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Structure and Evolution of Mount Etna [and Discussion]

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Structure and evolution of Mount Etna

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The present contribution is a short review of the actual state of our knowledge about the largest and most active European volcano. Some schematical figures will illustrate the results of research carried out recently on Mt Etna.

Pre-Etnean volcanism in eastern Sicily

The oldest volcanic rocks of Sicily have been encountered in wells sunk for petroleum research at Ragusa (SE Sicily). At a depth of about 1500 m submarine basaltic lavas, dykes and hyaloclastites are intercalated among Triassic sediments. Similar rocks exist also among lower Jurassic sediments, but the most important series of such rocks, reaching a thickness of 370 m, has been found in middle Jurassic deposits. Submarine basalts with hyaloclastites of Cretaceous age outcrop near Pachino and at Capo Passero.

Large amounts of basaltic and tephritic hyaloclastites, lavas and related pyroclastics outcrop more to the north in the Iblean Mountains. They were poured out from distension fissures on the bottom of a shallow sea in Neogene and early Pleistocene time. Locally, the volcanic activity lasted for longer periods, piling up central volcanoes which after tectonic uplift formed islands disseminated along tectonically weakened zones.

In the Middle Quaternary, on the area actually occupied by Mt Etna, there existed a large gulf in which clays of Sicilian age were deposited. Towards the end of this period, the volcanic activity migrated still farther north and reached this region. Submarine fissure eruptions of basaltic magmas produced mostly spilitized pillow lavas and hyaloclastites, at present well exposed at Aci Trezza and Aci Castello.

As a consequence of the tectonic uplift of Sicily, the pre-Etna gulf disappeared, and in its place a series of subaerial volcanoes built up the complex of Mt Etna.

Figure 1 illustrates the distribution and the migration of the volcanic areas from Middle Triassic time till today. The most important faults are indicated. As heavy basic magmas can erupt only if abyssal fissures are opened by regional tectonics, it implies that the whole region (including Libya and the sea south of Sicily) underwent tectonic distension characterized by fault-blocks and cratonic volcanism. This fact needs careful further investigation because it is very important for the understanding of the tectono-physics of the Mediterranean area.

To the north of Mt Etna, the tectonic style changes completely in the orogenic belt of the Peloritanian mountain range and in the volcanic Eolian island arc. This tectonic difference finds its counterpart in the bimodality of volcanism which demonstrates that there is no connexion and no magmatic relationship between Mt Etna and the volcanoes of the Eolian Islands. Strontium isotope ratios, σ and τ values,† alkali ratios and petrographical features confirm this statement.

† $\sigma = (Na_2O+K_2O)^2/(SiO_2-43)$ (Rittmann 1958),
$\tau = (Al_2O_3-Na_2O)/TiO_2$ (Gottini 1968; Rittmann 1967).

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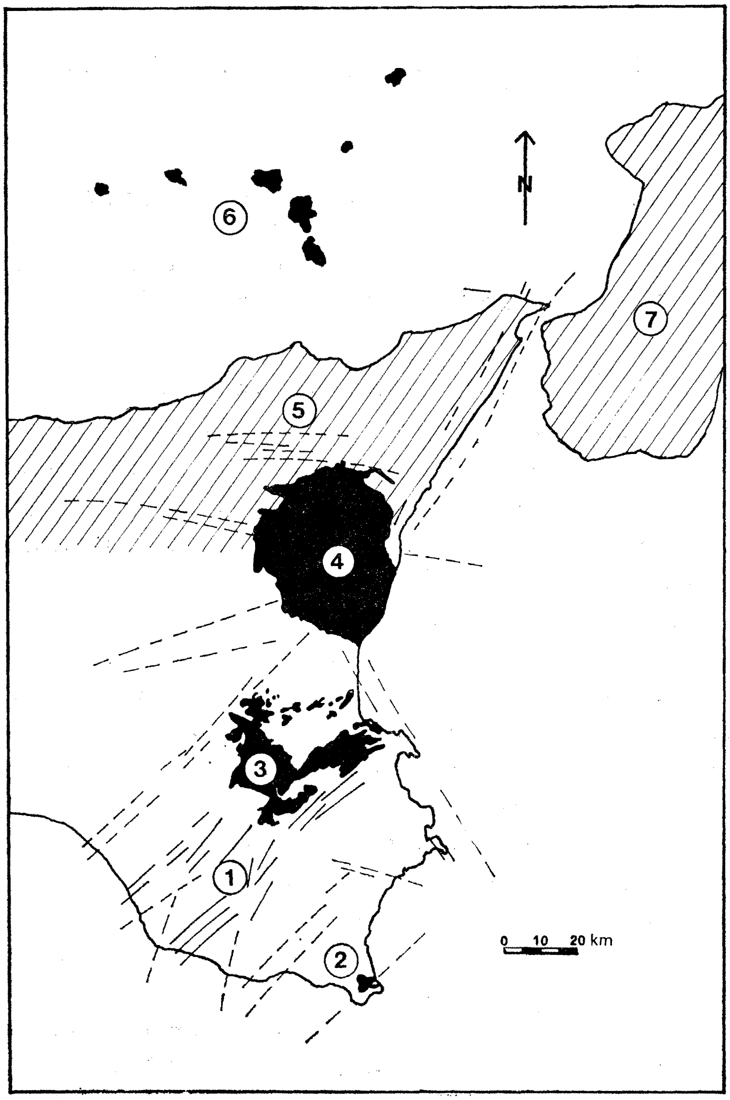

FIGURE 1. Volcanic formations in eastern Sicily. 1, Ragusa oil field (Triassic and Jurassic); 2, Pachino and Capo Passero (Cretaceous); 3, Iblean mountains (Neogene to Lower Pleistocene); 4, Mt Etna (Lower Quaternary to recent); 5, Peloritanian mountain range; 6, Eolian island arc (Quaternary); 7, Calabrian mountain range. 1 to 4: Cratonic volcanism: basaltic magmas and their derivatives; 6, orogenic volcanism: andesitic, dacitic and rhyolitic magmas. Important faults are indicated following the official geological map of Sicily (Beneo).

