PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Recent Trends in the Study of Etna [and Discussion]

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Recent trends in the study of Etna

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Etna is the most recent and northernmost part of the volcanic province of SE Sicily. It is located north of a fast subsiding recent depression (Catania Plain) in the axial region of an isostatically rising broad anticline trending E–W. This structure has been cut by a belt of regional faults parallel to the coast between Catania and Messina, with an overall seaward downthrow.

Mt Etna is composed of different volcanoes which have in part grown side by side and in part one on top of the other: several units of this complex sequence have been recognized, but the geological picture of Etna is far from being complete.

Few tholeiites and alkali basalts have been recognized among Etnean lavas, the bulk being alkali andesites (hawaiites l.s.) to latitandesites (mugearites l.s.). Petrological research on Etna can give valuable information about the differentiation processes affecting basaltic magmas in a similar tectonic setting.

Introduction

In SE Sicily volcanic activity has been intermittently present since middle Trias (Cristofolini 1966) and always showed features consistent with an origin of magmas in the upper mantle.

Volcanic rocks have been found in deep boreholes in the Ragusa and Gela oilfield at various levels in the sedimentary limestone sequence and outcrop at Pachino (the southern-most point of Sicily) where they are overlain by Cretaceous reef limestones.

Conspicuous outcrops of volcanic rocks of Upper Miocene to Pleistocene (Calabrian) in age are known from the northern part of the Iblean plateau, where different tectonic lines intersect. This region is to be considered as transitional between the foreland and the Sicilian geosyncline. Starting from Middle Miocene (Di Grande 1968) several sedimentary cycles took place around this unfolded area showing that this was subject to active vertical displacements. These movements gave rise to complicated sets of faults in the Iblean region and to a series of northward dipping flexures, gradational into faults, and small grabens along its northern boundary. Furthermore, a great regional tectonic line, that has been recently interpreted (Ogniben 1969) as a transcurrent fault, intersects this region, striking NNE from Còmiso to Messina.

These tensional tectonic movements can be held responsible for providing a way for deep-seated magmas up to the surface.

Structural features of Etna

Etna is located north of the Iblean shelf area on top of an E–W trending anticlinorium, at the southern boundary of a miogeosynclinal basin (Ogniben 1960, 1963), where this is cut by the Còmiso–Messina tectonic line. In the Etnean region the sedimentary sequence is formed of strongly eroded autochtonous material and allochtonous nappes, partly covered by marine Lower Pleistocene (Sicilian) marly claystones. These, and the subsequent alluvial deposits, in the Catania plain mark the area of the fast subsiding Pleistocene gulf that separated the Iblean plateau from the first volcanic occurrences in the Etnean region.

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Both the Iblean plateau and the Etnean region are isostatically rising so that Sicilian claystones are now found at an elevation of about 500 m near Militello (Iblean plateau) and at 800 m on the NE slopes of Etna. These vertical displacements are still active and evident according to Platania (1915) and G. Kieffer (oral communication) along the coast.

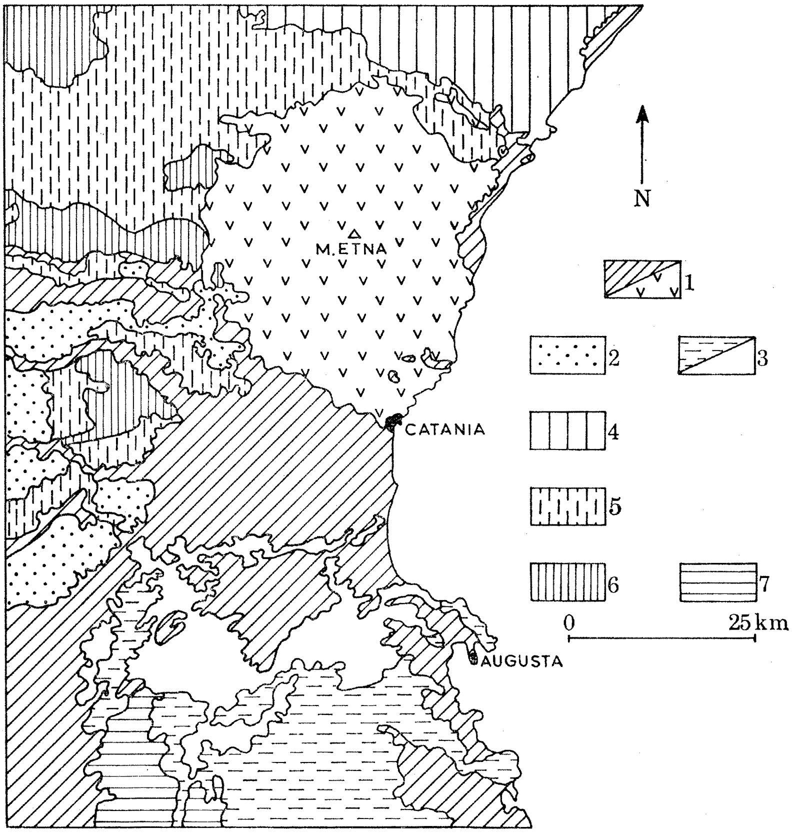


Figure 1. Geological sketch map of the region around Catania: (1) Pleistocene sedimentary rocks and volcanic rocks from Etna; (2) Middle Miocene to Lower Pliocene sedimentary rocks (mainly sandstones and claystones); (3) Middle Miocene to Lower Pliocene limestones and volcanic rocks from Iblean highlands; (4) Calabride complex; (5) Sicilide complex; (6) Basal complex (Lower Miocene), mostly quartzarenitic sandstones of the miogeosyncline basin; (7) Lower Miocene limestones of the Iblean foreland.

The significance of the tectonic position of Etna and the bearing of the regional tectonic features on the structural and chemical evolution of this volcano must be carefully evaluated. In the last few years some knowledge has been gained about these problems, and will be briefly discussed here.

Even if Etna can be easily considered as a part of the southeastern Sicily volcanic province (Burri 1961; Rittmann 1963; Cristofolini 1966), its products show systematic and significant differences from Iblean volcanic rocks. Most of the Iblean rocks were formed in an underwater environment, possibly from fissure vents and are basalts with tholeiitic and alkalic affinities accompanied by a few nephelinites. Furthermore, most Iblean rocks have a low content of phenocrysts and show little evidence of having undergone strong differentiation at shallow depth: even if much of the analytical work has yet to be done, intermediate and acid differentiates have not been found up to now.

Among Etnean lavas very few have been found with a primitive basaltic chemistry, most of them being alkali andesites (hawaiites l.s.) and tephrites to latitandesites (mugearites l.s.).

Much of the recent research has been devoted to a better understanding of the volcanic sequence in the Etnean region.

Etna is a complex volcano composed of many units or complexes that can be regarded as simple volcanoes, each characterized by an independent vent or eruptive axis. As a result the geological picture is very confusing because probably in no place can the whole sequence be found owing to the growth of single units side by side and partly overlapping.

For historical and geographical reasons the name Etna should be used for the complex volcano as a whole and the simple volcanoes should be given different names. Lyell (1859) and Gemmellaro (1860) showed the way by unambiguously naming the different simple volcanoes that can be recognized on Etna, after the name of the site of their main volcanic axis: they suggested Mongibello for the present-day volcanic unit and Trifoglietto for an ancient volcano whose products outcrop along the walls of a caldera (Valle del Bove), east of Etna's top.

Klerkx (1968, 1970) showed that volcanic activity migrated with time in the area of the Valle del Bove, and similar conclusions were reached by Marchesini, Conedera, Morabito & Maci (1964) from an analysis of the elliptical contour of the topmost part of Etna which is not consistent with growth from a stable central axis.

Considering recent and historical activity one must conclude that volcanic activity on Etna has readily migrated with time: some of the adventive cones, interpreted as 'eccentric' after Rittmann (1963), can be considered nothing else than abortive simple volcanoes.

All of these features can probably be related to the particular geologic and tectonic setting of the Etnean region. Detailed research devoted to the possible connexion between tectonic features and the development of the volcanic complex of Etna can be very fruitful.

