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THE ISLAND OF LIPARI

ABSTRACT. — Four periods of volcanic activity can be distinguished on Lipari, ranging in time from the Tyrrhenian I up to the Late Roman decade. The rocks represent a typical calc-alkaline series comprising *quartz-andesites* to *alkali feldspar rhyolites*. Among this series three different groups exist, each probably originating from a different magma source or/and a different kind of magma evolution. The magma of Lipari may have been formed in the upper mantle under low pressure but high H_2O conditions (melts of periods I and II). Parts of these subcrustal magmas (e.g. those of period II *b*) could have been contaminated by crustal material. With regard to the magma genesis of the acidic rocks (periods III and IV) an origin by anatexis of crustal rocks cannot be ruled out.

The calc-alkaline volcanics of the Aeolian archipelago show petrochemical similarities to typical continental « andesites » and differ significantly from island arc associations. Seismic and petrochemical data are inconsistent with a relation of the Aeolian islands to such an island arc system. Because of these data the existence of a seismic Benioff zone in the Tyrrhenian area and the origin of the Aeolian volcanic magmas from a down-going slab cannot be supported.

RIASSUNTO. — Sull'isola di Lipari possono essere distinti quattro periodi di attività vulcanica, compresi tra il Tirreniano I e l'Età Romanica. Le vulcaniti affioranti rappresentano una tipica associazione calco-alcalina, con termini di composizione variabile da quarzo-andesiti a rioliti alcaline. Tra le serie esaminate possono essere distinti tre diversi gruppi di rocce, ciascuno dei quali prende probabilmente origine da differenti sorgenti magmatiche e/o ha subìto processi differenti di evoluzione magmatica. I magmi di Lipari possono essersi formati nel Mantello Superiore in condizioni di bassa pressione totale ed alta pressione parziale di H_2O (magmi del I e II periodo). Taluni di questi magmi subcrustali (e.g. quelli del periodo II b) possono aver subìto la contaminazione di materiale crustale. Per quanto riguarda la genesi delle rocce acide (periodo III e IV) non è possibile escludere processi di anatessi di rocce crustali.

Le vulcaniti calco-alcaline dell'arcipelago Eoliano mostrano caratteri petrochimici simili a quelli delle tipiche « andesiti » di margine continentale e differiscono peraltro sostanzialmente dalle associazioni di arco insulare. I dati sismici e petrochimici non sono favorevoli nel mettere in relazione le Isole Eolie con un sistema di tipo arco insulare. Sulla base di tali dati non può essere sostenuta l'esistenza di una « zona di Benioff » nell'area del Tirreno, nè tantomeno l'origine dei magmi Eoliani da uno « slab » in subduzione.

Introduction

The main island of the Aeolian or Lipari archipelago, Lipari, has an area of barely 38 km² and consists entirely of volcanic rocks. Thick pumice series, which are mined in opencast working, are the wealth of the island. During Neolithic times, Lipari was one of the rare sources of obsidian in the Mediterranean and

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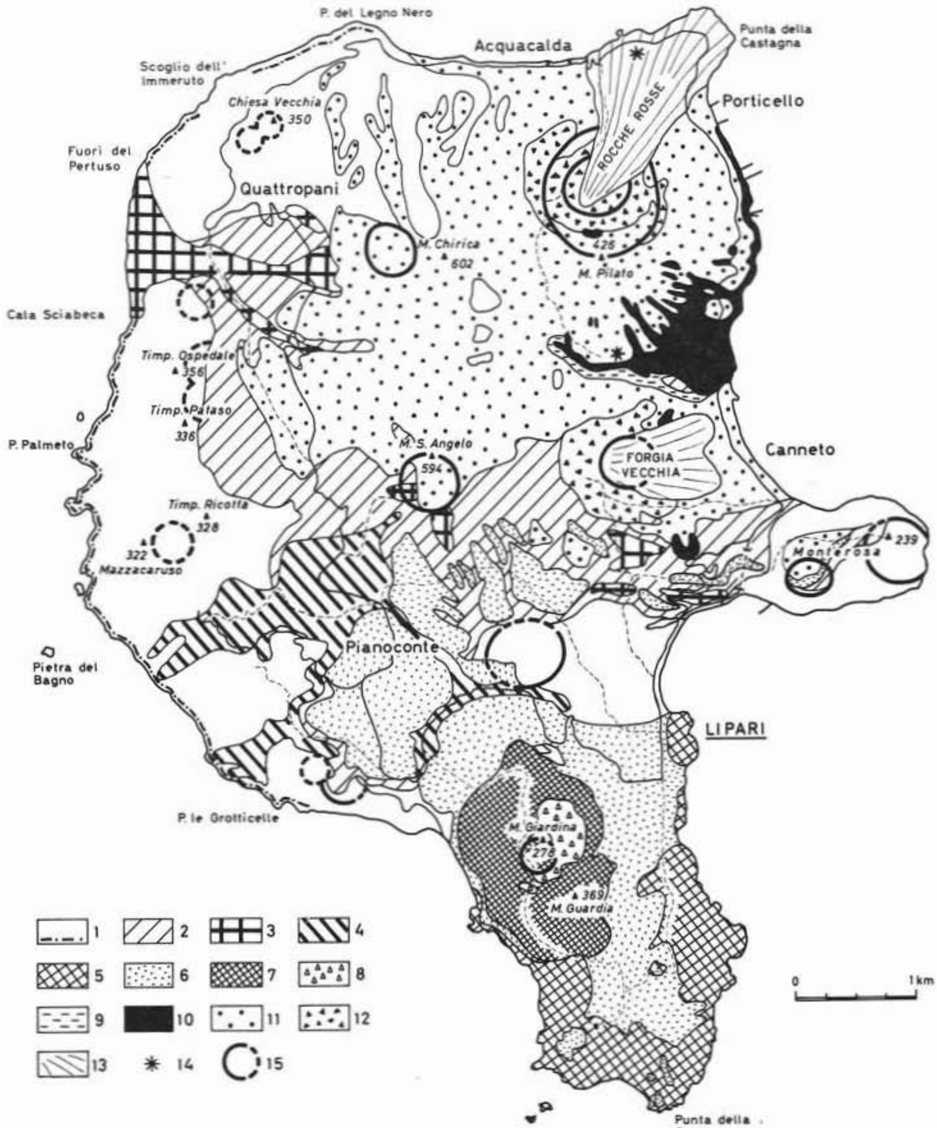


Fig. 1. — Geologic sketch map of Lipari. 1 - volcanics of period I, partly cut by the Tyrrhenian eustatic terrace (+ 18-35 m); 2 - period II, mostly pyroclastics; 3 - period II, lavas of sub-stages II *a* and II *c*; 4 - period II, cordierite-bearing lavas of sub-stage II *b*; 5 - period III, older extrusive lavas; 6 - period III, pumice series; 7 - period III, younger extrusive lavas; 8 - period III, glowing avalanche deposits of M.te Giardina; 9 - period IV, lower pumice series; 10 - period IV, older obsidianic lavas: 11 - period IV, upper pumice series; 12 - period IV, vent-opening breccias of Rocche Rosse and Forgia Vecchia; 13 - period IV, obsidian flows of Rocche Rosse and Forgia Vecchia; 14 - period IV, parasitic volcanic conelets; 15 - crater rims, visible/probable, of periods I-IV.

the Near East. Objects made of Lipari volcanic glass have been found on all Aeolian islands, on the islands of Ustica and Malta, in Eastern Sicily and in southern Italy up to Lucera and Bari (Dixon et al., 1968).