Tectonic setting of Mount Etna

The straight coast of NE Sicily is due to a system of NNE–SSW directed step faults which border the rising blocks of Sicily. Numerous earthquakes demonstrate that the tectonic movements are still going on along the major fault system. This is also confirmed by a series of very young fault scarps, locally called 'timpa'. A second series of faults is directed ENE–WSW, a third, less important one has ESE–WNW direction. The ascent of magma is particularly faciliated along the intersections of faults. The distribution of the eruptive centres reflects the regional tectonics of the basement as illustrated in figures 2 to 4.

The progressive uplift of the sedimentary substratum of Mt Etna is proved by outcrops of Sicilian clays (Lower Quaternary) at an altitude of about 800 m on the eastern slope of the

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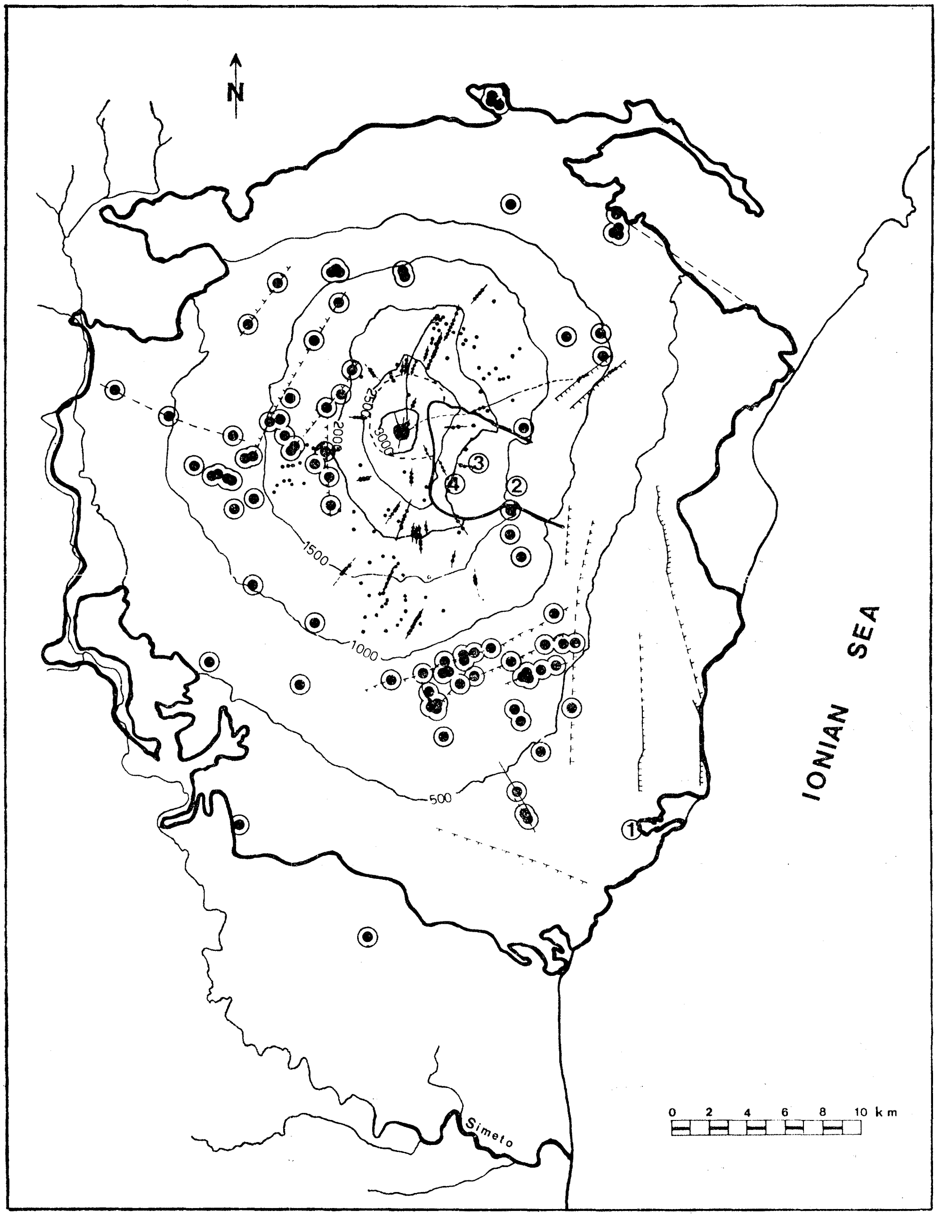

Figure 2. Volcano-tectonic sketch map of Mt Etna. —, Boundary of Etnean volcanic formations, and rim of the caldera of the Valle del Bove; · · ·, ——, Central Crater, lateral eruptive centres and eruptive radial fissures; ⦿, eccentric volcanoes ('adventive cones'). 1, Submarine volcanics of late Sicilian age; 2, Calanna volcano; 3, Trifoglietto I volcano; 4, Trifoglietto II, volcano. Fault scarps ('timpe') and faults or fissures, deduced from the alinement of eccentric volcanoes, are indicated (– – – –).

volcano, whereas at its western foot Neogene marine sediments reach 1050 m above sea level. To the north, lava flows of Mt Etna cover the front of quite superficial nappes of the Peloritanian mountain range, which rest on a block faulted substratum.