The sequence of volcanic activity in the Etnean region

There is fairly good evidence that among the first lavas to be erupted some had a tholeiitic chemistry (Atzori 1966; Cristofolini 1972; Sturiale 1968; Tanguy 1967). Some of them, mostly subaerial lavas, outcrop along a terrace scarp low on the SW slopes of Etna between Adrano and S. Maria di Licodìa while others, to be interpreted as shallow intrusions and submarine eruptions, are found in skerries (Faraglioni) and on shore between Aci Trezza and Aci Castello (a few kilometres north of Catania). They belong to one or more cyles of activity that eventually built several small shield volcanoes, which are now hidden below the mass of later lavas.

The subvolcanic masses of Aci Trezza–Aci Castello are intruded near the top of lower Pleistocene (Sicilian) marly claystones, while the Adrano–S. Maria di Licodìa level forms the highest and therefore the oldest order of river terraces in the southwest part of Etna (Cristofolini 1967, 1972) and lies over folded and deeply eroded Tertiary sedimentary rocks of the basal complex at an elevation between 600 and 400 m above sea level.

This level can be stratigraphically correlated southeastwards with small outcrops of similar lavas lying on top of the Sicilian claystones (Motta S. Anastasia, Valcorrente) and with polygenetic conglomerates that could either mark the end of the Sicilian transgressive cycle (Wezel 1967) or be much younger (G. Kieffer 1971, personal communication). In this area the volcanic activity could therefore be as old as late Sicilian or even younger.

These early erupted basalts, with marked tholeiitic affinities, were followed and perhaps accompanied in part by much more voluminous lavas forming the bulk of the complex volcano and belonging to an alkali basalt–trachyte differentiation series (Chayes 1963).

The main features of the whole sequence are a generally high content of phenocrysts (up to 40 % by volume), except for the highly differentiated lavas, the complex zoning of the plagioclase phenocrysts, the presence of glomerophyric aggregates with mafic and salic minerals generally tending to cluster separately.

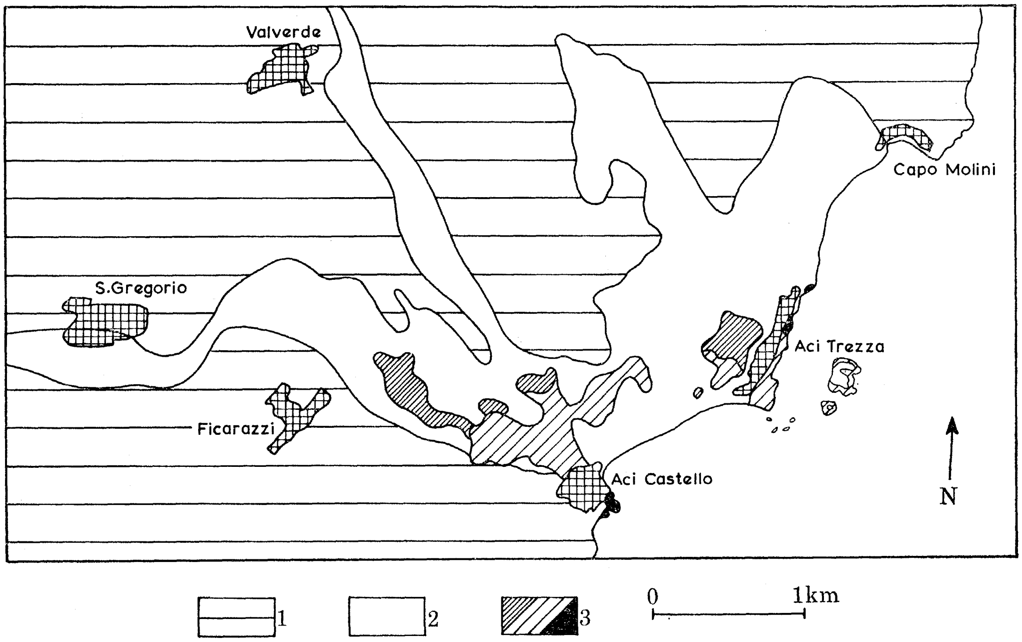


FIGURE 2. Geological map of the area near Aci Castello (modified from Sturiale 1968): (1) lavas from Etna; (2) Lower Pleistocene (Sicilian) marly claystones; (3) volcanic breccias with pillows; subvolcanic columnar masses; pillow-lavas.

Chemistry of these rocks is peculiar because true basalts are almost absent among them (Carapezza 1962*a*; Spadea 1972), alkali andesites (hawaiites l.s.) and latitandesites (mugearites l.s.) being the most common rock types (Carapezza 1962*a*; Castiglione 1958; Cristofolini & Lo Giudice 1969*b*). In some units tephrites are present.

In the latitandesites and tephrites, alkali feldspar and nepheline respectively are occult in the groundmass and can be detected only by X-ray diffraction methods (Tanguy 1966; Cristofolini & Lo Giudice 1969*b*); the latitandesites quite often possess kaersutite and small brown apatite phenocrysts (Klerkx 1964, 1966, 1968; Cristofolini & Lo Giudice 1969*b*; Lo Giudice 1970) as a distinctive character.

The oldest members of this widely evolved sequence are probably best exposed along the eastern slopes of Etna between Acireale and Piedimonte. In this area many N–S trending fault scarps (Carapezza 1962*b*; Cassinis, Cosentino, Ponzini & Riuscetti 1971) dissect old volcanic piles, which only with difficulty can be correlated with relatively well-known volcanic units. These old sequences have been only poorly examined; preliminary investigation plus the collection of some chemical data from previously published papers, show that quite differentiated members are very often present among these lavas. Latitandesite pumice (Sturiale 1967*b*) has been found in the top layers of the Sicilian claystones of Mt Vamboleri (near Aci Trezza), that could be tentatively correlated with the lowest differentiated flows outcropping near sea level along the Acireale fault scarps. If so, this sequence could be late Sicilian in age and contemporaneous with the shallow intrusions of tholeiitic affinities that occur at Aci Trezza; i.e. two volcanic centres characterized by widely differing products were active in contiguous areas.

The Acireale sequence is overlaid by a thick tuffaceous, conglomeratic layer, containing marine fossils (Ferrara, in preparation). This horizon is not easily related to any of the volcanic units outcropping in the Valle del Bove and recognized by Klerkx (1968, 1970) owing to the complex fault pattern in this densely populated and cultivated area, and the uniform appearance of the outcropping lavas.

The presence of several widespread volcaniclastic units could be very useful in recognizing the whole sequence, once their extension, significance, and stratigraphic position has been established. Kieffer (1970*a*, *b*) dates the youngest of these levels, a fine-grained yellowish ash with latitandesite pumice fragments, as about 5000 years old, and refers it to the formation of the caldera depression in the Valle del Bove.

Two objections are raised by Klerkx (1970) to this interpretation; (*a*) the last lavas to be erupted by the Trifoglietto II were tephrites, and there is no evidence for the presence of latitandesites at this stage; (*b*) the time gap between the Trifoglietto II (older than 25000 years) and the latitandesite pumice eruptions is too large to allow such a correlation in a volcanic area as complex as Etna, where volcanic activity looks to have been quite continuous.

Other volcaniclastic layers, partly interbedded in the volcanic sequence and partly forming a sedimentary body like an alluvial fan at the foot of the fault scarp west of Giarre, have been recently interpreted either as alluvial deposits from a fast-rising topographic high (Cassinis *et al.* 1971), or as partly reworked mud flow deposits (or lahars) from phreatic explosions (Kieffer 1970*a*).

Lithological similarities are unfortunately not sufficient to establish certain relations at these levels and a very detailed study taking into account every feature of them is needed before they can be taken as useful markers in the geology of Etna.

In the Valle del Bove and surrounding areas the best sequence has been established. From top to bottom the following units have been recognized:

(*a*) Mongibello sequence (Lyell 1859; Cristofolini 1967) also includes products from parasitic vents (subterminal, lateral and eccentric eruptions) (Rittmann 1963) related to the main eruptive axis, active also at the present time.

(*b*) Vavalaci complex (Cristofolini & Lo Giudice 1969*b*; Lo Giudice 1970), that is best exposed along the SW edge of the Valle del Bove, and outcrops also downslope near Adrano and Biancavilla.

(*c*) Trifoglietto II lavas and pyroclastic sequence (Klerkx 1968, 1970), which is particularly well exposed along the walls of the Valle del Bove.

(*d*) Trifoglietto I unit (Klerkx 1968), which is essentially pyroclastic and outcrops at the bottom of the Valle del Bove near its northern wall.

(*e*) Calanna unit (Klerkx 1968): a deeply eroded volcanic pile whose outcrops are found in the SE part of the Valle del Bove.