The first systematic studies of the geology and petrography of Lipari were performed by CORTESE and SABATINI (1892) and BERGEAT (1899). Both publications include schematic geologic maps to a scale of 1 : 50,000. BERGEAT (1910) first made a detailed study on the cordierite- and garnet-bearing « andesitic » lava of Lipari, which had been discovered by that author some years before (1895). Some small notes on the geology and morphology of Lipari were published by DE FIORE (1927 a,

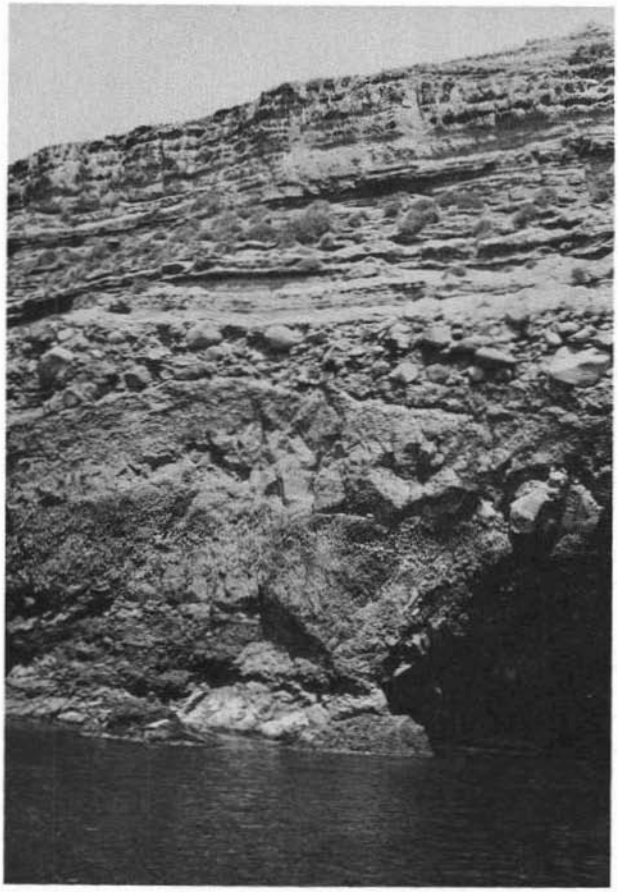


Fig. 2. — Conglomerate of the Tyrrhenian eustatic terrace (+ 20 m) covering submarine volcanics of period I. The conglomerate is overlain by pyroclastic series of periods II and III. South of Cala Fico, western coast of Lipari.

b, c, 1928), who also wrote a very useful bibliographic compilation on the Aeolian islands containing the literature up to the year 1925. Until the beginning of the last decade only very few petrochemical data existed on the volcanics of Lipari. Between 1961 and 1964 fieldwork on Lipari and mapping of the island to a scale of 1 : 10,000 were carried out by the author who, at that time, was working at the International Institute of Volcanology (I.I.V.) in Catania, directed in those days by Prof. Dr. A. RITTMANN. Parts of the results of the author's studies on Lipari and the adjoining islands have been previously published (PICHLER, 1967, 1968, 1970). The works on Lipari are a part of an extensive research program of the Italian C.N.R., thanks to which the printing of the Geological Map of Lipari 1 : 10,000 could be done.

The volcanic activity on Lipari is restricted to post-volcanic phenomena, i.e. some low-temperature fumaroles (east of Timpone Ospedale and Timpone Pataso) (80-90° C) and the hot-springs of S. Calogero in the western part of the island with a temperature of 57° C (CAVALLARO, 1954).

Geological setting

Four periods or stages of volcanic activity can be distinguished on Lipari. Age and stratigraphic relationships of these four units could largely be clarified by means

Fig. 3. — Pillow-like lavas embedded in hyaloclastic material of period I. North of Punta delle Fontanelle, western coast of Lipari.

of Pleistocene coast-lines of eustatic origin, which are developed on four of the seven Aeolian islands, and by absolute age determinations using the ^{14}C and the fission track methods. The youngest volcanic events during the Neolithic and Historic times are datable on the basis of their stratigraphic position within archeologic standard sections (PICHLER, 1967, 1968; KELLER, 1970; BIGAZZI and BONADONNA, 1973).

First Period

Subaerial lavas, dikes, welded scoriae, tuffs and submarine lavas and hyaloclastic volcanics of *quartz latiandesitic* to *quartz andesitic* composition build up at least twelve morphologically strongly eroded strato-volcanoes which from the framework of Lipari (fig. 1). Most of these volcanoes are totally or partially covered by the products of periods II, III and IV. In the western part of Lipari these volcanic ruins reach altitudes of between 200 and 350 metres (Timpone Carrubbo 195 m, M.te Mazzacaruso 322 m, Timpone Pataso 336 m, Timpone Ospedale 356 m, Chiesa Vecchia volcanoes 350 m, etc.). Greater initial heights are shown by some volcanoes of period I a in the central part of Lipari, buried under younger pyroclastic series, i.e. the Chirica volcano (602 m) and the Cugno di Mandra volcano (470 m). On some volcanoes remnants of craters can be found or supposed by means of discordant bedding or the occurrence and thickening up of welded scoriae banks (Chiesa Vecchia volcanoes).

In the western part of Lipari, from Punta del Legno Nero in the north to P.ta le Grotticelle in the south, an eustatic terrace of Pleistocene age is cut into the volcanics of period I, but not into those of the three younger stages (fig. 2). The altitude of this fossil coast-line ranges between 18 and 35 m above the present sea-level. Near Scoglio dell'Immeruta, on the nothwestern coast of Lipari, this terrace lies locally about 70 m above the sea-level. Field observations show that the eustatic terrace, despite its different altitude, belongs, to the same episode of high sea-level, i.e. to the Tyrrhenian I (corresponding to the Mindel-Riss-Interglacial). The various heights of the terrace are due to local volcano-tectonic movements which occurred during the activity of the volcanoes of period I. The throws of these faults reach mostly only a few metres.

It is important to point out that those volcanics of period I up to the level of the Tyrrhenian I terrace are of typical submarine origin. Hyaloclastic products can be found along the entire western coast of Lipari intercalated by submarine lavas and dikes. North of P.ta delle Fontanelle also pillow-like lavas occur (fig. 3). On account of the more acidic composition of the period I volcanics of Lipari, compared with the classic submarine volcanics in the Iblean region in Sicily, the Lipari hyaloclastites and pillows show less pronounced hyaloclastic and pillow-like features. On the other hand, the volcanics of period I, which are situated above the level of the terrace, are products of subaerial volcanic activity. This means stratigraphically that the volcanism of period I (with exception of the Monterosa volcanoes) occurred during, but not before the Tyrrhenian I episode of high sea-level.

Very probably a volcano-tectonic subsidence occurred at the end of period I a, which destroyed the eastern part of the Timp. Ospedale-Pataso twin volcanoes and parts of the neighbouring volcanoes. This *Castellaro caldera* (or *caldera I*) was filled up in the following periods, mainly with P II tuffs.

In the eastern part of Lipari the volcanic activity continued into the post-Tyrrhenian I. At that time the level of the sea was lower than the present one and therefore no eustatic terrace could have developed. The twin volcanoes of the Monterosa promontory, which were formed in the post-Tyrrhenian I, are called, in contradistinction to the older P I a volcanoes, P I b edifices.

Second Period

Between the end of the first period of volcanic activity on Lipari and the beginning of a new volcanic stage a long non-volcanic interval of approximately 60,000 to 120,000 years elapsed.

During period II a large strato-volcano, M.te S. Angelo (594 m), was formed in the central part of Lipari. Its crater, about 450 m wide and yet 90 m

Fig. 4. — Lahar deposits of period II, M.te S. Angelo strato-volcano, eastern slopes.

deep, is morphologically still well-preserved. About 2 km north of M.te S. Angelo, a second strato-volcano, the Costa d'Agosto volcano, situated on the western side of the old Chirica volcano of period I, was active. Large terminal and subterminal lava flows of *quartz latiandesitic* composition poured out of the western and southern side of the volcano and reached the sea between Fuori del Pertuso and Cala Sciabeca.

The volcanic activity of period II can be subdivided in three substages. In the oldest one lavas and pyroclastics of *quartz latiandesitic* to *quartz latitic* composition were produced (fig. 6). Effusive activity was predominantly concentrated on the Costa d'Agosto volcano while the S. Angelo volcano was in long-lived explosive activity which took approximately 30,000 years. Within the pyroclastic series of that volcano, reaching a thickness of up to 300 metres, at least five paleosoil horizons are intercalated indicating long breaks of inactivity of several thousand years each. Some of these horizons contain fossil plants, for example palms (Dolomieu, 1783; Gaudin and Mandralisca, 1860). The fossil flora indicates that the climatic conditions at that time were nearly the same as at present. During the volcanic activity of M.te S. Angelo cold and hot lahars and even some glowing avalanches of incandescent scoriae, lapilli and ashes were formed (fig. 4).

The second sub-stage of period II is restricted to M.te S. Angelo. In the southwestern section of that volcano large subterminal lava flows, up to 3 km long and up to 20 m thick, poured out and covered a wide area in the southwestern part of Lipari. At Punta delle Fontanelle some of these flows reached the coast, overlying the conglomerates of the Tyrrhenian terraces. These predominantly *rhyodacitic* lavas are of specific petrologic interest on account of their content of cordierite, garnet, andalusite, sillimanite and spinel. Inclusions of metamorphic rock fragments, mostly hornfelses, are common.

The third and last sub-stage of period II (P II c) is characterized by explosive activity and by terminal effusion of a viscous flow of *quartz latiandesitic* lava on the southern slope of M.te S. Angelo.

In the following epoch of approximately 20,000 years of volcanic inactivity the uppermost parts of the P II pyroclastic series were more or less strongly reworked by rainwash and deflation, especially on the steeper slopes of M.te S. Angelo. Heavy rains during the winter time produced cold mudflows (rain lahars). Lifting and removal of sand and dust by wind, especially from the pyroclastic layers, is typical for periods of non-volcanic activity on all Aeolian islands and led to the formation of a special type of aeolian sediment, a fine-grained, dark brown sand, the so-called *Tufflöss*.