On the eastern slope of Mt Etna there exists a wide horseshoe-shaped caldera called Valle del Bove. The walls of this nearly 1000 m deep depression offer an insight into the structure of the volcano permitting us to deduce the evolution of this complex edifice.

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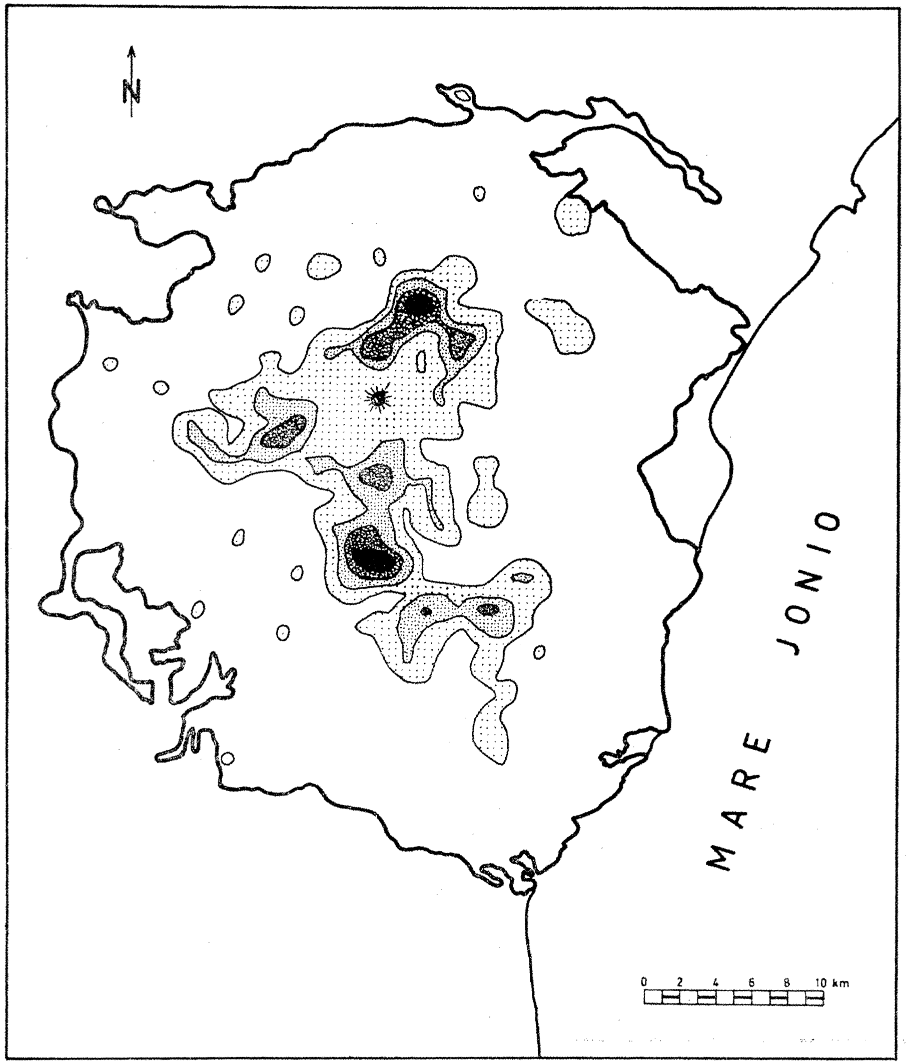

Figure 3. Density distribution of eruptive centres on Mt Etna. The dark areas of greatest density contain more than two centres per square kilometre. The distribution reflects the regional tectonics of the substratum, providing thus an argument against the existence of a large magma chamber.