Except for the two upper members of this sequence, stratigraphic correlation with other units from areas outside the Valle del Bove is very difficult.

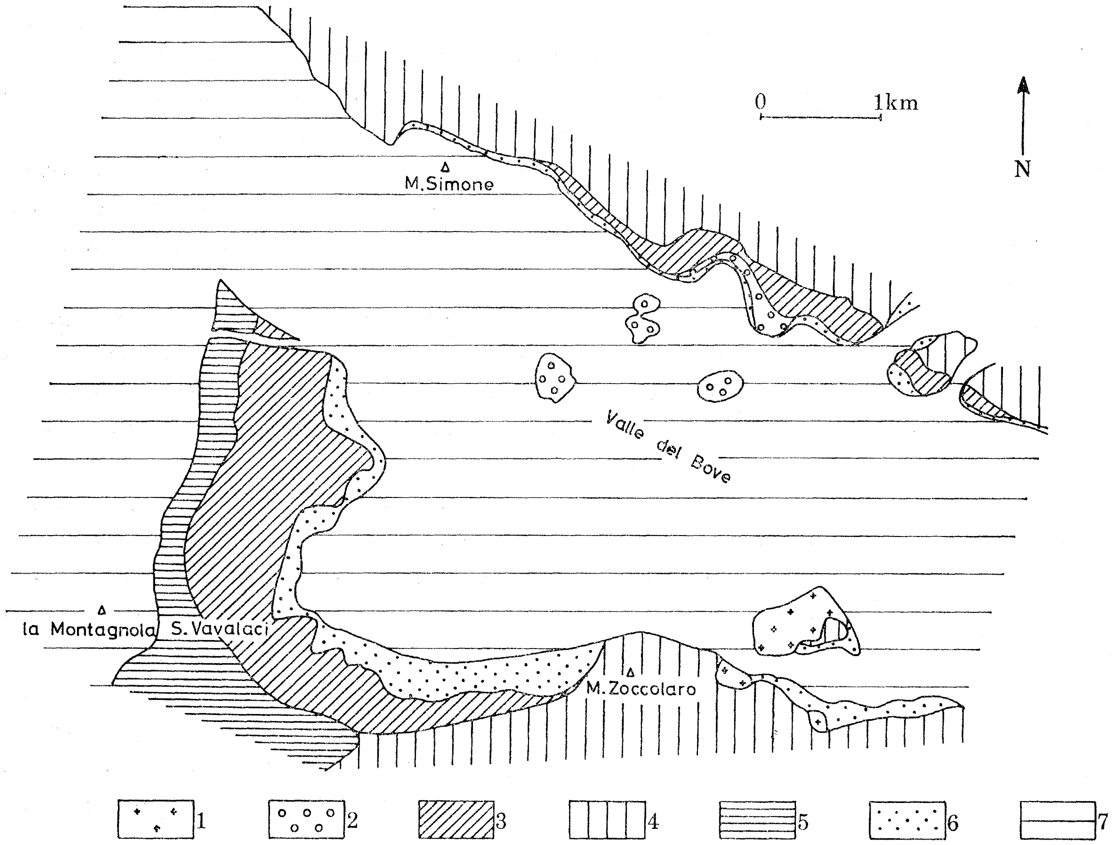


Figure 3. Geological map of the Valle del Bove and surrounding areas (from Klerkx 1968; Lo Giudice 1970): (1) Calanna unit; (2) Trifoglietto I volcano; (3) pyroclastic levels of the Trifoglietto II volcano; (4) lava flows of the Trifoglietto II volcano; (5) Vavalaci unit; (6) Talus; (7) Mongibello unit.

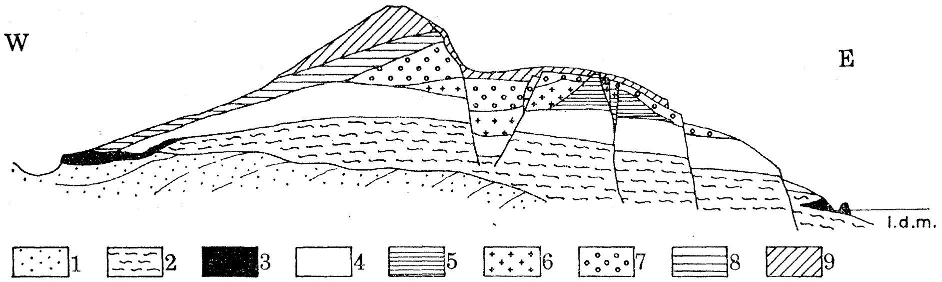


Figure 4. Idealized E–W section of Etna volcano showing relationship among the different units: (1) folded and eroded sedimentary basement; (2) Lower Pleistocene (Sicilian) marly claystones; (3) basalts with tholeiitic affinities; (4) undivided volcanic levels; (5) Calanna unit; (6) Trifoglietto I volcano; (7) Trifoglietto II volcano; (8) Vavalaci unit; (9) Mongibello. (Feeding dykes and adventive vents are omitted for simplicity.)

PETROLOGY

In the Etnean region two different series are present, probably originating from different magmas: the former shows distinct tholeiitic affinities, the latter being derived from an alkali olivine basalt.

In this section a comprehensive examination of the features of both series is given, in order to get some information about their origin and evolution.

(*a*) *Basalts with tholeiitic affinities*

These basalts are found only in scattered outcrops (figure 5) at the base of Etna. They were very fluid and probably had a near-liquidus temperature at the time of their eruption, as they show typical pahoehoe flow structures and a few phenocrysts of olivine, seldom accompanied by plagioclase (Atzori 1966; Cristofolini 1972). Clinopyroxene is wholly confined to the intergranular groundmass and sometimes is pigeonite. The chemistry of these basalts is interesting in that the only major variations involve silica and magnesia (Cristofolini 1972), but the evolution pattern cannot be accounted for by subtraction of olivine (figure 6). However, this mineral is the only phenocrystic phase that could settle from the topmost levels of the magma column under low-pressure ($< 10^9$ Pa; 10 kbar) conditions.

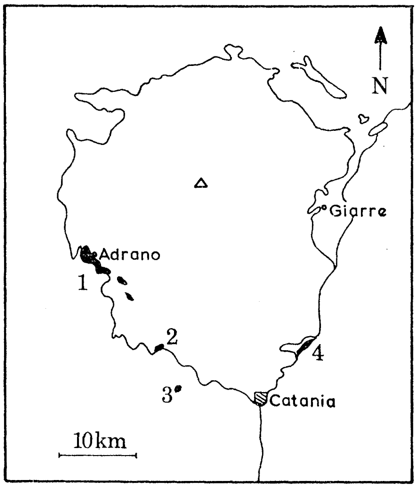


FIGURE 5. The map shows the distribution of basalts with tholeiitic affinities in the Etnean region: (1) Adrano–S. Maria di Licodìa; (2) Valcorrente; (3) Motta S. Anastasia; (4) Aci Trezza–Aci Castello.

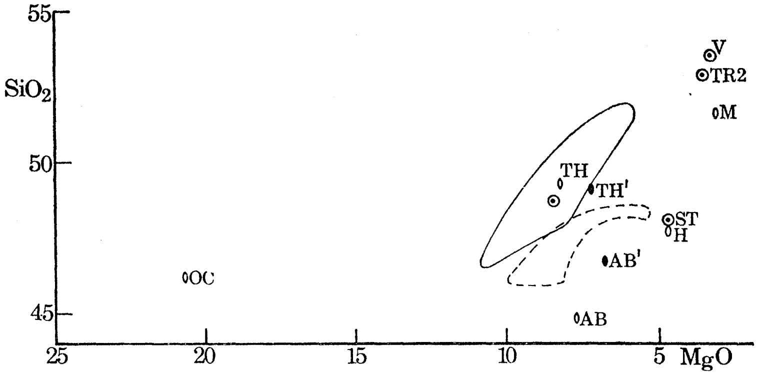


FIGURE 6. MgO–SiO_2 variation diagram showing the distribution fields of tholeiitic basalts from Adrano–Motta S. Anastasia (—) and from Aci Trezza–Aci Castello (– – –): ⊙, averages for Etnean lavas (TR 2: Trifoglietto II; V: Vavalaci unit; ST: historic lavas); ◐, averages for Hawaiian lavas (Macdonald 1969) (OC: oceanite; TH: tholeiites; AB: alkali basalt; H: hawaiite; M: mugearite); ♦, world averages for lavas from oceans (Manson 1967) (TH′: tholeiites; AB′: alkali basalts).