Excellent outcrops of such reworked P II series, covered by P III pyroclastics, are exposed by road cuttings north of the village of Varesana di Sopra. The outcrops show several unconformities, mostly covered by cold lahar deposits with intercalation of paleosoil horizons. Near the base of the cuttings a conspicuous, up to 70-cm-thick bipartite layer of dark grey scoriaceous lapilli exists. Lithologically, these lapilli are identical to the *Grey Porri Tuffs* of Salina (Keller, 1966). This Porri tephra is, according to a ^{14}C determination of Keller, more than 36,000 years old. The layer of Porri tephra is very common on Lipari, especially in its western region, and represents an important stratigraphic key horizon.

There is no evidence of the existence of primary P II pyroclastic material in the capping beds of the Porri tephra layer. That means, that the P II volcanic activity ended before the deposition of the Porri tephra or, absolutely measured, is not younger than approximately 40,000 years. This corresponds with a ^{14}C determination of a carbonized remnant of a palm-tree found in a paleosoil horizon in the capping beds of the Porri tephra (site of find: near the cementery of Quattropani). The ^{14}C age is 39,000 ± 2,000 years; this corresponds to Würm II/III interstadial.

A second key horizon in the road cuttings of Varesana di Sopra is represented by a bed of only a few centimetres of white pumice ash. According to its chemical and mineralogical composition (e.g. sphene, biotite and brown hornblende) this conspicuous layer, which was first found on Salina, Filicudi and Panarea by KELLER (1969), is identical with the *Ischia tephra* having an age of about 25,000 years. Locally, owing to aeolian accumulation, the Ischia tephra reaches a thickness of up to 60 cm on Lipari.

At the end of period II, a volcano-tectonic collapse occurred, which caused the southern piedmont subsidence of the S. Angelo volcano. The following volcanic events, both on Lipari and on Vulcano, were concentrated on this submarine *P II caldera* (or *caldera II*) which extended from the present southern Lipari to northern Vulcano. By this activity the volcanic rocks of period III were formed on Lipari, while on Vulcano the predominantly extrusive edifices of the Lentia region were built up.

Period III

The occurrence of the Ischia tephra at the bottom of the P III series indicates that the P III activity did not start before 25,000 years ago. According to field studies the volcanism of period III ranges in age from about 20,000 to 13,000 years B.P.; this corresponds to the end of Würm III and to Würm IV. During period III not only the southern part of Lipari but also the Lentia hills on the northwestern side of Vulcano were built up.

An older and a younger extrusive sub-stage, in which voluminous endogenous domes rose up, are subdivided on Lipari by a strongly explosive phase, producing pumice, ashes and blocky material. Petrochemically the volcanics of period III are *rhyolites* and *alkali feldspar rhyolites* (fig. 6). The older sequence of many clustered endogenous domes was partially blown up and two large craters, i.e. those of M.te Guardia and M.te Giardina, were formed. Explosive activity of these craters produced pumice- and ash-fall layers which were spread over the entire island of Lipari, covering the top paleosoil horizon of P II. This pyroclastic series of P III (P III pumice series) comprises at least four explosive phases, subdivided by an up--to-1.5-m-thick paleosoil horizon which was formed during a non-volcanic period of several thousand years.

After the P III explosive activity the two great craters were filled by extruding high-viscous lavas which built up two complex endogenous domes, i.e. the M.te Guardia (369 m) and the M.te Giardina (278 m; fig. 5). The last volcanic event of period III was the explosion of the top of the M.te Giardina dome and the formation of a small crater (280 × 210 m). Thereby a downward directed glowing avalanche was erupted and deposited on the eastern slope of M.te Giardina. During

TABLE 1

Average chemical composition and norms of the volcanics of periods I-IV from Lipari 1 = period I (average of 20 major element analyses), corresponding to quartz latiandesite. 2 = period II, substage a and c (6 analyses), corresponding to quartz latite. 3 = period II, sub-stage b (8 analyses), corresponding to (cordierite-bearing) rhyodacite. 4 = period III (4 analyses), corresponding to alkali feldspar rhyolite. 5 = period IV (17 analyses), corresponding to alkali feldspar rhyolite.

	1	2	3	4	5
SiO_2	54.60	59.00	59.30	72.10	72.30
Al_2O_3	16.30	17.80	16.50	13.00	12.80
Fe_2O_3	3.20	2.60	4.30	0.90	1.10
FeO	4.90	2.80	2.50	1.30	0.80
MnO	0.20	0.10	0.10	0.00	0.00
MgO	5.20	2.30	2.20	0.70	0.30
CaO	9.30	6.40	5.30	1.60	0.90
Na_2O	2.20	2.90	2.00	3.90	4.00
K_2O	1.70	3.70	3.50	4.80	4.70
TiO_2	0.70	0.70	0.60	0.10	0.00
P_2O_5	0.20	0.30	0.20	0.00	0.00
	98.50	98.60	96.50	98.40	96.90
CIPW NORM					
Q	8.94	11.87	20.09	26.79	28.71
or	10.05	21.87	20.68	28.37	27.78
ab	18.62	24.54	16.92	33.00	33.85
an	29.58	24.63	24.99	3.79	3.09
di	12.30	4.15	0.00	3.41	1.13
hy	12.59	5.76	5.71	1.54	0.75
mt	4.64	3.77	6.23	1.30	1.59
il	1.33	1.33	1.14	0.19	0.00
ap	0.46	0.70	0.46	0.00	0.00
c	0.00	0.00	0.26	0.00	0.00
RITTMANN NORM					
Quartz	8.6	11.4	17.9	27.4	29.1
Sanidine	9.5	29.2	26.9	60.1	63.8
Plagioclase	53.6	46.1	41.9	5.9	2.6
Clinopyroxene	13.2	4.1	0.0	3.1	1.1
Hypersthene	12.6	6.7	11.2	1.1	1.1
Biotite	0.0	0.0	0.0	1.8	1.7
Cordierite	0.0	0.0	0.9	0.0	0.0
Magnetite	1.5	1.2	0.9	0.6	0.5
Ilmenite	0.7	0.7	0.0	0.0	0.0
Apatite	0.4	0.6	0.4	0.0	0.0
C.I.	27.9	12.7	12.9	6.6	4.5
Q	12.0	13.2	20.6	29.3	30.5
A	13.2	33.7	31.0	64.3	66.8
P	74.8	53.2	48.3	6.4	2.7
F	0.0	0.0	0.0	0.0	0.0
A	22.8	46.7	38.8	75.6	80.6
F	46.7	37.1	45.7	18.3	16.6
M	30.4	16.3	15.5	6.1	2.8
Sigma (Rittmann)	1.31	2.72	1.86	2.60	2.58
Tau (Rittmann)	15.67	14.90	18.13	91.00	–

the following non-volcanic interval of 3,000 to 5,000 years, which separates period III from period IV, the top layers of the P III pumice series were decomposed to a capping paleosoil horizon up to 2 m in thickness.

Fourth period

During the last period of volcanic activity on Lipari, about 10,000 to 1,400 years ago, thick pumice series and obsidianic lavas were produced in the northeastern part of the island. The volcanics of the famous M.te Pilato (476 m) and Forgia Vecchia (303 m) volcanoes are of the same petrochemical composition as the rocks of period III, i.e. *alkali feldspar rhyolites* and *rhyolites*. The first volcanic event of period IV is manifested by the *Lower Pumice Series* (P IV-1) cropping out in

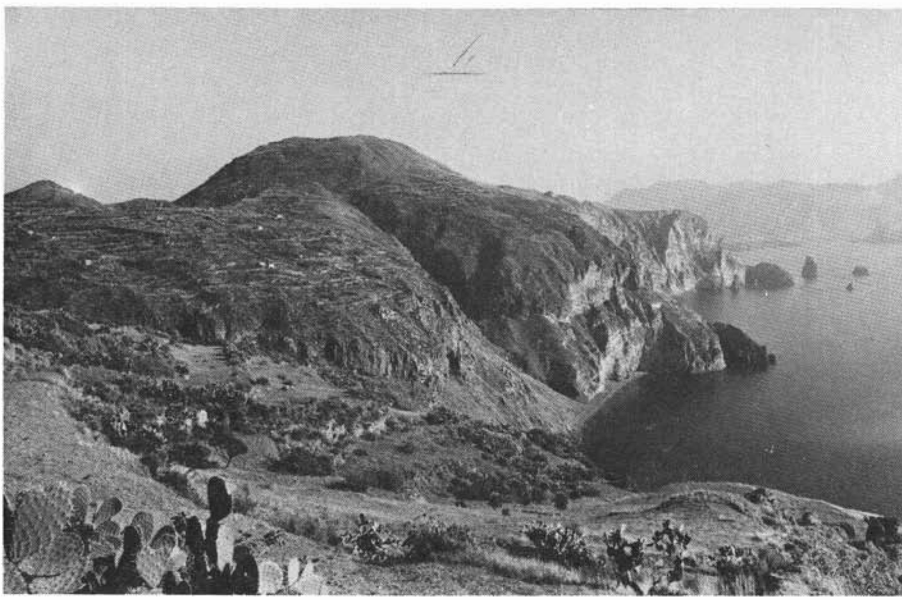


Fig. 5. — The younger endogenous domes M.te Guardia (369 m) and M.te Giardina (278 m) of period III in the southern part of Lipari. The crater of M.te Giardina, formed by the blowing up of the top of the dome, is clearly visible. At the coast remnants of older endogenous domes. In the background the island of Vulcano.