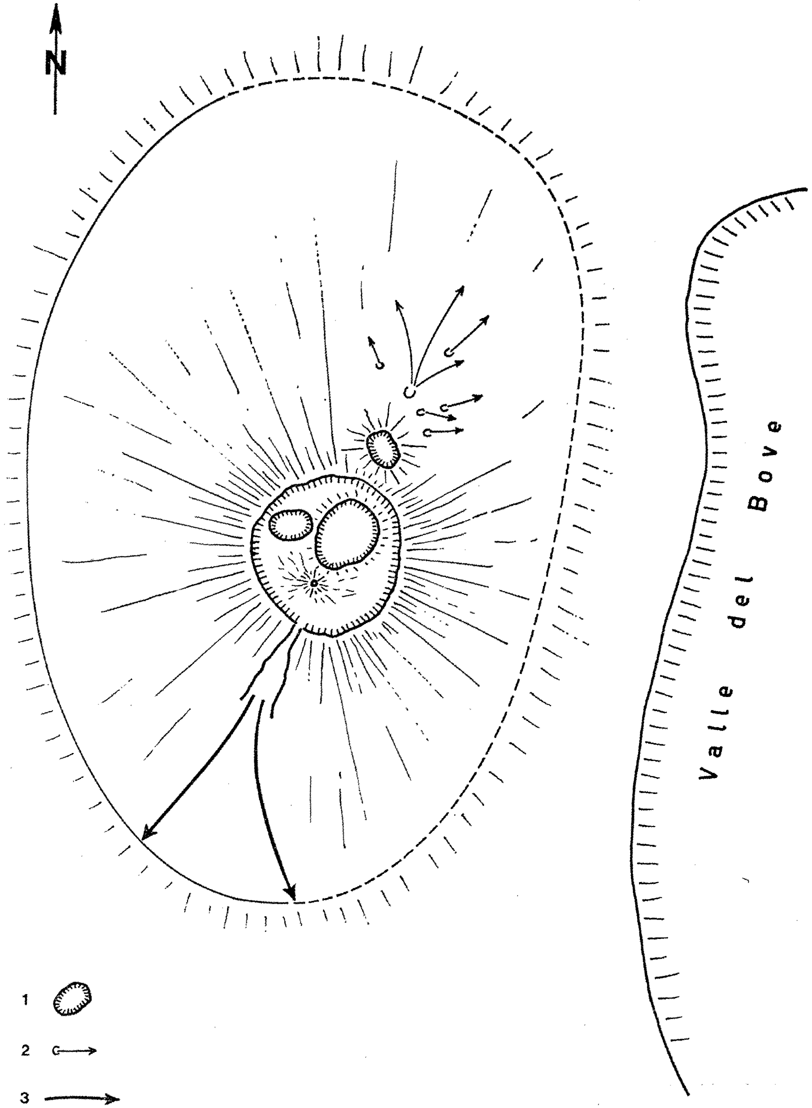

Figure 4. Sketch of the summit region of Mt Etna. 1, Crater rims; 2, ephemeral effusive boccas; 3, direction of lava flows. The NNE–SSW alinement of the 1964 cone, the chasm and the NE-crater indicates the direction of the regional tectonics of the substratum.

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The evolution of Mount Etna

The five schematical sections of figure 5 represent the known stages of the evolution of Mt Etna, which may be characterized briefly as follows:

(1) *Pre-Etnean volcanic activity*

Some 300000 years ago, fissure eruptions at the bottom of the pre-Etnean Gulf produced lava flows, pillow lavas and hyaloclastites of originally basaltic composition. Most of these rocks became altered by spilitization.

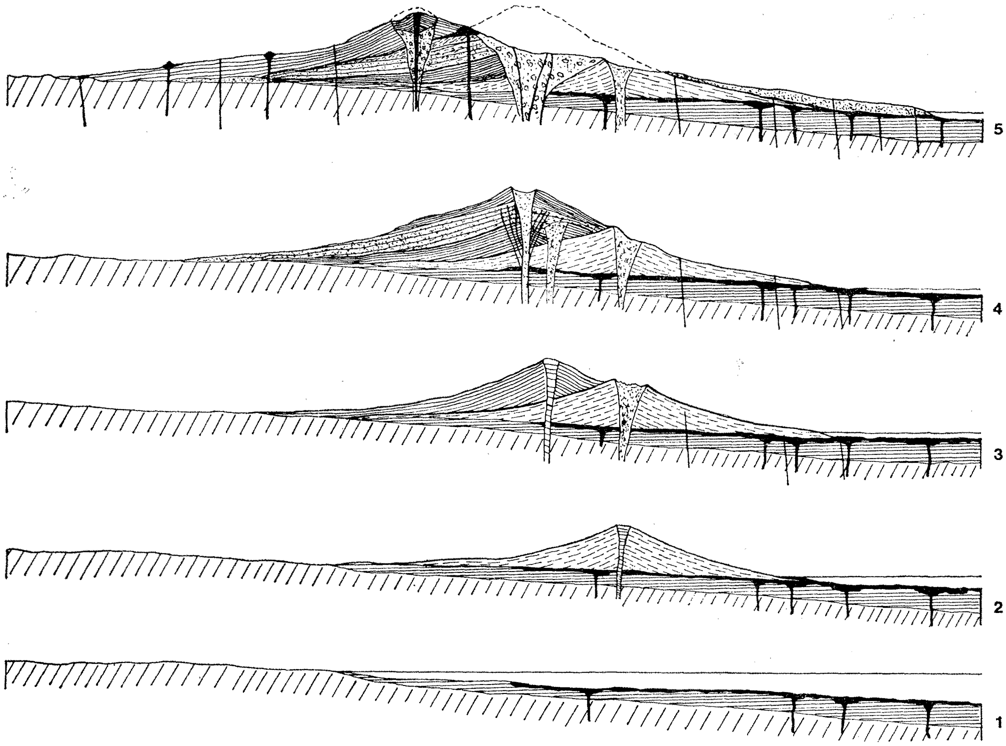

FIGURE 5. Schematical sections illustrating the evolution of Mt Etna. 1, Submarine fissure eruptions in the Pre-Etnean Gulf; 2, subaerial volcano of Mt Calanna; 3, Trifoglietto I volcano; 4, Trifoglietto II volcano; 5, Mt Etna at present.

(2) *Calanna volcano*

Much later, after considerable tectonic uplift, a subaerial strato-volcano was piled up by lava flows and cinders. Its remnants outcrop in the Val Calanna. Other subaerial volcanoes may have been formed earlier, but up to now no corresponding outcrops are known.

