Rocche and Tarderia volcanoes.

Concluding remarks

On the basis of a new stratigraphic setting of Etna volcano and $^{40}Ar/^{39}Ar$ age determinations we recon-

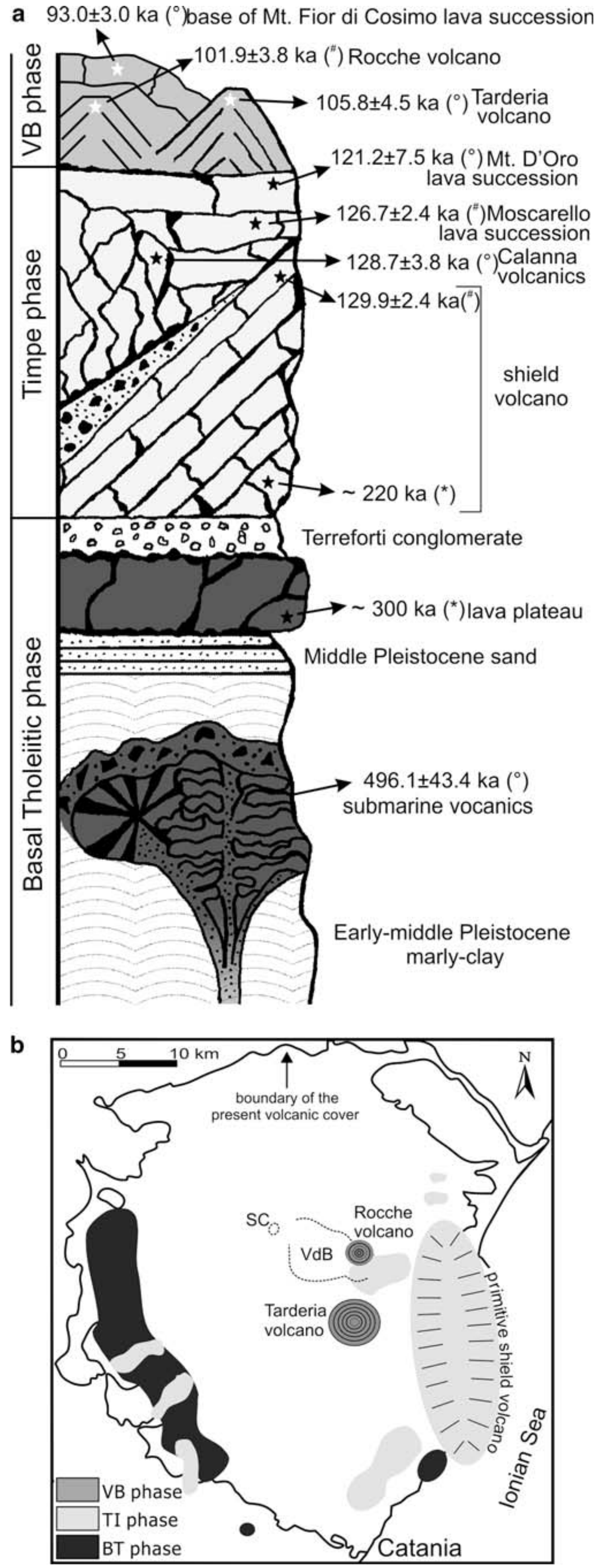


Fig. 10 Schematic reconstruction of: **a** stratigraphy from earliest products of the BT phase until the first central volcanism of the VB phase. Isotopic data: (*open circles*) this study; (*hashes*) De Beni et al. 2005; (*asterisks*) Gillot et al. 1994; and **b** areal distribution of the volcanic products erupted in this time span. *SC* summit craters; *VdB* Valle del Bove

struct a detailed geochronological evolution of the eruptive activity in the Etnean region from the early dispersal fissure eruptions until the central-type activity (Fig. 10) and we infer its relationship with the geodynamic framework of eastern Sicily. The main evolutionary stages are here summarized in the following steps.

1. About 500 ka ago tholeiitic pillow lavas were erupted on the sea floor of the Gela–Catania Foredeep basin.
2. It seems that a long hiatus preceded the eruptive activity in the Etnean region during which the regional uplift produced the gradual emergence of the sedimentary basement. Fissure-type eruptions produced thin tholeiitic lava flows that were emplaced on the paleo-alluvial plain of the Simeto River at about 300 ka ago forming a plateau more than 25 km wide. These lava flows reached the ancient coastline that was located close to Paternò town at about 14 km inland from the present coastline.
3. Between 220 and 121 ka ago volcanism became Na-alkaline and concentrated mainly along the Ionian coast. In this area fissure-type eruptions formed a shield volcano at least 15 km-long on a N–S direction. During this time span scattered effusive eruptions also took place in a wide area that corresponds at present to the lower south–west and south–east flanks of Etna. During the final stage of the growth of the shield volcano, about 129 ka ago, the eruptive activity moved, for the first time, to the area between Val Calanna and Moscarello locality evidencing that the plumbing system shifted westward from the Ionian coast. An intense fissure-type activity formed a thick lava succession that unconformably covered the shield volcano.
4. During the VB phase the stabilization of the plumbing system in the Valle del Bove area marked the beginning of the central-type activity with the initial construction of two small polygenic centres, Tarderia and Rocche volcanoes. They result aligned along a N–S direction and ended their eruptive activity about 106 and 102 ka ago, respectively.

The whole geochronological and geological dataset allow us to better understand the long-term relationships between tectonics and volcanism in the Etnean region. In particular, during the earliest BT phase the magma rise was driven by a general E–W extensional regime related to a major change in the geodynamics setting of eastern Sicily that reactivated the Malta Escarpment lithospheric fault system. The gradual development of this transform boundary between the Ionian basin and the Hyblean Foreland formed the Timpe fault system in the Etnean region. Starting from about 220 ka the extensional tectonic of the Timpe faults affecting the Ionian margin favoured the transition from the scattered volcanism of the BT phase to the shield volcano-forming activity during the TI phase. In this geodynamic context the magmatic supply rate from the mantle increased gradually favouring the stabilization of the Etna plumbing system in correspondence of the northern termination of the Timpe fault system. Since 129 ka ago, a gradual westward shifting of the volcanic activity from the tip of Timpe faults toward the VdB area, recorded by Calanna, Moscarello, Tarderia and Rocche volcanics, marked the transition from fissure to central-type eruptive activity.

Finally, further isotopic and geological investigations are in progress with the aim of defining the evolution of eruptive activity in the last 100 ka during which the large Etna statovolcano edifice was built.

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