the Gabellotto gorge northwest of Canneto. This pumice is overlaid with the older obsidianic lavas which form the substructure of the M.te Pilato volcano. Once, these highly viscous lavas composed a large complex endogenous dome with some tongue-like offshoots, passing downward on the eastern slopes into short thick lava flows. Fission track ages of these older obsidians gave as result 11,400 ± 1,800 and 8,300 ± 860 years B.P. (Bigazzi and Bonadonna, 1973; Wagner et al., 1976); this corresponds to the post-Pleistocene pre-Boreal time. Later on, parts of M.te Pilato lava dome were blown up and a large crater, about 1 km in diameter and at least 200 m deep, the Fossa delle Rocche Rosse, was formed. Probably at the same time a second crater, that of Forgia Vecchia, was active. From these two large craters the bulk of the *Upper Pumice Series* (P IV-2), which reach a thickness of up to 300 m, was produced. This pumice, being intensively mined, especially on the eastern slopes of M.te Pilato, covers nearly totally the old M.te Pilato lava dome. The formation of the P IV-2 pumice series occurred very rapidly (within

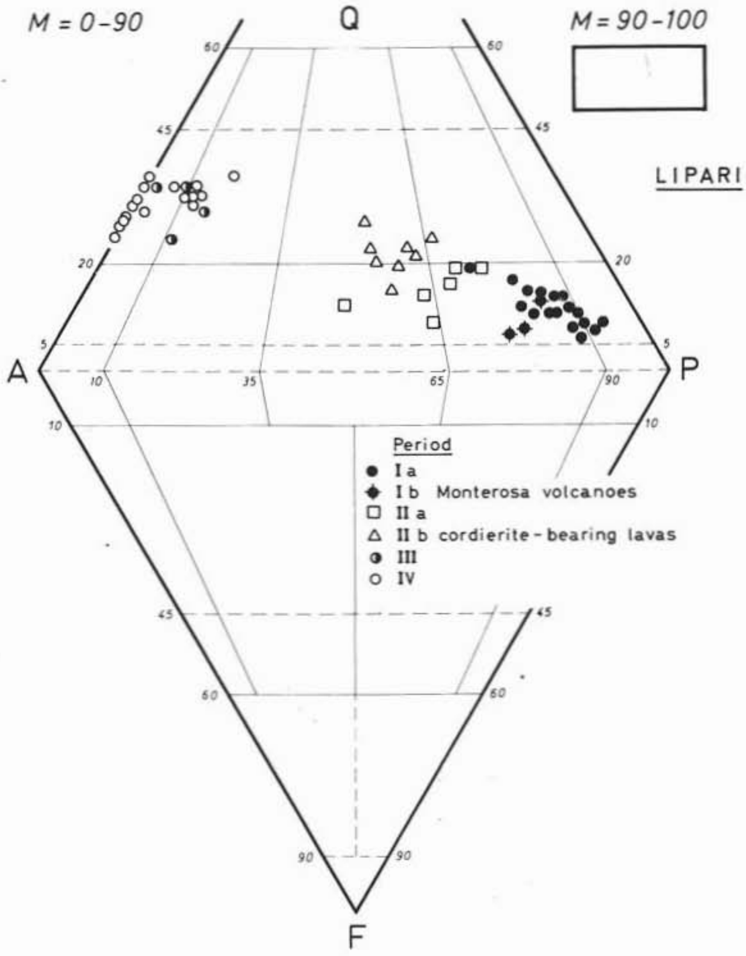


Fig. 6. — QAPF double-triangle plot of the analysed volcanics of Lipari.

days to a few weeks); the date of the eruption lies between 4,800 and about 10,000 years B.P.

The uppermost horizons (P IV-3) of the Upper Pumice Series, however, with a thickness of only up to 10 m, represent a still younger volcanic event. This is indicated by the fact, that these capping pumice layers (P IV-3) are separated from the bulk of the Upper Pumice Series (P IV-2) by a thin, locally up-to-0.5-m-

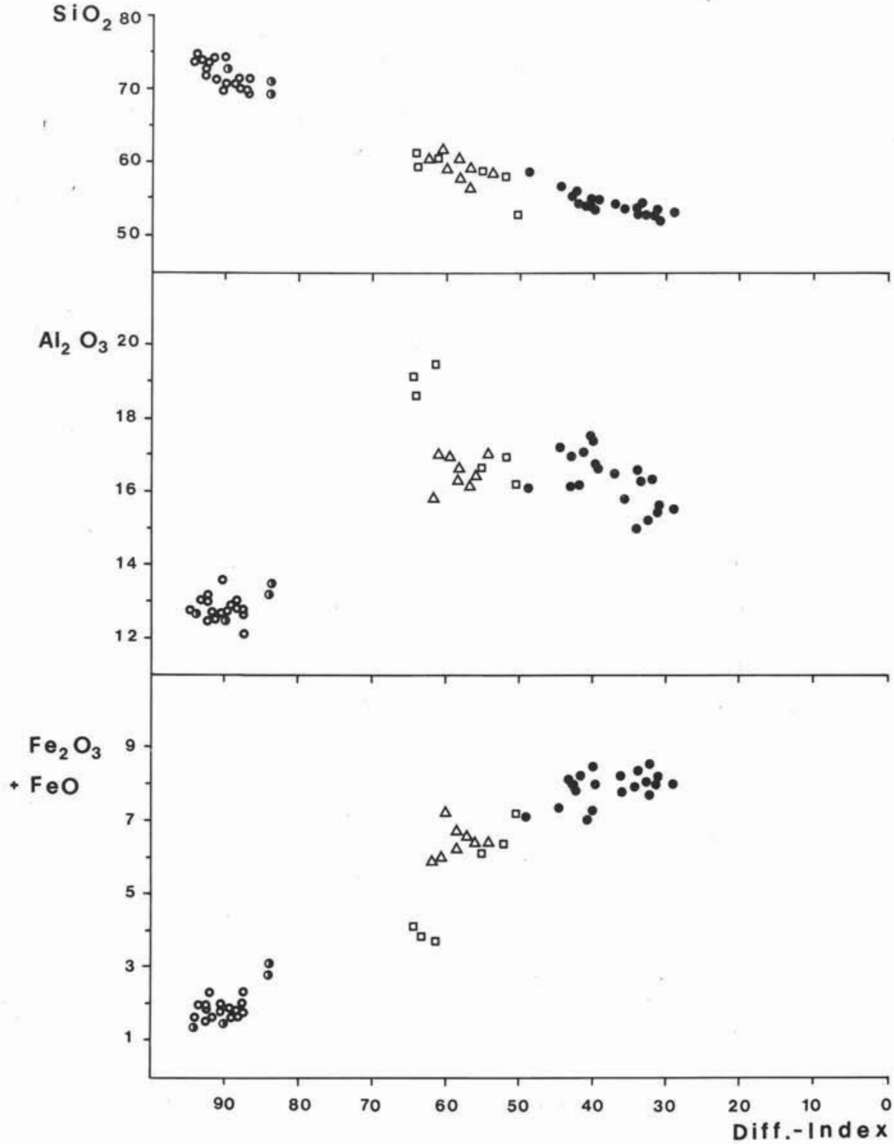


Fig. 7. — Major element (in weight %) of Lipari versus THORNTON and TUTTLE's differentiation index. Full circles = period I; squares = period II *a, c*; triangles = period II *b* (cordierite-bearing volcanics); half-full circles = period III; circles = period IV.

thick paleosoil horizon. This horizon, predominantly consisting of wind-laid deposits deriving mostly from older paleosoil horizons of the island, contains locally obsidian and cheramic artefacts of Neolithic age (BUCHNER, 1949; PICHLER, 1968). The paleosoil horizon represents an interval of non-volcanic activity of at least 3500 years. This is indicated by the differing results of five ^{14}C age determinations, i.e. 4810 ± 60, 3270 ± 100, 2875 ± 110, 1765 ± 95 and 1220 ± 100 years B.P.