Furthermore, the most basic members of this sequence (and also the Aci Castello–Aci Trezza products) show affinities towards alkali basalts both in the SiO_2-alkali diagram (figure 7) and in their normative composition (Barth 1962; table 1), whereas the most silica-rich members are clearly tholeiitic. In this case a quite unusual trend has developed from mildly alkalic basalts to quartz-bearing tholeiites.

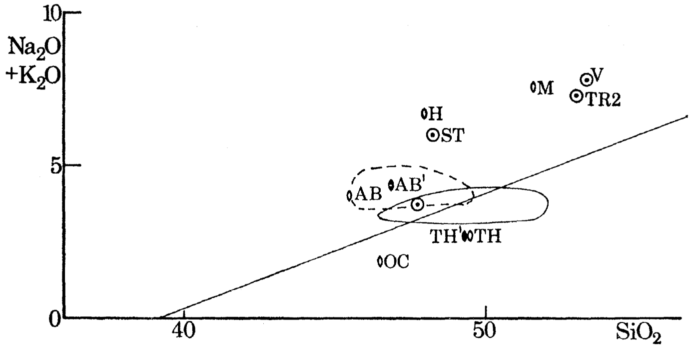


FIGURE 7. SiO_2-alkali variation diagram for Etnean basalts with tholeiitic affinities (symbols same as in figure 6): the distribution field for rocks from Adrano cuts across the boundary line between tholeiitic and alkali basaltic lavas. The Aci Trezza–Aci Castello basalts lie among alkali basalts, and their distribution partly overlaps the field of Adrano lavas.

TABLE 1. MOLECULAR NORMS (BARTH 1962)

	1	2	3	4	5	6	7
Q	—	—	—	0.71	—	—	—
Or	1.25	1.59	1.83	0.77	1.65	1.60	2.43
Ab	28.88	23.27	28.38	28.26	30.11	30.69	31.35
An	27.53	26.05	27.35	26.27	26.49	26.04	24.87
Ne	—	2.53	—	—	—	—	0.54
Di	14.38	17.27	10.76	15.94	16.94	12.93	15.97
Hy	10.87	—	13.60	22.90	0.49	18.09	—
Ol	11.12	25.50	13.30	—	18.99	5.98	18.92
Il	1.94	1.67	1.87	1.92	1.87	1.81	2.22
Mt	3.47	1.50	2.18	2.70	2.84	2.30	2.85
Ap	0.55	0.60	0.71	0.53	0.61	0.54	0.84
	T 1	T 2	A 1	A 2	A 3	R 1	
Q	2.57	—	—	—	—	—	—
Or	2.09	4.09	2.01	1.90	2.12	1.89	
Ab	32.49	31.77	28.74	27.05	27.95	24.65	
An	22.24	26.53	26.75	27.55	26.28	24.66	
Ne	—	—	—	—	—	1.72	
Di	18.52	16.18	16.15	14.27	14.39	17.85	
Hy	13.20	8.75	8.64	10.87	12.86	—	
Ol	—	7.30	12.87	10.77	10.52	24.30	
Il	2.26	2.37	1.91	2.22	2.15	2.56	
Mt	4.79	2.15	2.25	4.69	3.02	1.78	
Ap	0.82	0.84	0.67	0.67	0.71	0.57	

1–7, Cristofolini (1971); T 1–T 2, Tanguy (1967); A 1–A 3, Atzori (1966); R 1, Romano (1970, an. 1).

It can be shown (Cristofolini 1972) that for the basalts from the southwest slopes of Etna (Adrano, Valcorrente, Motta S. Anastasia), that the most basic members have compositions which are consistent with the composition of a low melting fraction derived by partial melting of a peridotite under high-pressure conditions ($> 3 \times 10^9$ Pa; 30 kbar) (Kushiro & Kuno 1963).

Use of the least squares method suggested by Bryan, Finger & Chayes (1969), using highly approximated mineral compositions (cation percentages), showed that the evolution pattern of these basalts can be partly related to subtraction of garnet and pyroxene from a liquid approaching the composition of the most basic members. Table 3 gives mineral and rock compositions used for the computation together with the results.

Table 2. Mantle norms with garnet (Kushiro & Kuno 1963, modified)

	2	5	7	1	3	6	4	T 1	T 2	A 1	A 2	A 3	R 1
Q	−0.1	3.2	3.1	5.1	5.6	8.3	9.8	9.1	8.5	5.7	3.6	5.3	0.4
Gar	39.1	39.2	35.6	40.0	40.4	38.8	39.2	31.2	37.6	39.6	39.2	36.8	32.8
Ac	4.0	4.0	4.4	4.0	4.0	4.0	4.4	4.4	3.6	4.0	4.0	3.6	4.0
Jd	19.2	21.2	23.2	20.0	20.4	21.6	18.8	23.2	24.8	20.4	19.2	20.4	19.6
Ca–Ti pyx	3.2	3.6	4.4	4.0	3.6	3.6	3.6	4.4	4.8	3.6	3.6	4.4	5.2
Wo	10.4	8.6	8.8	8.0	7.2	7.0	7.8	9.0	7.4	8.4	8.4	8.4	10.2
En	15.4	11.4	11.8	11.2	11.6	9.4	9.0	9.4	7.8	11.0	13.6	13.4	18.2
Fs	8.4	8.4	8.4	7.4	7.2	7.0	7.0	8.4	5.2	6.8	7.2	7.4	9.4

Proportions among Fe^{2+}, Mg, and Ca are the same in the computed garnet and pyroxene. Fe^{3+} has been computed as 12% Fe_{tot}.

A closer approximation to mineral composition taking into account alkalis and titania in the pyroxene should give more satisfactory results but was not attempted in view of our lack of knowledge of mineral compositions in the upper mantle.

Table 3. Minerals and rock compositions (cation %) with results from least squares computation

cation %	Hy	Di	Gar		parent		
				1	2	3	6
Si	50.00	50.00	37.50	45.42	43.32	45.68	47.29
Ti	—	—	—	0.97	0.83	0.93	0.90
Al	—	—	25.00	17.04	16.23	16.98	16.87
Fe_{tot}	5.00	2.50	11.25	8.63	8.79	8.50	8.58
Mn	—	—	—	0.14	0.11	0.12	0.14
Mg	45.00	22.50	18.75	12.10	14.74	12.84	10.73
Ca	—	25.00	7.50	9.44	9.90	8.60	8.78
Na+K	—	—	—	5.77	5.49	5.67	6.13
P	—	—	—	0.25	0.31	0.36	0.31

parent Hy Di Gar C

97.7 (2) − (3.3 + 5.2 + 13.1) = 76.1 (1) S = 1.97
97.5 (2) − (0.6 + 7.0 + 14.0) = 75.2 (3) S = 2.49
96.7 (2) − (2.9 + 8.6 + 22.6) = 62.6 (6) S = 3.95

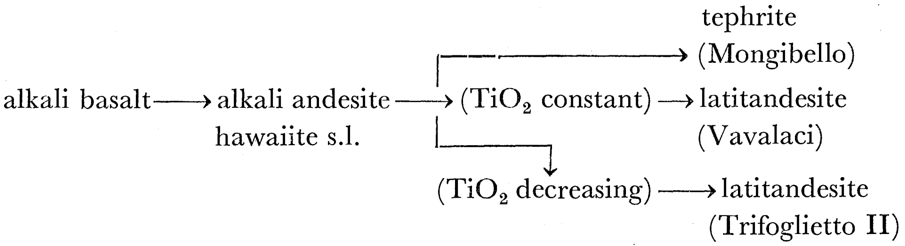
S = sum of squared residuals between actual and computed parent composition.

The Aci Trezza–Aci Castello shallow intrusions and subaqueous lavas form a slightly different group from the Adrano–S. Maria di Licodìa basalts. Yet it is difficult to state whether their different chemistry is original or related to complex hydrothermal processes having taken place during and after their consolidation: in this respect the thermal aureole in the marly claystones of Lachea Island must be recalled, with new-formed minerals (see Di Franco 1930), and the widely diffused zeolites and montmorillonoid minerals in the groundmass and amygdales of these rocks.