(3) *Trifoglietto I volcano*

While the Calanna volcano had become inactive and partially eroded, a new strato-volcano was built up farther west and covered most remnants of the previous one.

(4) *Trifoglietto II volcano*

After another westward shifting of the eruptive centre, the Trifoglietto I was also buried in its turn beneath the pyroclastic materials and lava flows of a great strato-volcano which grew to a height of more than 3000 m. On its western slope, some small volcanoes were formed; then

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the central parts of the Trifoglietto volcanoes were destroyed by explosions or collapsed, and in their place there originated a deep depression called Valle del Bove.

(5) *Mongibello* (name given to the presently active volcanic cone).

This youngest and still active part of Mt Etna is situated again to the west of the older volcanoes. In accordance with its predominating effusive activity, Mongibello has the structure of a shield volcano, but being established on a horst-like sedimentary substratum and on the remnants of older volcanoes, it has rather the shape of a somewhat asymmetrical strato-volcano with a 2000 m wide elliptical crater in which a 300 m high cone of cinders and lava flows has been piled up, which, in its turn, has a 500 to 600 m wide summit crater. During the terminal eruption in 1964, also in this central crater, a cinder cone was built which has grown higher than the crater rim. The actual vent of Mt Etna terminates within the central crater in a deep chasm. In 1968 a blow hole opened from which, for about two years, glowing gases were puffed out violently at short intervals. A new crater originated in 1921 at about 500 m to the NNE of the central crater. This subterminal 'NE-crater' has been active since its birth (figure 4).

Activity of Mount Etna

Most of the time, Mt Etna exhibits a so-called persistent activity, either in the central crater or in the subterminal NE crater. The mechanism of this persistent activity consists in dynamic equilibrium fluctuations between the gas tension of the magma and the external pressure due to the load of the magma column and to the viscosity and surface tension of the melt. At depth, where the external pressure is greater than the gas tension, the gases are molecularly dispersed in hypomagma. At higher levels, the gas tension overcomes the hydrostatic pressure, causing the separation of a gas phase in the pyromagma. Bubbles and trains of bubbles are rising and exploding at the surface violently enough to throw clods and spatters of lava into the air. Such a *persistent activity* can last for months and years with fluctuations, until the dynamic equilibrium is broken by an outside event.

The manifold eruptive activity of Mt Etna may be classified accordng to two different principles based either on the location of the eruptive centre, or on the type of eruptive mechanism. In the past these two parameters have been mingled, so that some denominations could be misunderstood. In order to improve the nomenclature of Etnean eruptions, the following terms are here proposed:

(A) *terms indicating the location of the event:*

terminal (central crater);
subterminal (summit region above 3000 m);
lateral (flanks of the volcano between 1000 and 3000 m);
sublateral (lower flanks beneath 1000 m);
peripheric (outside the area occupied by the main volcano).

(B) *terms indicating the types of eruptive mechanism:*

persistent activity at an open vent (terminal or subterminal);
central eruptions (terminal), explosive or mixed;
mantle sill effusions (subterminal or lateral), connected with strong persistent activity;

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mantle sill eruptions (subterminal or lateral), mixed;
radial fissure eruptions (subterminal, lateral, sublateral), mixed;
eccentric eruptions (lateral, sublateral, peripheric), mixed,
independent of the existing vents.

With the exception of the explosive central eruptions, all eruptions of Mt Etna are predominantly effusive with an average index of explosivity, E, about 4 % (E = 100 pyroclastics/total production), i.e. like most Hawaiian volcanoes.