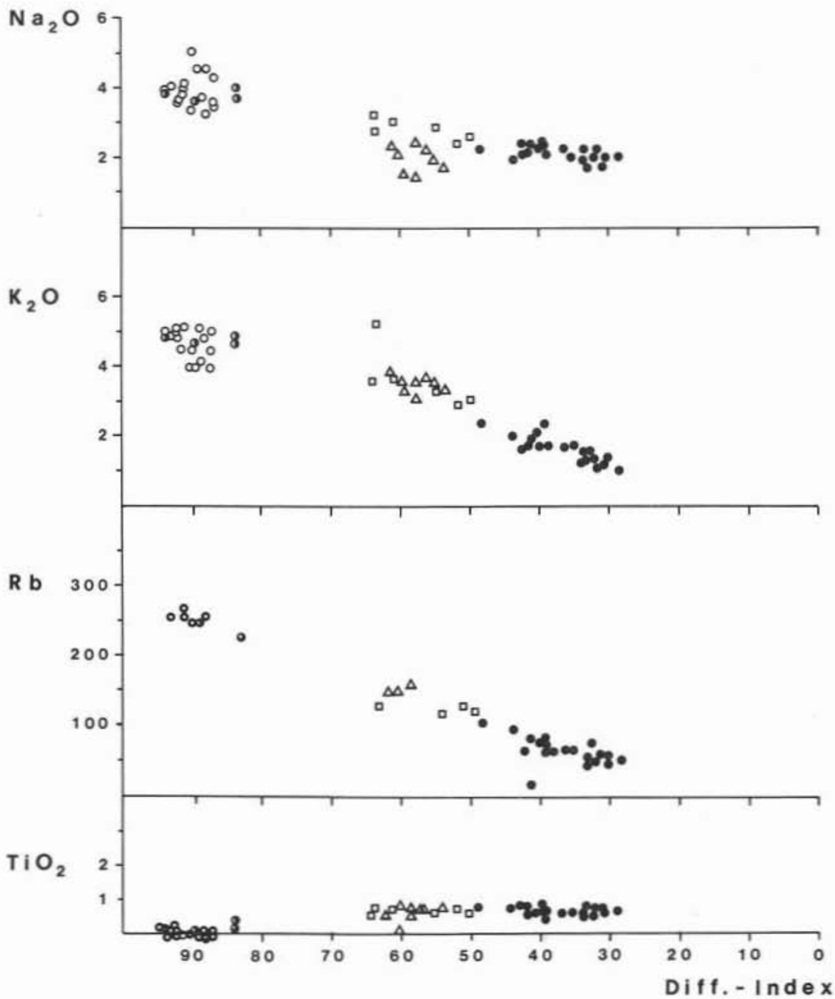


Fig. 8. — Major (in weight %) and trace element (in ppm) distribution of Lipari volcanics versus Differentiation Index by THORNTON and TUTTLE (1960). Symbols as in Fig. 7.

The P IV-3 pumice layers, overlying that paleosoil horizon, represent the youngest volcanic episode on Lipari, which occurred in the Late Roman Decade, about 1400 years ago (KELLER, 1970). The P IV-3 pumice-fall was followed by the extrusion of high-viscous lava both in the Rocche Rosse and in the Forgia Vecchia crater. In both craters the glass lava froze solid as plugs, which soon after were blown up by violent explosions. Thus the blocked vents in both craters became opened. Vent-opening breccias, consisting mostly of fragments of obsidian, occur around both craters, in which overheated acidic magma then rose up and formed the famous obsidian flows of the Rocche Rosse and Forgia Vecchia. The block lava flow of the Rocche Rosse, about 2 km long, represents one of the rare, typical glass lava

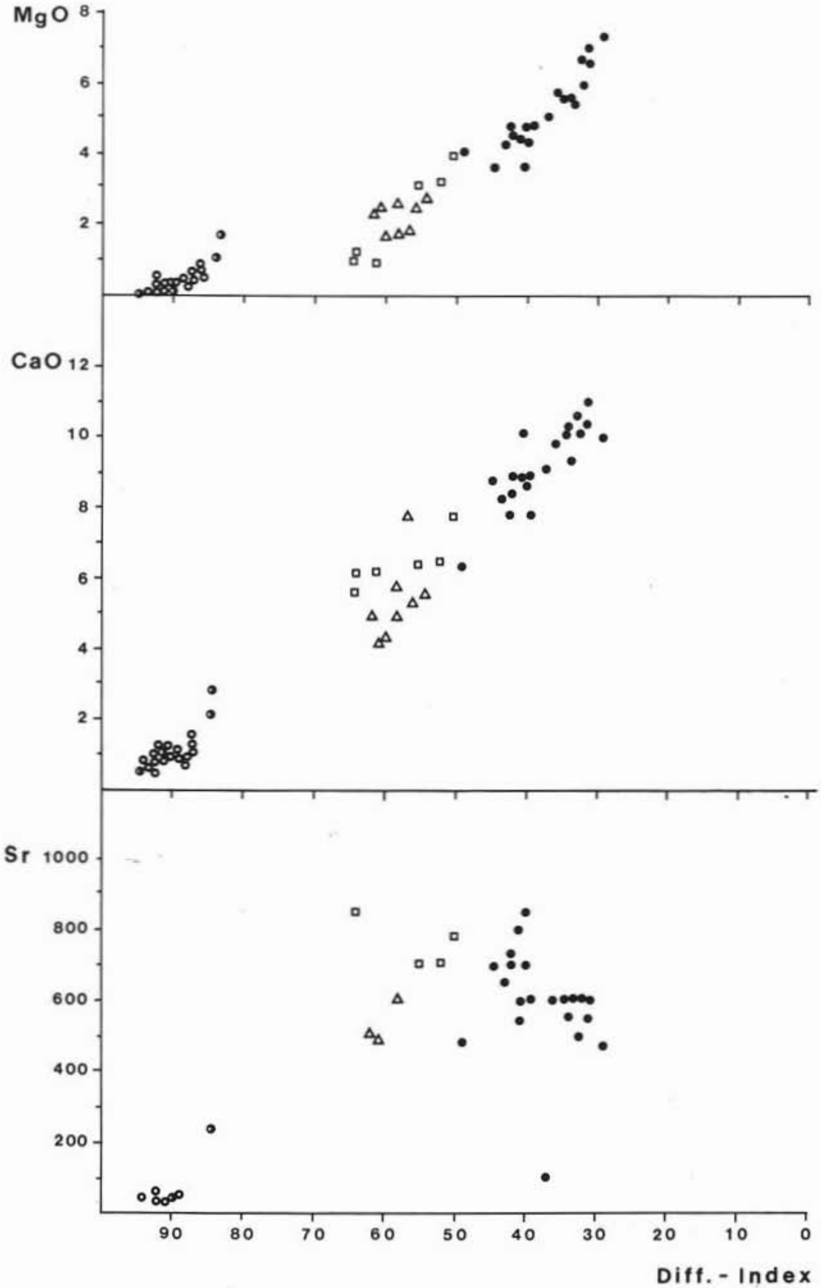


Fig. 9. — Major (in weight %) and trace element (in ppm) distribution of Lipari volcanics versus Differentiation Index by THORNTON and TUTTLE (1960). Symbols as in Fig. 7.

flows, whereas that of the Forgia Vecchia must be described as a tongue-like offshoot of a lava dome of highly viscous melt, poured out over an inclined surface.