(*b*) *Rocks differentiated from alkali basalts*

As already stated rocks of this kindred form the bulk of Etna and can belong to distinct evolution series.

For the lavas of alkalic parentage, gravitational differentiation due to settling of different mafic minerals accompanied by gaseous transfer, is held responsible for the development of various evolution trends (Cristofolini 1971; Pichler 1970; Romano 1970) that can be summarized as follows:



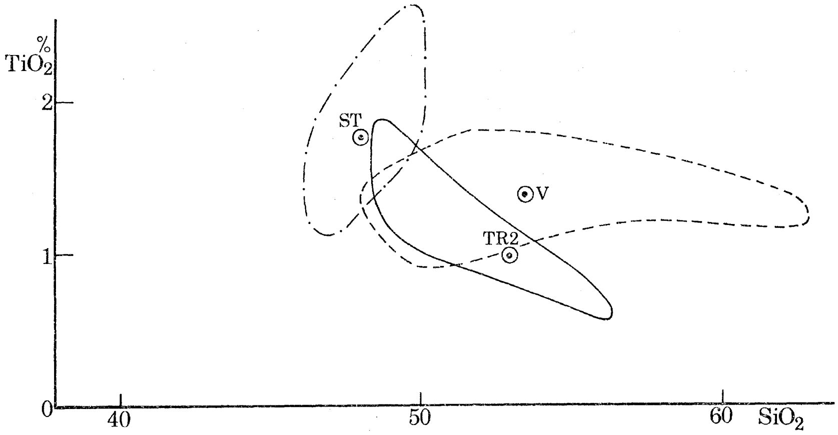


FIGURE 8. SiO_2-TiO_2 variation diagram for Trifoglietto II (TR 2), Vavalaci (V) and historic (ST) lavas from Etna. The fields are diverging from a common area and show that similar magmas can evolve differently.

The most common basic members on Etna approach alkali andesitic (hawaiitic) to phonolite–tephritic composition and are typically represented by the historic lavas of the Mongibello unit, though similar lavas are found in older units. With respect to hawaiites from Hawaii (Macdonald 1969) these rocks are chemically different having distinctly lower titania (about 1.8 % versus 3.4 %) (Cristofolini 1971) and higher alumina (about 17.5 % versus 15.9 %) content.

The most acid lavas on Etna are latitandesites to leucolatitandesites according to Streckeisen (1967): their similarity to the Hawaiian mugearites and benmoreites (Macdonald 1969) is quite poor, owing to their lower olivine content (Cristofolini & Lo Giudice 1969*b*), their higher Al_2O_3 value and their different variation pattern for TiO_2 (Cristofolini 1971).

Petrochemical data to define their evolutionary trends are sufficient only for the Trifoglietto II and Vavalaci units (Klerkx 1968; Cristofolini & Lo Giudice 1969*b*; Lo Giudice 1970); they are only exceptionally oversatured and are on average more strongly differentiated in the Vavalaci than the Trifoglietto unit (Cristofolini & Lo Giudice 1969*b*). The Trifoglietto II sequence shows a marked decrease in TiO_2 content during its evolution, whereas in the Vavalaci latitandesites there is a tendency for titania to be constant (Cristofolini 1971).

Use of systematic terms according to Rittmann's suggestion (1970) for discriminating cratonic from orogenic volcanic associations on the basis of the τ value of their analysed lavas (Gottini Grasso 1968) should be avoided here, because for Etna this value has its frequency maximum right on the proposed boundary region (Cristofolini 1971). For this reason systematic names should be as neutral as possible with regard to the origin of magmas, unless a discriminant value is found to unambiguously ascribe Etna among the cratonic or orogenic associations, and convenient systematics are defined accordingly. Besides, a petrologic explanation should be found for the commonly high Al_2O_3 and low TiO_2 values in these lavas.

From a petrographic point of view some features are common to most of the members of this series: they are commonly porphyritic with glomerophyric aggregates, except for some of the most acid members, so that a classification, with little petrologic meaning, based on the most common phenocryst phases could be suggested (Di Franco 1930; Carapezza 1962*a*). Phenocrysts commonly form 30 to 40 % by volume of the rock. The plagioclase phenocrysts commonly exhibit a complex oscillatory zoning, while pyroxenes are less obviously zoned. Furthermore, even in the same sample the plagioclase grains can show a different zoning pattern, giving evidence for their complicated cooling history. As a rule aggregates are formed either of plagioclase alone or of mafic minerals, usually augite with some olivine and magnetite. These features show that salic and mafic minerals underwent different fates during crystallization.

These observations, and the scarcity of true alkali basalts (Spadea 1972) among Etnean lavas, are not consistent with a direct ascent of undifferentiated magmas from the upper mantle but require long periods of cooling and fractionation at intermediate depth. If we maintain that the persistent activity of the last centuries is a character of the overall Etnean volcanism, then the above stated conditions can be fulfilled only if the magma undergoing differentiation is stored in relatively large batches, so that the ratio between the amount of extruded lava and the total volume of magma is low. In this case a continuous supply of fresh magma from depth could provide a means of keeping the average composition of the stored magma fairly constant over long periods: in the Mongibello, Vavalaci, and Trifoglietto II units we find that the average composition is roughly constant over long periods of time and there is no definite trend with time within each unit, so that the frequency distribution pattern for most oxides shows a random distribution around the average values.

As far as the mechanism of differentiation is concerned, the crystal settling of mafic minerals from an alkali basalt could produce a differentiate of alkali andesitic (hawaiitic l.s.) composition (cf. Klerkx & Evrard 1970). From this stage on settling of different minerals (Klerkx 1968; Romano 1970; Sturiale 1967*b*) and volatile transfer in various degrees could possibly account for the presence of the distinct trends found. For some historic lavas there is evidence that a single flow can vary in chemical composition, ranging over almost all the composition interval of the Mongibello products (see table 4, 1928 flow analyses): this can be interpreted as a consequence of a compositional gradient in the feeding fissures immediately before eruption, or of a magma coming either from different levels of the same chamber or from distinct pockets, where different evolutionary stages had been reached. The latter hypothesis can be especially true when the eruptive vent migrated for long distances along tensional lines of regional tectonic or volcano–tectonic origin.

The composition of the minerals from the Etnean lavas has not so far been studied in great detail: exceptions to this are some recent papers (Cristofolini & Lo Giudice 1969*a*; Klerkx 1964, 1966, 1968; Lo Giudice 1970; Spadea 1972; Tanguy 1966), where chemically analysed minerals are considered in relation to overall rock compositions with the aim of gaining information about the evolution mechanisms of Etnean magma. This kind of study has been confined to those minerals which occur as phenocrysts, i.e. plagioclase, clinopyroxene, olivine, to which kaersutite and apatite are to be added in some special cases.

TABLE 4. MEAN AND STANDARD DEVIATION VALUES FOR HISTORIC FLOWS (42 ANALYSES) AND 1928 FLOW ANALYSES

	$\bar{x}$	σ	1	2	3	4	5	6	7	8	9
SiO_2	48.21	0.96	48.93	47.95	48.52	47.53	47.56	47.05	47.14	49.62	47.80
TiO_2	1.78	0.31	1.90	2.11	1.96	1.77	1.86	1.99	1.83	1.64	1.61
Al_2O_3	17.52	0.97	18.76	18.11	16.86	17.86	17.31	17.69	17.18	16.00	17.49
Fe_2O_3	4.14	1.15	5.98	3.80	2.97	4.21	4.52	2.32	6.52	2.81	4.39
FeO	6.64	1.07	3.49	6.55	7.54	6.44	6.51	6.98	5.07	7.61	6.14
MnO	0.11	0.07	0.15	0.09	0.09	0.13	n.d.	n.d.	0.24	0.13	0.10
MgO	4.93	1.06	3.63	5.10	4.93	5.26	5.46	5.33	5.41	5.20	6.18
CaO	10.11	0.79	9.12	10.03	10.03	10.33	10.53	10.61	10.68	10.25	10.78
Na_2O	4.41	0.65	4.98	3.97	4.88	4.23	4.03	5.40	3.88	4.12	3.46
K_2O	1.53	0.28	1.89	1.33	1.83	1.60	1.23	1.87	1.14	1.46	0.74
P_2O_5	0.40	0.23	0.67	0.42	0.53	0.34	0.44	0.44	0.35	0.62	0.92

Sources of analyses: 1–7, Carapezza (1962*a*): 8, Elskens, I., Tazieff, H. & Tonani, F. 1969 Investigations nouvelles sur le gaz volcanique. *Bull. Volcan.* **32**, 523–574. 9, Carapezza, M. 1966 Influenza della fugacità d'ossigeno nella temperatura di fusione delle lave. *Rc. Accad. Naz. Lincei* (8) **40**, 970–978.