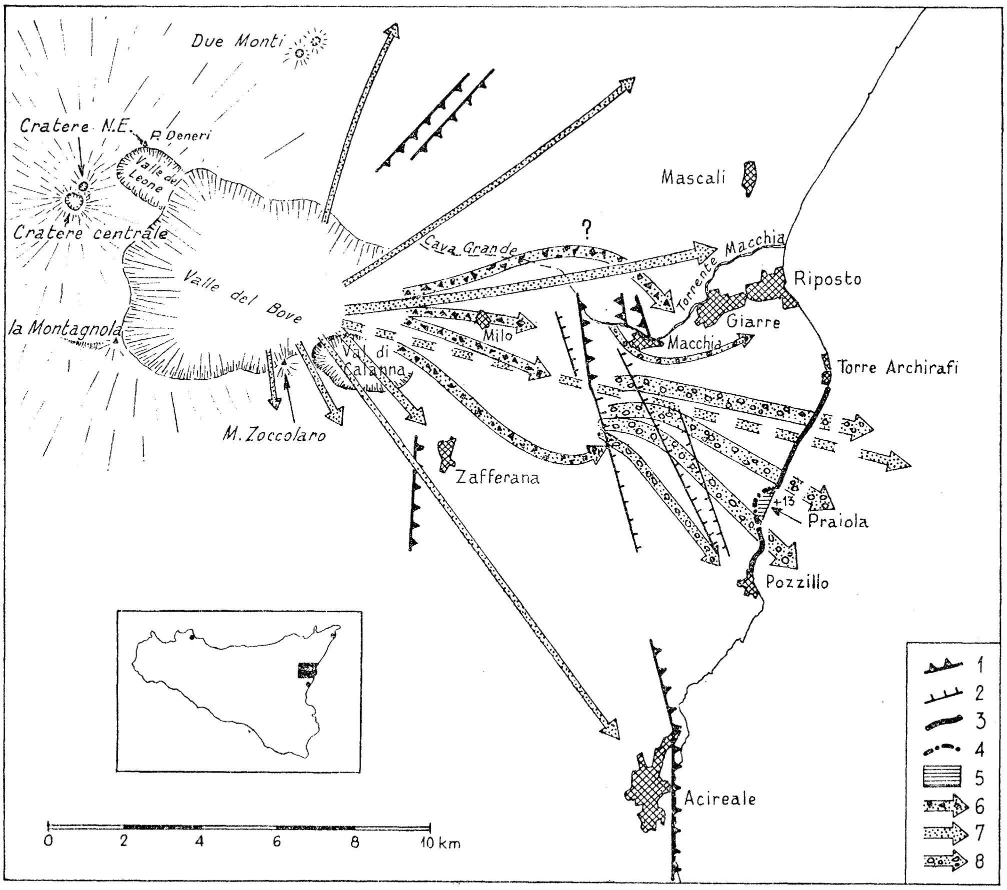

FIGURE 6. Scheme of the dispersion of loose materials deriving from the Valle del Bove (after Kieffer 1970). 1, Faults (older than the deposits); 2, faults (younger than the deposits); 3, cliffs in formation; 4, ancient cliffs; 5, uplifted beach; 6, breccia (mostly lahars); 7, ash with pumice; 8, conglomerates (mostly reworked lahars).

Origin of the Valle del Bove

Several hypotheses have been proposed by authors to explain the origin of the horseshoe-shaped caldera on the eastern slope of Mt Etna. Erosion by torrents or glaciers, tremendous volcanic outburst, volcano-tectonic collapse after such an explosion or in consequence of a lateral withdrawal of magma from a great magma chamber beneath the Trifoglietto volcanoes have been invoked to solve the problem. In the author's opinion, none of these attempts offers a satisfactory explanation. Till now, the best solution of this puzzling problem seems to be the following.

Similar to the Bandai San Caldera formed in 1883, the eccentric caldera of Mt Etna may have originated with phreatic explosions which demolished the eastern part of the Trifoglietto

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volcano causing a series of lahars. The deposits of these mud flows, partly reworked by torrential floods, cover the lower flank of the volcano and form a large delta on the coast (figure 6). Later magmatic explosions occurred and ejected considerable amounts of ash, sand and pumice. Most of these loose pyroclastics are now eroded, but in many places up to 20 m thick deposits are still preserved. After such an outburst, the caldera was enlarged by a volcano-tectonic collapse. Landslides and erosion caused a further enlargement. This hypothesis explains the observed facts, but a detailed study of the deposits, locally called 'chiancone' will reveal a more accurate story of the origin and evolution of the Etnean caldera.

The lavas of Mount Etna

The pre-Etnean lavas are basalts and alkali basalts. The Calanna volcano poured out hawaiites and phonolitic tephrites, whereas the products of the Trifoglietto volcano are mugearites, latite andesites and, later on again, hawaiites and tephrites. The products of the active volcano are mostly hawaiites and tephrites. Some representative analyses are given in table 1, and the calculated mineralogical composition is illustrated in figure 7.

Table 1. Chemical analyses of some typical lavas of Mount Etna

	1	2	3	4	5	6
SiO_2	46.68	49.48	49.10	56.08	57.24	50.10
Al_2O_3	14.40	15.43	19.66	19.35	16.95	18.83
Fe_2O_3	1.70	2.15	6.25	4.22	3.27	2.70
FeO	9.48	8.56	2.39	2.22	3.59	5.52
MnO	0.17	0.16	0.14	0.08	0.15	0.13
MgO	10.89	8.61	3.79	2.08	2.62	2.79
CaO	9.81	9.88	8.68	4.61	5.19	8.09
Na_2O	3.06	3.20	4.63	6.16	5.40	6.97
K_2O	0.32	0.34	1.59	3.43	2.66	2.24
TiO_2	1.84	1.37	1.17	0.78	1.49	1.97
P_2O_5	0.27	0.32	0.71	0.46	0.69	0.67
H_2O^-	0.05	0.23	0.40	0.37	—	none
H_2O^+	—	0.58	1.02	0.65	0.46	0.02
l.o.i.	1.05	—	—	—	—	—
total	99.82	100.31	99.53	100.49	99.71	100.03

1, Olivine basalt. C. da Fossa della Creta, Biancavilla. Analyst: R. Romano (total iron as Fe_2O_3 = 12.23).
2, Basalt. Costa Menola, Adrano (Atzori 1966).
3, Hawaiite. Valle del Bove: lava flow post-Trofoglietto. Analysts: M. J. Fancois, I. Roelandts & G. Bologne (Klerkx 1968*a*).
4, Mugearite. Mt. Zoccolaro, Valle del Bove. Analysts: M. J. Francois, I. Roelandts & G. Bologne (Klerkx 1968*a*).
5, Latite-andesite. Mt. Calvario, Biancavilla. Analyst: R. Romano.
6, Phonolitic nepheline tephrite. Lava of 1329, Mt. Rosso, near Fleri. Analyst: M. G. Keyes (Washington, Aurousseau & Keyes 1926).