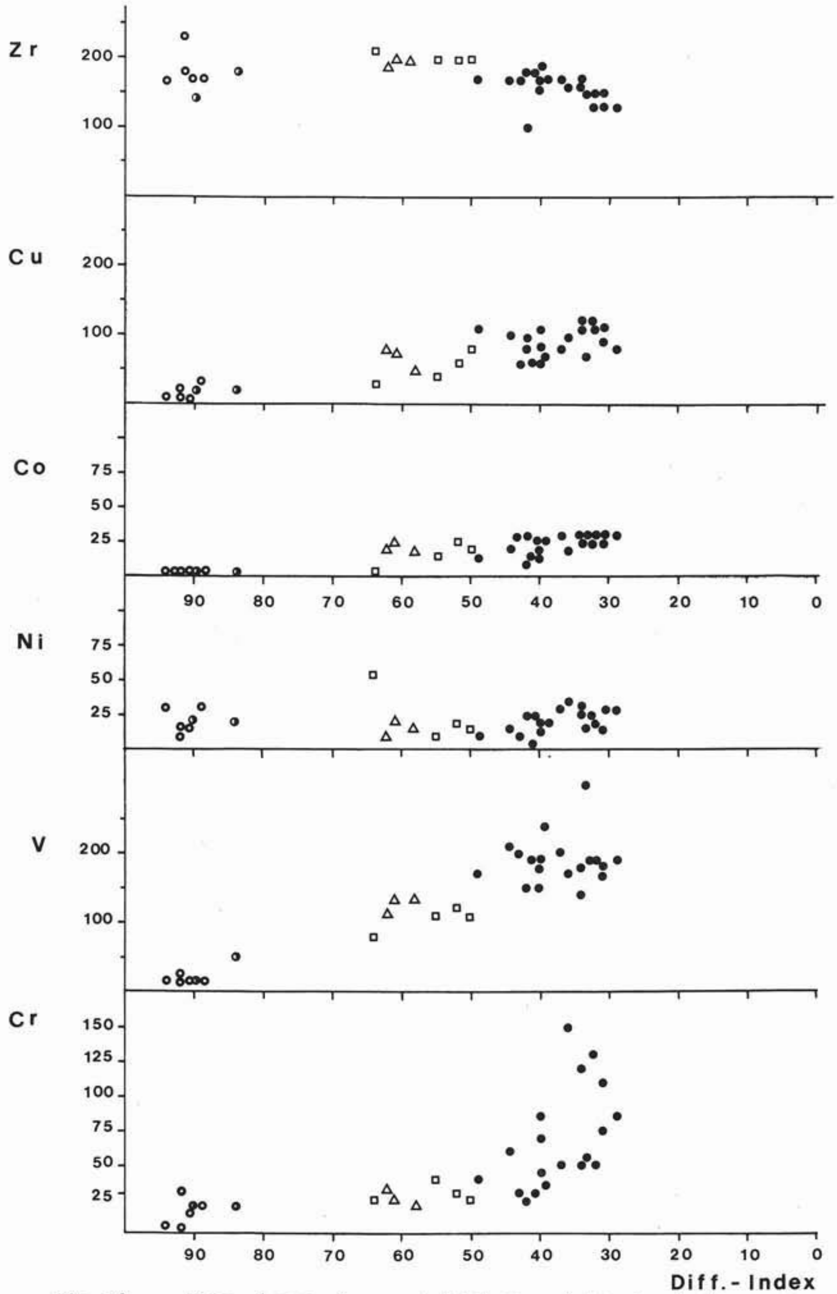


Fig. 10. — Trace element (in ppm) distribution of Lipari volcanics versus Differentiation Index by THORNTON and TUTTLE (1960). Symbols as in Fig. 7.

The formation of the youngest pumice (P IV-3), of the vent-opening breccias and of the Rocche Rosse and Forgia Vecchia obsidian flows occurred during the 6th century A.D. This is indicated by the fact, that the P IV-3 pumice tephra covers,

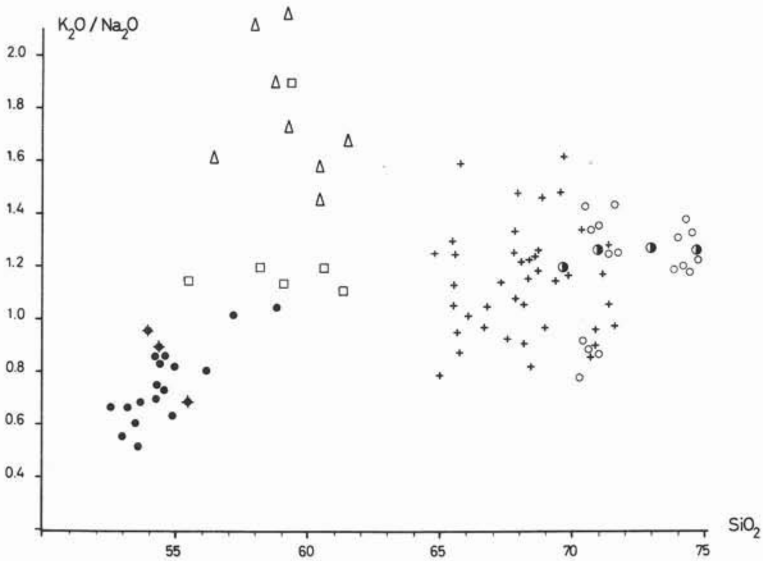


Fig. 11. — K_2O/Na_2O ratio versus SiO_2 (in weight %) diagram of the analysed volcanics from Lipari. Symbols as in fig. 6. Crosses represent the analysed volcanics from the Lentia region, northern part of the island of Vulcano (from JAKOB, 1958 and BALDANZA et al., 1973).

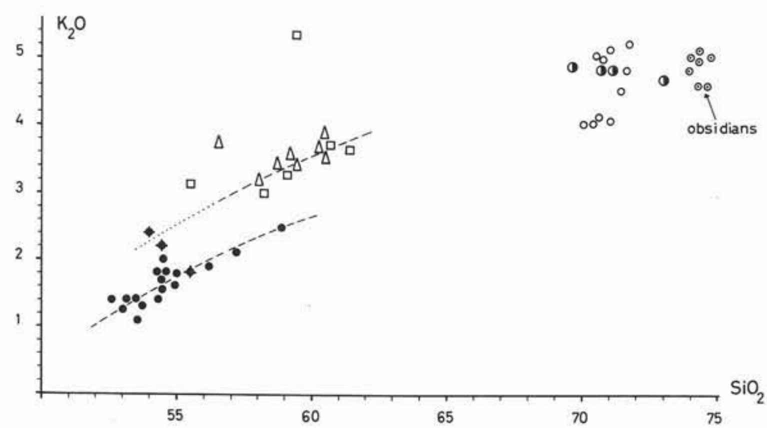


Fig. 12. — K_2O versus SiO_2 diagram of the analysed volcanics of Lipari. Symbols as in fig. 6.

at that place with a thickness of 25 cm, the Creco-Roman necropolis of Lipari, i.e. strata of the 4th and 5th century A.D. (KELLER, 1970). These last volcanic events on Lipari are reflected by the legend of S. Calogero (524-562 A.D.) saying that the pious hermit had exorcised the devils and their fire from the « Black Stone » of Lipari. After that the devils took up residence in the Vulcanello, but they were also driven out from this place by the patron saint of Lipari into the Fossa of Vulcano. This legend was already transmitted by DOLOMIEU (1783, p. 73) who connected it with the last volcanic eruptions on Lipari: « I suggest, that the last volcanic outbursts on this island did not end until the 6th century of the Christian chronology... ».

Petrography

The volcanics of periods I and II represent typical calc-alkaline series comprising *quartz andesites, quartz latiandesites, quartz latites, dacites* and *rhyodacites* (fig. 6). According to TAYLOR's (1969) nomenclature, which is based on the potassium versus silica relationship, these rock types correspond to high-Al basalts, low-Si andesites, and andesites (period I) and to high-K andesites (period II). A quite similar calc-alkaline trend is developed on four other islands of the Aeolian archipelago, i.e. on Salina, Filicudi, Alicudi and Panarea (fig. 13).

Mineralogically, these porphyritic lavas are composed of phenocrystic *plagioclase* (mostly strongly oscillatory zoned with An_{75-55}), *augite* 2 $V\gamma$ = 44°-54°; $n\gamma/c$ = 40°-44°) and mostly microphenocrystic *bronzitic orthopyroxene* (2 $V\alpha$ =

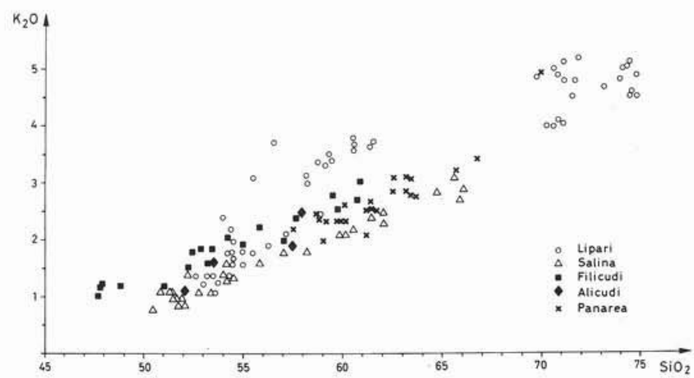


Fig. 13. — K_2O versus SiO_2 diagram of the analysed volcanics of Lipari, Salina, Filicudi, Alicudi and Panarea. The volcanic rocks of Lipari show three different trends: a typical calc-alkaline one (comprising the P I volcanics; identically with the grouping of the other four islands), a K-rich (shoshonitic) trend, which caracterizes the rocks of period II *a, b, c,* and the high-potassium and high-silica groups of period III and IV.