Amphibole (kaersutite) is sometimes found as phenocrysts or megacrysts especially in latitandesites, although Spadea (1972) found some evidence of its presence also in alkali basalts, and it is thought to play an important rôle in the evolution of Etnean rocks (Klerkx 1968; Romano 1970; Sturiale 1967*a*). In table 5 amphibole compositions from Etna are given.

TABLE 5. KAERSUTITE ANALYSES FROM ETNA

	1	2	3
SiO_2	41.37	41.02	42.07
Al_2O_3	12.21	14.45	15.05
Fe_2O_3	6.55	5.05	4.49
FeO	4.51	5.46	6.60
MnO	0.20	0.12	0.09
MgO	13.55	13.16	12.74
CaO	13.83	11.64	11.62
Na_2O	2.13	2.77	2.74
K_2O	0.66	0.74	0.58
TiO_2	4.20	4.00	3.18
H_2O	0.61	1.82	1.16

(1) $Na_{0.62}K_{0.12}Ca_{2.20}Mg_{3.00}Fe^{2+}{}_{0.56}Mn_{0.03}Al^{vi}_{0.28}Fe^{3+}{}_{0.73}Ti_{0.47}Al^{iv}_{1.85}Si_{6.15}O_{23.39}(OH)_{0.61}$.
(2) $Na_{0.78}K_{0.14}Ca_{1.81}Mg_{2.84}Fe^{2+}{}_{0.66}Mn_{0.01}Al^{vi}_{0.44}Fe^{3+}{}_{0.56}Ti_{0.44}Al^{iv}_{2.04}Si_{5.96}O_{22.24}(OH)_{1.76}$.
(3) $Na_{0.77}K_{0.11}Ca_{1.81}Mg_{2.77}Fe^{2+}{}_{0.81}Fe^{3+}{}_{0.49}Mn_{0.01}Ti_{0.35}Al^{vi}_{0.72}Al^{iv}_{1.86}Si_{6.14}O_{22.87}(OH)_{1.13}$.

(1) Kaersutite from the Vavalaci unit (Cristofolini & Lo Giudice 1969*a*).
(2) Kaersutite from ejecta near Milo (Cristofolini & Lo Giudice 1969*a*).
(3) Kaersutite from the Calanna complex (Klerkx 1964).

The average and core composition of the plagioclase commonly gets more sodic during differentiation: in widely differentiated sequences (Vavalaci Complex, Lo Guidice 1970; Trifoglietto II, Klerkx 1968) a fairly good relation is found between silica percentage in the rock and An content of the plagioclase cores, determined both chemically and optically, while in lavas found near Piedimonte Etneo on the NE slope of Etna, bytownite–labradorite cores are common.

In figure 9 compositions of feldspars from the Vavalaci unit are plotted (mol %) for phenocrysts, normative feldspar from whole rock analyses, and modal feldspars determined by X-ray diffraction methods (Cristofolini & Lo Giudice 1969*b*; Lo Giudice 1970). In one instance the composition of the total plagioclase approximates to that of the phenocrysts, whereas other total plagioclase compositions are distinctly more sodic than the phenocrysts. Groundmass alkali-feldspar ranges from anorthoclase to Na-sanidine, and there is definite evidence that the feldspars crystallized under strong disequilibrium conditions. In some cases, where plagioclase crystals with calcic cores are found in latitandesites, this could mean that phenocrysts were inherited from a less differentiated melt.

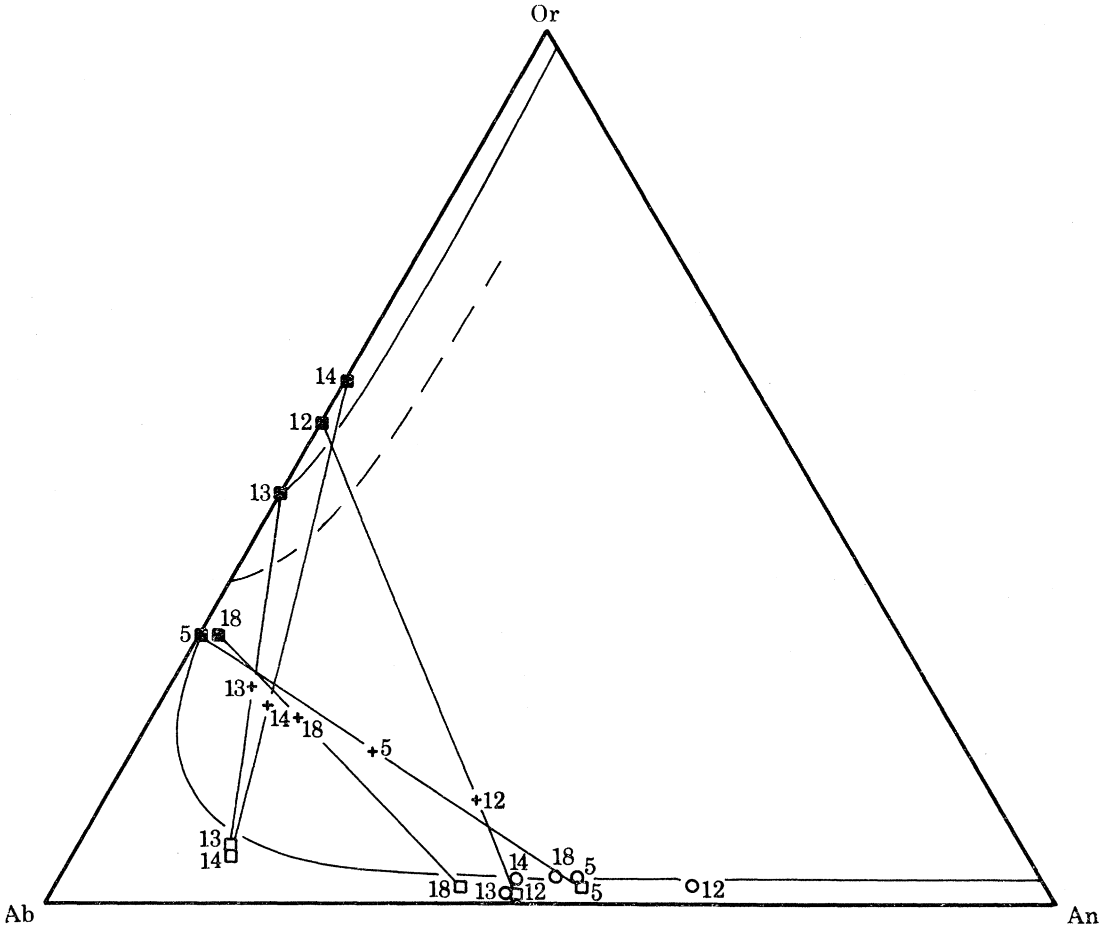


Figure 9. Compositions (mol %) of phenocryst cores, total normative feldspar and modal average plagioclase and alkali feldspar plotted in the system Or–Ab–An. (Sample numbers same as in Lo Giudice 1970.) ○, Phenocrystal cores; □, average modal plagioclase; ■, average modal alkali feldspar: +, total normative feldspar.

Analytical data available for clinopyroxenes from alkali basalts to latitandesites (Lo Giudice 1970; Klerkx 1968; Spadea 1972; Tanguy 1966) show that they are salite augites with very little iron enrichment during differentiation, whereas there is a much larger spread in their Ca content (figure 10). The iron enrichment index computed for recently analysed pyroxenes ranges from 35 to 43, with the exception of two analyses of cores of phenocrysts (Klerkx 1968, table 11, an. 7; Spadea 1972), of diopsidic augite composition that show significantly lower iron enrichment indexes. In one instance augite, being similar to the clinopyroxenes from ultramafic inclusions in alkali basalts (Spadea 1972), is found associated with Fo-rich olivine megacrystals (1 cm across) (86 % Fo from d_{130} X-ray, unpublished data; 84 % Fo, Spadea 1972). For this reason it looks reasonable to regard it as a relic of ultramafic nodules, otherwise absent on Etna. The pale green diopsidic augite is mantled by salite which crystallized from the alkali basalt magma.