The succession of the various types of magmas is irregular. During the same period of activity, different lavas have been poured out at different places. Even in single lava flows, rather large variation in composition has been found. These facts confirm the non-existence of a single great magma reservoir beneath Mt Etna. On the contrary, they can easily be explained by admitting a series of abyssal fissures through which the deep-seated magma rises toward the surface.

An interesting heteromorphy can be observed, especially in hawaiitic lavas, which may contain many large phenocrysts of plagioclase or largely predominating phenocrysts of

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clinopyroxene. The former type, locally called 'cicirara', is common in subterminal lava flows, whereas the augite porphyritic type is characteristic of eccentric or lateral lava flows. This heteromorphy is evidently due to different water pressure during the formation of phenocrysts and gives a hint about the depth at which the early crystallization took place.

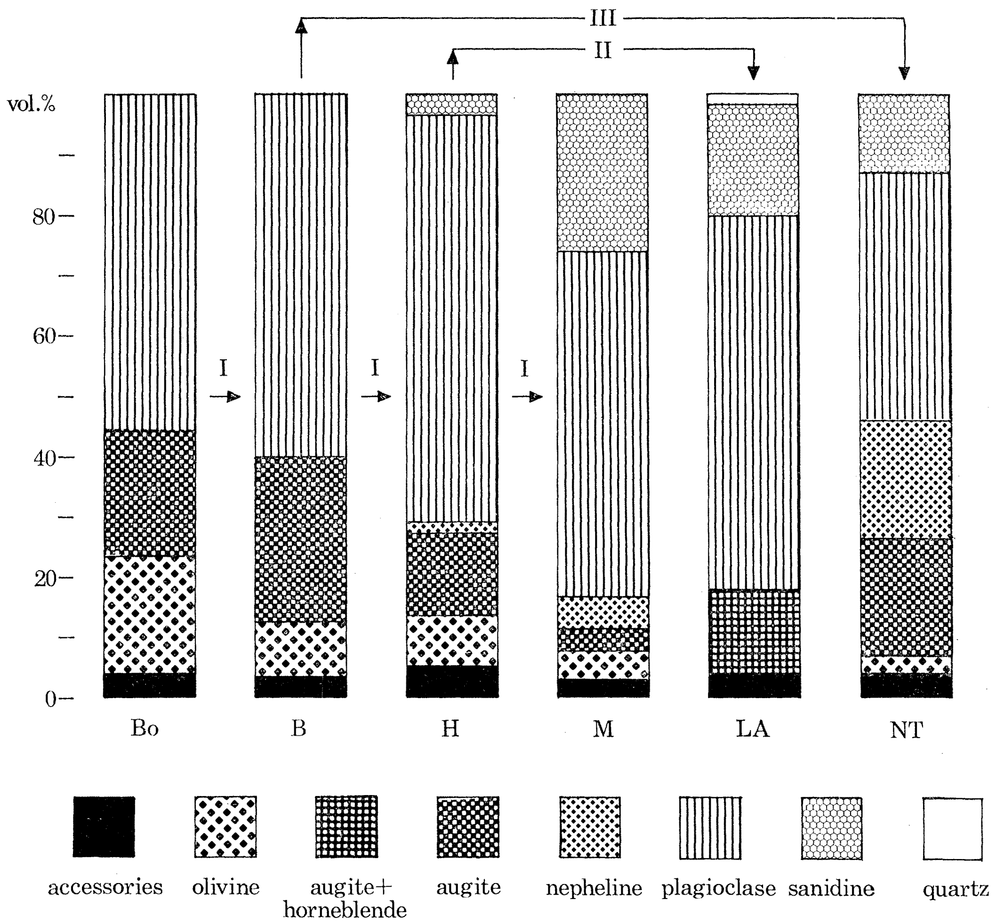

FIGURE 7. Calculated mineralogical composition (R-norm) of some Etnean lavas. OB, Olivine basalt; B, alkali-basalt; H, hawaiite; M, mugearite; LA, latite-andesite; T, nepheline tephrite; I, gravitative crystal differentiation; II, complex differentiation; III, pneumatolytic differentiation.

Differentiation of Etnean magmas

Like most lavas in the Iblean mountains, the oldest Etnean lavas are olivine basalts and alkali basalts of upper mantle origin. All other types found on Mt Etna must be considered as differentiates of a primary basaltic magma. No sign of contamination by non-magmatic rocks could be detected.

On many occasions, as for instance in the lavas of the recent eruption (R. Romano 1972, this volume), the effects of complex processes of differentiation could be ascertained. There is evidence of pneumatolytic differentiation, due to gaseous transfer of pneumatophile elements such as Na, Fe, Ti, etc. For instance, alkali basaltic magmas may be converted into tephritic ones by the supply of these elements, whereby the colour index remains practically unchanged. The counterpart of this process consists in an impoverishment in sodium of the deep-seated

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alkali basaltic magma which, thus, becomes less undersaturated or perhaps even slightly oversaturated.

Gravitative crystal differentiation in alkali basaltic magma leads to hawaiitic and mugearitic rocks with low colour index in consequence of olivine and augite being subtracted. Under high P_{H_2O}, hornblende may form instead of olivine and augite. Its subtraction by gravitative differentiation may produce remaining melts of oversaturated latite-andesite composition, especially if the original magma was already impoverished in Na by gaseous transfer.