= 65°-80°; Fs_{15-30}) set in a groundmass of microlitic plagioclase (An_{65-45}), clinopyroxene, ore minerals and glass. Some corroded *olivine* (Fa_{25-30}), oftenly showing a reaction rim of *pigeonitic clinopyroxene* (2 $V\gamma$ = 25°; $n\gamma/c$ = 38°), occurs in the volcanics of period I. This Ca-poor clinopyroxene is sometimes found also in some volcanics of period II, forming there reaction rims around orthopyroxene. Rare opacitized phenocrysts of brown *hornblende* are present only in a single lava flow of period I. Biotite is absent in all volcanics of periods I and II with the exception of the cordierite-bearing lavas of period II.

These lavas carry corroded xenocrystic cordierite, up to 10 mm in diameter, K-feldspar and spinel besides garnet, andalusite, sillimanite, biotite, zircon, apatite,

TABLE 2

Major and trace element data and $^{87}Sr/^{86}Sr$ ratios of five samples representative of periods I-IV of Lipari. Sr isotopic relations, Rb and Sr abundances from KLERKX et al. (1974, p. 298).

	Li I	Li II b	Li II c	Li III	Li IV
SiO_2	55.50	60.5	58.20	71.00	74.3
Al_2O_3	16.99	15.8	16.92	13.20	13.1
Fe_2O_3	4.30	4.5	2.50	–	0.79
FeO	4.13	1.8	4.04	2.70	1.1
MnO	0.17	0.07	0.11	0.07	–
MgO	4.31	2.3	3.25	1.10	0.33
CaO	8.30	4.9	6.54	2.10	0.84
Na_2O	2.58	2.4	2.49	3.80	3.7
K_2O	1.79	3.8	2.99	4.80	5.1
TiO_2	0.80	0.6	0.71	0.15	0.09
P_2O_5	0.12	0.16	0.24	0.06	Sp.
H_2O	0.68	3.2	1.70	0.40	0.5
CO_2	0.19	n.d.	0.09	n.d.	0.2
	99.85	100.03	99.78	99.38	100.05
Rb	55	160	111	280	314
Sr	706	499	653	181	21
Ba	650	800	550	200	270
Zr	170	190	200	180	190
Cu	60	80	40	20	20
Co	30	20	25	5	5
Ni	10	10	15	30	20
V	200	110	120	50	30
Cr	30	30	25	20	25
K/Rb	271	197	223	142	98
Rb/Sr	0.08	0.32	0.40	1.55	14.95
$^{87}Sr/^{86}Sr$	0.7051	0.7057	0.7053	0.7045	0.7061

Li I: Quartz latiandesite, Lipari, period I, lava, Monterose volcanic complex, western cone, directly at the harbour on the southern side of Monterosa.

Li II b: Cordierite-bearing rhyodacite, Lipari, period II b, lava, old cave at the road somewhat east of Belvedere (Quattr'occhi).

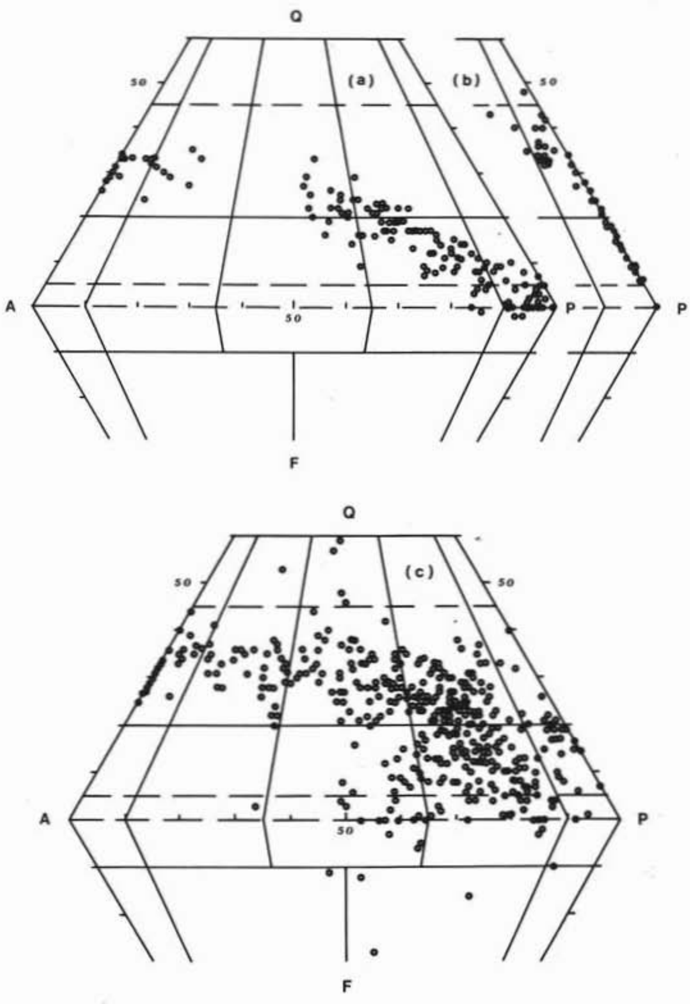
Li II c: Quartz latiandesite, Lipari, period II c, lava, summit flow of M.te Sant'Angelo volcano (southern rim).

Li III: Rhyolite, Lipari, period III, lava, old cave north of Capistello, southern part of Lipari.

Li IV: Rhyolite, period IV, lava, Rocche Rosse obsidian flow. (Major element analysis taken from VON PLATEN, 1965, p. 339).

Rare-earth elements and U, Th, Hf, Sc contents for sample nos. Li I, Li II c and Li IV are published in KLERKX et al. (1974, p. 300).

corundum, rutile and quartz (BERGEAT, 1910; MACCARRONE, 1963, 1967; HONNOREZ and KELLER, 1968). This mineral assemblage and the abundant inclusions of metamorphic rocks, mostly hornfelses, evidence that a part of the magmas of period II was contaminated by partial resorption of metamorphic material of a continental crust underlying parts of the Tyrrhenian Sea. Up to the Miocene the Tyrrhenian aerea was occupied by the so-called Tyrrhenian Block of Calabro-Peloritan Landmass which linked the crystalline zones of Calabria and NE-Sicily (Peloritan Mount-



Figs. 14 *a*, *b*, *c*. — STRECKEISEN double-triangle plots of all available major element analyses from the Aeolian archipelago excepting Vulcano and Stromboli (above, to the left), from the Tonga-Kermadec island arc (above, to the right), and from the Central Andes (below). Data from literature and from the Author's, unpublished stock.

tains). The partially resorbed material represents in our case a typical high-grade assemblage of a contact-metamorphic rock with cordierite and K-feldspar as diagnostic minerals (WINKLER, 1974, p. 97).

The *rhyolitic* to *alkali feldspar rhyolitic* volcanics of periods III and IV, however, are clearly separated from the volcanics of periods I and II. The gap between both groups is evident in all diagrams (figs 7-10). Nevertheless, there is no doubt that the acidic group belongs to the calc-alkaline association, though the average serial index is slightly higher ($\sigma \sim 2.6$) than that of period I ($\sigma = 1.31$; Table 2). The slight increase of the serial index, which is already developed with regard to the oldest volcanics of period II, is due to a modestly increased potassium level in spite of a gradually higher SiO_2 content. This slight increase of potassium within the calc-alkaline series of Lipari proceeded in time.

Petrographically, the volcanics of periods III and IV consist nearly entirely of glass with refractive indices between 1,490 and 1,504. Some strongly corroded phenocrysts of augite and, very rarely, even of olivine occur within the obsidian-like lavas of period III. The pumice and obsidianic lavas of periods III and IV represent over-heated melts with temperatures of about 900°-1000° C. This is evidenced by the fact, that inclusions of *quartz latiandesitic* volcanics, frozen in the older obsidians of period III, are preserved in a stretched, formerly plastic, high-viscous state.

Major element geochemistry

Average chemical composition of the volcanics of periods I-IV and norms are given in Table 1. Differences of single major element levels are gradual and depend on the increasing silica content in time, i.e. decrease of Al_2O_3, total iron, MgO, CaO and increase of Na_2O and K_2O (cf. figs 7-10). As mentioned above, there exists, in spite of a gradually higher SiO_2 content, a slightly stronger increase of the potassium content in time. If we, however, consider the K_2O/Na_2O ratio (fig. 11), a gap between the older (periods I, II) and younger acidic group (periods III, IV) is clearly obvious. Therefore, no connexion exists between the acidic group and the non-cordierite-bearing volcanics of period II which show a similar K_2O/Na_2O ratio as the acidic group, i.e. > 1.0. This gap indicates a different magma origin for both groups. A clear similarity is evident between the acidic group and the Lentìa volcanics from the neighbouring island of Vulcano (fig. 11). Such a similarity is also obvious with regard to the petrography and the age of the lavas of period III and the bulk of the Lentia volcanics which occur opposite the period III volcanics of southern Lipari across a small and only up-to-40-m-deep channel.