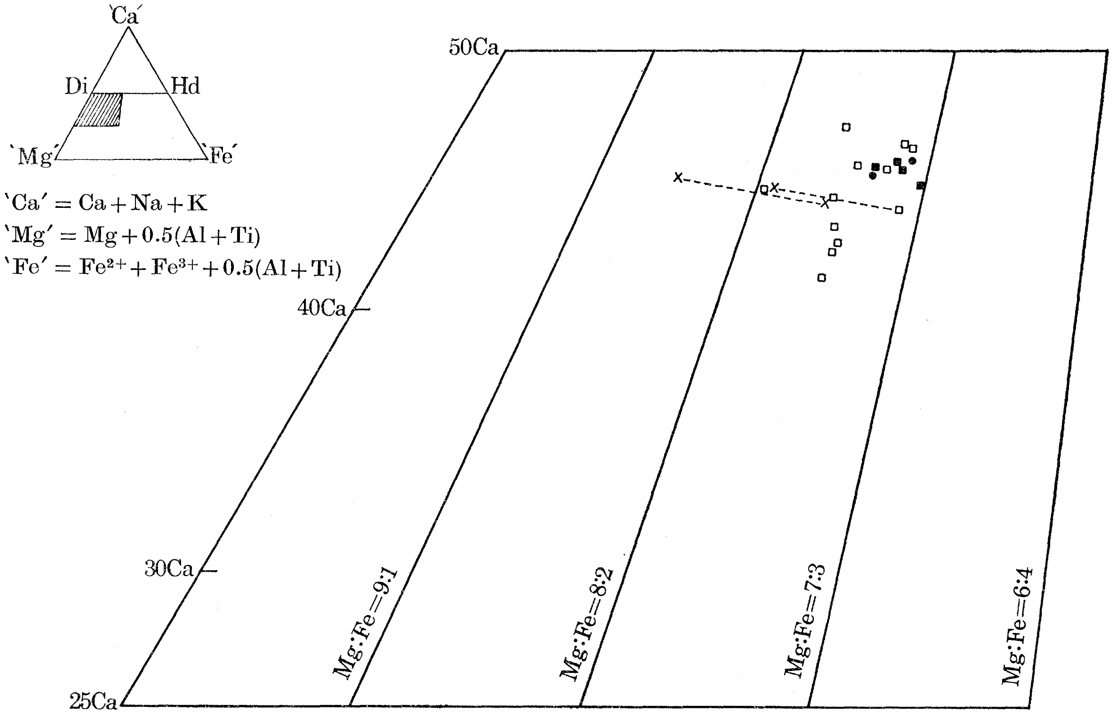


FIGURE 10. Pyroxene compositions (atoms %) plotted on a Ca–Mg–Fe diagram. □, Trifoglietto and Calanna pyroxenes (Klerkx 1968); ●, Vavalaci pyroxenes (Lo Giudice 1970); ▨, Mongibello pyroxenes (Tanguy 1966); ×, pyroxenes from alkali basalt of undetermined geologic position in Etnean sequence.

Whereas the small spread of the pyroxene iron enrichment values agrees with their having crystallized from a magma of alkali basaltic parentage (Brown 1967), the wider range of Ca values is to be related to the appearance of another Ca-bearing phase (amphibole) according to Klerkx (1968), but can be better explained with a shift of the partition coefficients for Ca and Al (Barberi, Bizouard & Varet 1971) in plagioclase, pyroxene, and kaersutite with changes of total and water pressures. In fact, contrary to Klerkx's (1968) suggestions, the pyroxene which crystallized at the same time as large amounts of kaersutite shows the highest Ca content among the pyroxenes from Etna.

A detailed study, using the computation method suggested by Bryan, Finger & Chayes (1969), about the magmatic evolution of the Vavalaci lavas (Lo Giudice 1971) showed that the whole Vavalaci series can be obtained by subtracting minerals of the compositions found in an analysed alkali andesite lava (table 6). The computation results, however, do not mean that the alkali andesite is actually the starting material of this sequence, as it could be obtained by adding appropriate proportions of the same minerals to any of the intermediate members.

Table 6. Mineral and lava analyses from the Vavalaci unit with results from least squares computation (Lo Giudice 1971)

	1	2	3	4	5	6	7	8	9
SiO_2	48.10	50.68	51.12	51.45	51.63	52.51	53.70	54.55	55.14
Al_2O_3	18.15	18.24	19.37	18.20	18.86	18.20	17.74	18.48	17.99
FeO†	10.64	8.74	8.03	8.12	7.40	8.34	7.35	7.55	6.93
MnO	0.15	0.16	0.16	0.20	0.12	0.18	0.12	0.16	0.20
MgO	4.87	4.13	3.64	3.48	4.57	3.29	3.75	3.06	2.60
CaO	9.95	8.57	8.24	7.20	7.98	7.36	7.23	6.87	5.67
Na_2O	4.06	4.67	4.75	5.35	4.75	5.41	5.07	5.25	5.78
K_2O	1.48	1.82	2.03	2.71	1.86	2.35	2.28	2.32	2.84
TiO_2	1.37	1.63	1.34	1.77	1.36	1.69	1.25	1.01	1.34

	10	11	12	13	14	Pl_1	Pyx_1	Ol (Fa_{25})	Mt
SiO_2	56.01	56.20	56.70	60.76	62.50	52.00	50.88	39.53	0.64
Al_2O_3	17.71	17.13	17.40	15.47	16.42	30.20	3.44	—	6.50
FeO†	6.77	5.89	6.38	5.75	4.77	—	8.03	17.65	71.07
MnO	0.17	0.19	0.19	0.15	0.21	—	0.16	—	0.39
MgO	2.72	2.81	2.35	2.19	1.49	—	13.14	42.82	5.54
CaO	4.80	5.00	5.13	3.81	3.11	12.68	21.20	—	0.74
Na_2O	6.12	5.87	5.96	5.82	6.01	4.14	0.83	—	—
K_2O	2.78	2.90	2.77	3.23	3.17	0.33	—	—	—
TiO_2	1.62	1.65	1.61	1.48	1.22	—	1.63	—	10.83

† $FeO = FeO + 0.9\ Fe_2O_3$.

parent Pl Pyx Ol Mt Cn
100.04 (1) − (17.70 + 8.87 + 1.54 + 5.30) = 66.63 (2) S = 0.2636
99.99 (1) − (15.33 + 11.64 + 1.43 + 5.80) = 65.79 (3) S = 0.1676
100.55 (1) − (25.59 + 13.51 + 2.19 + 6.79) = 52.47 (4) S = 0.2821
100.05 (1) − (17.17 + 11.83 − 0.02 + 6.86) = 64.21 (5) S = 0.3002
99.67 (1) − (26.56 + 12.86 + 2.65 + 6.80) = 50.80 (6) S = 0.2493
99.64 (1) − (28.30 + 12.55 + 2.13 + 7.93) = 48.73 (7) S = 0.2889
99.06 (1) − (28.66 + 14.05 + 2.63 + 7.83) = 45.89 (8) S = 0.2794
99.70 (1) − (32.93 + 15.87 + 2.93 + 8.54) = 39.43 (9) S = 0.2805
99.60 (1) − (35.15 + 16.92 + 2.69 + 8.87) = 35.97 (10) S = 0.4252
100.02 (1) − (36.00 + 16.09 + 2.83 + 9.39) = 35.71 (11) S = 0.4931
99.57 (1) − (36.03 + 15.95 + 3.30 + 9.10) = 35.19 (12) S = 0.4856
99.07 (1) − (41.99 + 15.75 + 3.70 + 9.96) = 27.67 (13) S = 0.7189
98.87 (1) − (41.80 + 16.97 + 3.77 + 10.31) = 26.02 (14) S = 0.8168

S = sum of squared residuals between actual and computed parental composition.

This research also excluded any possibility that gravitational settling of kaersutite alone, or with other phases, could produce the latitandesites of the Vavalaci complex. The results show that a generally low amount of alkalis should have been lost, presumably through volatile transfer, during the differentiation processes. If no alkalis are lost a tephrite–phonolitic trend can be produced by fractional crystallization alone.

Preliminary results, obtained from the above-mentioned method of computation, are also available for the first two stages of the Trifoglietto sequence.