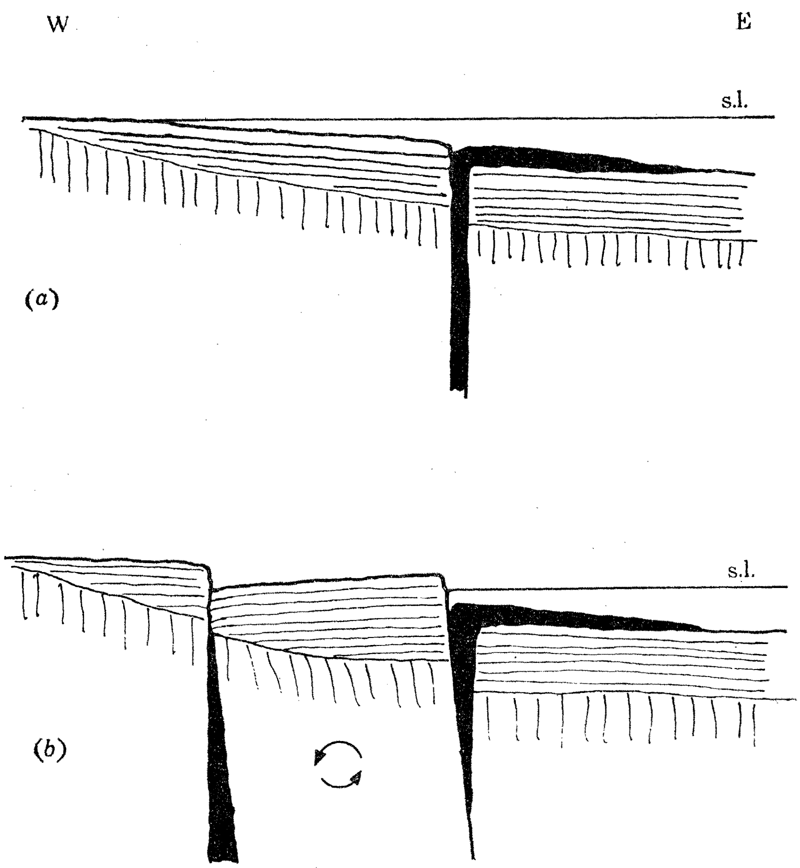

FIGURE 8. Tectonic control of magmatic differentiation. Opening of fissures by distensional tectonics (*a*) permits eruption of undifferentiated magma. Tilting of blocks (*b*) closes the fissures and favours differentiation (after Romano 1970).

Any process of differentiation requires an adequate physical environment. The most favourable condition for gaseous transfer is realized in the pyromagma by a weak to moderate two-phase convection which, generally, is linked to fumarolic activity in the crater. During a period of persistent activity, the pyromagma is continuously stirred by violent convection which prevents any gravitative crystal differentiation but favours gaseous transfer. However, the explosive degassing will drag the pneumatophilic compounds into the open air without producing any appreciable pneumatolytic differentiation.

On the contrary, gravitative crystal differentiation can occur only in a not too viscous stagnant magma. Its effect depends, naturally, upon the composition of the magma and its gas content.

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Tectonic control of the differentiation

The more or less favourable conditions for a given process of differentiation are governed by the mechanism of opening of the feeding fissures or vents, which in turn is conditioned by tectonic movements of the crustal blocks. If an abyssal fissure opens to the surface, undifferentiated basaltic magma will be poured out. If the uppermost part of the fissure or vent is blocked by debris, pyroclastics or lavas, allowing only a fumarolic activity, then pneumatolytic differentiation will set in. On Mt Etna, the top of a feeding fissure may also be closed hermetically by clays. In this case, crystal differentiation will occur within the quiet magma and the gases will accumulate in the remaining melt in which the vapour pressure may become so high as to cause the formation of hornblende instead of augite (figure 8).

This short and incomplete account of the actual state of our knowledge about Mt Etna shows that, notwithstanding the considerable results of recent research, many problems are only approximately solved or are still open. Much research work has to be carried out till we get a satisfactory picture of the complicated features of Mt Etna, which in many respects is the most interesting volcano for its eruptive mechanism, the origin and evolution of its magmas and, particularly, for its tectonic setting in relation to the general tectono-physics of the extremely complicated Mediterranean region.

A systematic survey of Etna's activity by means of well-equipped geophysical stations does not exist. Even a careful geological survey, correlated to more extended petrographical and geochemical studies, is badly needed. Investigation of gases and fumarolic products should be intensified, to mention only a few items.

Much time and a great number of specialists are necessary to reveal the fascinating secrets of Europe's most important volcano. Such an extended and manifold research work can be carried out only in the frame of a well-organized international collaboration.

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Discussion

Dr M. Sato asked if the mechanism of evolution of the 1971 lavas envisioned by Dr Romano would require temporary pooling of the magma in some kind of reservoir. This hypothesis is in contradiction to Professor Rittmann's statement that there is no magma chamber beneath Etna. How does Dr Romano or Professor Rittmann resolve this contradiction?

Professor Rittmann: The field evidence on Mt Etna supports the view that eruptions are related to a complex fissure zones trending NNE and ENE across the mountain. Each eruption occurs from one individual segment within the zone. It is also observed that eccentric eruptions are usually independent of activity at the summit. From this it is concluded that magma differentiation takes place in individual dykes within this system, and that there is no pool of lava forming a magma chamber in the classical sense. Instead, lava is stored in a complex dyke system. The small amount of differentiate produced in the 1971 eruptions is consistent with this concept.