Klerkx (1968) states that the latitandesites of stage B (Trifoglietto II) can be obtained by subtracting material composed mainly of amphibole from the alkali andesites of stage A (Trifoglietto I). Computation results are shown in table 7. Even if further research must be directed to the whole Trifoglietto II sequence, it is apparent from these data that kaersutite has only a minor rôle in the evolution of latitandesites of Trifoglietto II.

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TABLE 7. MINERAL AND LAVA COMPOSITIONS FROM TRIFOGLIETTO WITH RESULTS FROM LEAST SQUARES COMPUTATION (KLERKX 1968)

	Kaersutite (Klerkx 1968 tab. 13, an. 1)	Pyx (Klerkx 1968 tab. 11, an. 7)	Ol (Fa_{37})	Mt	Pl (An_{70})	A (Klerkx 1968 an. 6)	B (Klerkx 1968 an. 8)
SiO_2	38.9	46.4	38.1	0.6	49.5	48.8	54.9
TiO_2	4.5	1.6	—	10.8	—	1.5	0.9
Al_2O_3	12.0	5.9	—	6.5	31.2	17.9	19.0
FeO_{tot}	11.4	7.4	31.5	71.1	0.9	10.0	5.9
MgO	14.0	13.7	30.5	5.5	0.1	4.9	2.9
CaO	13.8	22.7	—	0.7	14.0	9.5	7.4
Na_2O	2.5	0.4	—	—	3.4	4.0	4.7
K_2O	0.8	—	—	—	0.2	1.2	2.1

parent Kaers Pyx Ol Mt Pl

99.8 A − (6.4 + 8.6 + 2.2 + 5.7 + 13.6) = 63.3 B S = 0.19

CONCLUSIONS

Etna is placed where an E–W trending anticlinorium of alpine age is intersected by a complex belt of regional faults with an overall seaward downthrow. This belt stretching from Còmiso (S Sicily) to Messina and farther northward, is probably characterized also by conspicous transcurrent faulting (Ogniben 1969). Its detailed study is of primary interest for the interpretation of the origin of the volcanic activity and the evolution of magmas in the Etnean region.

The first Etnean lavas flowed over a deeply eroded sedimentary basement of Tertiary age, partly overlain by lower Pleistocene marly claystones. This sedimentary basement outcrops at elevations up to about 800 m on the NE slopes of the volcano and is probably found at elevations above 1000 m underneath the central region (Ogniben 1966). Etna is a complex volcano and several units have been recognized, but interpretation of the whole sequence is not easy and far from being complete due to the uniform appearance of the lavas, the lack of continuous natural sections (except in the Valle del Bove) and the complex overlapping of the different units.

Products of Etna mostly belong to an alkali basaltic suite, where mildly to strongly fractionated members are very common; basaltic lavas with tholeiitic affinities are confined to among the first episodes of volcanic activity in the Etnean region. As a rule Etnean lavas are strongly porphyritic, so that they do not lie on a liquid line of descent and consequently no lava is representative of the composition of a melt. Because of these facts it looks as though the magma in its passage from the upper mantle is undergoing differentiation processes mainly consisting of gravitational settling of crystals and mixing with fresh magma. These conditions can occur only if the magma, which is undergoing differentiation, is stored in relatively large batches so that the ratio of the amount of extruded lava to total volume per unit time is low: in this case the composition of the stored magma is held roughly constant over long periods, by the addition of fresh magma from depth, until some external factor (e.g. opening of new tectonically controlled fractures) changes the equilibrium conditions.

The differentiation of Etnean magma follows distinct lines for different units, but generally speaking these are tephrites and latitandesites; only in few cases is a thorough analysis of the process of differentiation possible using mineral and lava compositions found in each unit: results show that crystal settling of various minerals can explain most of the variation pattern observed in the units: another factor affecting lava composition can be the loss of alkalis through gaseous emanations into the atmosphere (Lo Giudice 1971).

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Discussion

G. W. Grindley: In view of the comparatively rapid tectonic elevation since the Sicilian clays were deposited some 500000 years ago – it would seem desirable to extend any Earth deformation network of bench marks and geodimeter lines well outside the immediate vicinity of the volcano, preferably on to the underlying basement rocks to the north, west and south. It is also probable that the whole of Mt Etna may be tilting southward into the Catania basin. If the volcano-tectonic movements are sufficiently large, these small tectonic movements may be neglected. However, if Etna is fed from deep fissures and not from a shallow horizontal magma chamber susceptible to inflation and deflation, then the Earth movements accompanying volcanism may be quite small and of the same order of magnitude as the regional tectonic movements in this part of Sicily.

R. Cristofolini: The kind of information indicated by Dr Grindley about ground deformation in the Etnean area is actually what we need before any sound conclusion can be drawn about the shape and volume of the feeding system under Mt Etna. I strongly believe that a ground deformation study should be planned in order to give the petrographers and the geologists useful information about the structure of Etna.

G. W. Grindley: Is there any direct observational evidence for strike slip movement on any of the faults cutting the volcano of Mt Etna? It appeared likely from the E–W direction of folding in northern Sicily that the region was being shortened in a N–S direction so that conjugate strike-slip faults might be expected trending NNW and NNE intersecting at 50 to 60°. This appeared to be the case both during the recent eruption and in previous eruptions, and observational evidence for dextral movement on the NNW faults and sinistral movement on the NNE faults would be worth looking for.

R. Cristofolini: Due to the dense fracture network in lavas, fault scarps are subject to fast collapsing and no evidence of the original fault surface is left. Moreover, any evidence for the direction of the fault movement will be very poor on the original surface, owing to the low depth where faulting takes place.

Anyhow if indications for a strike slip movement are found, this is not accounted for by a shortening in N–S direction related with folding phenomena that ended in lower Miocene, but rather is to be connected with the regional transcurrent fault from Cómiso to Messina.

Dr M. Sato: The use of a computer for arriving at the conclusion that garnet and clinopyroxene were probably removed from the magma to produce the chemical difference has been mentioned. Was this the method used by Wright & Fiske when studying the differentiated lavas of Kilauea?

R. Cristofolini: The computer facilities available to us did not allow the use of programs as elaborate as Wright & Fiske's; we adopted a simplified version of the computation program devised by F. Chayes at the Geophysical Laboratory.

Dr M. Sato: You postulated continuous differentiation and compensatory introduction of new magma to maintain the uniform chemical composition over a period of time. Did you find any textural evidence such as partly reduced Fe–Ti oxides (cf. Anderson & Wright) to substantiate the hypothesis?

R. Cristofolini: The hypothesis I favour looks consistent with available data showing that Etnean magma is being actively fractionated (undifferentiated lavas are rarely found and large amounts of phenocrysts are commonly present), even if lava compositions do not show any clear evolutionary trend with time, and rather oscillate around average values.

I agree that this is a working hypothesis that has to be substantiated by more evidence; your suggestions can be useful for us in this respect.

Dr R. B. McConnell: Is it possible to date precisely the earliest volcanic activity on the site of Mt Etna? Was it contemporaneous with the beginning of the E–W upwarp mentioned by Dr Cristofolini?

R. Cristofolini: The first volcanic eruptions in the Etnean area are probably no earlier than Sicilian; the isostatic uplift of the folded area where Etna is placed should have begun before volcanic activity, as some of the first flows (near Adrano) overlay a strongly eroded sedimentary basement of Tertiary age. A sufficient time gap must be allowed for these sedimentary layers to be eroded after having been raised, and before they were covered by the flows.

H. Tazieff: The cross-section you showed of Mt Etna seems to disagree with the description of the geology and tectonics of it as given by Professor Rittman. You show no horst-like structure underneath the recent volcanics of Mongibello, and no Quaternary sediments outcrop. Do you actually disagree with Professor Rittman's interpretation and, if so, why?

R. Cristofolini: Whether the west flank of a horst structure is concealed by recent lavas from Mongibello can be a matter of debate, but recent geological work in sedimentary areas around Etna and on Etna itself showed no evidence for this structure: for instance, no major fault scarps, so peculiar of the landscape in the lowest east slope of Etna, are found on its west flank. This view has been summarized by Ogniben (1966), and has been quoted among others by Romano (1970).

Quaternary outcrops are not interpreted here although they are shown outcropping along the sea coast, enclosing the Aci Trezza intrusions. In this respect I would like to point out that the cross-section of figure 4 is a simplified picture of the known volcanic sequence of Mt Etna along an E–W direction, and only some of the major aspects and data about the Etnean geology have been shown there.