Concerning the volcanics of periods I and II, a sharp increase of the K_2O/Na_2O ratios exists. The volcanics of period I mostly show K_2O/Na_2O ratios < 1.0, whereas those of period III have values > 1.0. According to the diagram, it seems that the cordierite-bearing and the non-cordierite-bearing volcanics are separated from each other by a gap due to very high K_2O/Na_2O ratios for the cordierite--bearing group. The difference of K_2O/Na_2O between both groups of period II, however, results only from a lower Na_2O level of the cordierite-bearing group related to a similar K_2O content in comparison with the non-cordierite-bearing volcanics (cf. Table 1). In reality, both groups of period II are tightly clustered.

TABLE 3

Major characteristics of typical island arcs (left column) with regard to the Aeolian Islands (right column)

1) Arcuate continuation of islands	Yes
2) Prominent volcanic activity at present	Yes (Stromboli)
3) Deep-sea trench on the oceanic side	No
4) Marked gravity anomaly	Yes (MORELLI 1970)
5) Active seismicity, including deep- and intermediate-focus earthquakes	Relatively low seismicity; only some deep- but no intermediate-focus earthquakes (SCHICK 1972; RIUSCETTI and SCHICK 1975)
6) Earth movements in progress	?
7) Coincidence of arcs with orogenic belts	Yes (Mti. Peloritani)
8) High heat-flow	Yes (MORELLI 1970)
9) Composition of volcanic rocks	Not typical for island arcs
10) Distinct zonality of the volcanic rocks, parallel to the arc	No, but shoshonites related to fracture zones across the arc.

TABLE 4

Average of the major element composition of volcanic rocks from Lipari, Salina, Filicudi, Alicudi and Panarea (column I; 156 analyses) in comparison with a typical island arc association (Tonga-Kermadec = To-Ke; 30 analyses). III = 9 Aeolian quartz-andesites; To-Ke (IV) = 18 Tonga-Kermadec quartz-andesites; V = 52 Aeolian quartz-latiandesites; An (VI) = 65 central Andean quartz-latiandesites. Data for Tables 4 and 5 from literature and from the Author's own, unpublished stock

	I	To-Ke (II)	III	To-Ke (IV)	V	An (VI)
SiO_2	58.6	59.2	53.2	52.8	57.3	59.4
Al_2O_3	16.7	14.6	17.6	16.7	16.8	16.9
Fe tot.	6.7	9.5	9.1	10.1	7.3	5.8
MgO	3.7	3.7	4.9	5.4	3.9	3.4
CaO	7.1	8.5	9.9	11.4	7.9	6.1
Na_2O	2.8	2.3	2.5	1.7	2.8	3.7
K_2O	2.4	0.7	1.2	0.4	2.1	2.4
TiO_2	0.6	0.7	0.6	0.6	0.6	0.8
P_2O_5	0.2	0.1	0.2	0.1	0.2	0.2
H_2O	1.2	0.7	0.8	0.8	1.1	1.3
	100.0	100.0	100.0	100.0	100.0	100.0
CI	20.2	26.0	27.7	33.3	21.7	16.2
Sigma	1.9	0.6	1.3	0.4	1.8	2.5
K_2O/Na_2O	0.8	0.3	0.5	0.2	0.8	0.6

This is demonstrated for instance by the Na_2O or K_2O versus differentiation index plots (fig. 9).

On the other hand a clear separation between the volcanics of periods I and II is evident in most of the diagrams, reflecting different magma sources or a different magma evolution for both periods. Thus, three different groups of calc-alkaline volcanics exist on Lipari, i.e.:

a) the typical (strong) calc-alkaline volcanics of period I (serial index $\sigma = 0.91\text{-}1.61$);
b) the K-rich calc-alkaline (shoshonitic) volcanics of period II ($\sigma = 1.42\text{-}2.69$);
c) the K- and SiO_2-rich calc-alkaline (shoshonitic) volcanics of periods III and IV ($\sigma = 2.02\text{-}2.03$).

It is suggested that each of these groups has originated from a different magma source or/and a different kind of magma evolution.

These three different calc-alkaline groups on Lipari are clearly distinguished in the K_2O versus SiO_2 diagram (fig. 12). This plot shows three trends of different K_2O level related to increasing SiO_2. It is possible that a part of the youngest volcanics of period I, i.e. those of the Monterosa volcanoes ($\sigma = 1.53\text{-}2.18$), belong to the group which comprises the volcanics of period III. Additionally, in the light of the K_2O versus SiO_2 plot, it is apparent that most of the volcanics of periods I and II were involved in differentiation processes occurring in individual magma chambers. Such a fractionation trend is evidenced by gradually increasing K_2O levels related to a corresponding increase of SiO_2. It seems that no fractionation exists within the acidic group (periods III, IV). It may be noted, however, that the obsidianic lavas of period IV show the highest SiO_2 level ($> 73.5\,\%$) not only among the Lipari volcanics but also within the whole Aeolian archipelago.

Trace element geochemistry and $^{87}Sr/^{86}Sr$ relations

Trace element abundances and Sr isotope ratios of five samples representing periods I-IV of Lipari are listed in Table 2. Additionally, a lot of unpublished trace element data are incorporated into figs 7-10. Rb abundances increases proportionately with increasing K_2O. A strong dispersion exists with regard to Sr. Even within the volcanics of period I an obvious difference in the Sr level is evident in spite of nearly the same differentiation index (30-45). Strong differences are also significant in the period II. Low Sr levels (< 50 ppm) appear in the volcanics of the acidic group (periods III, IV), though single samples reach high values (> 150 ppm). Nearly the same Zr level (150-200 ppm) has been found for all four periods, with a slightly higher concentration for the volcanics of period II. Co is in the same range for periods I and II (20-30 ppm) but very low in the rocks of the acidic group (< 5 ppm). Ni shows the same low level (10-30 ppm) for all four periods, V decreases rapidly with increasing SiO_2 content (from about 200 to < 30 ppm). Cr exhibits partly high concentrations in some volcanics of period I (up to 150 ppm) whereas other samples of period I have low Cr contents (< 50), similar to those of periods II, III and IV (< 50 ppm).

$^{87}Sr/^{86}$ ratios (Tab. 2) of Lipari volcanics are in the range of 0.7045 to 0.7061 (Klerkx et al., 1974; Barberi et al., 1974). Contrary to expectation, the cordierite-bearing lava of period II, which is evidently contaminated by crustal rocks, shows only a slightly increased Sr isotope ratio (0.7057). The lowest value (0.7045) was found for the obsidianic lavas of period III, whereas the Rocche Rosse obsidian of period IV is characterized by an obviously higher ratio (0.7061). K/Rb ratios are higher (> 250) for the typical calc-alkaline volcanics of period I, whereas the K-richer calc-alkaline rocks (periods II, III, IV) show lower K/Rb ratios (< 250-100).

Discussion

For some years, the Aeolian archipelago has been considered to be an island arc structure « similar to western Pacific island arcs ». Its volcanism is interpreted to be related to an inclined seismic Benioff zone dipping 50°-60° WNW from the Ionian to the Tyrrhenian Sea. A « rapid deepening » of the Benioff zone « in a restricted time (less than 1 m.y.) » under the Aeolian Islands is suggested « by the increase of K content observed in recent volcanics » (Barberi et al., 1973, 1974; Keller, 1974; Caputo et al., 1970, 1972; Morelli, 1970; Ninkovich and Hays, 1972; etc.).

According to Sugimura and Uyeda (1973) island arcs are characterized by typical features, which are compiled in Table 3.

It should be noted, however, that marked gravity anomaly and high heat-flow are characteristics not only for island arcs but also for other volcanic regions on the continents or on mid-oceanic ridges. Arcuate continuation of islands can also be found in other non-volcanic or volcanic archipelagos, and prominent volcanic activity at present is not restricted to island arcs. Thus, as *typical* features of island arcs there remain:

1) active seismicity representing an inclined Benioff zone;
2) peculiar composition of volcanic rocks.

Ad 1): Based on a critical recalculation of hypocenter locations of all available seismic events for the southern Tyrrhenian and the adjoining Calabrian and Sicilian area, Schick (1972, 1977) and Riuscetti and Schick (1975) have recently found that the hypocenters never fall in the depth range between 35 and 200 km. This broad gap in seismicity is inconsistent with the presence of a Benioff zone in that region. The active seismicity is restricted to a depth of 200-350 km. The lack of seismic activity within a broad depth range is interpreted as an argument for a « senile stage » of the Aeolian island arc (Barberi et al., 1974). Recently, Keller (1974) has explained this « very mature evolution stage » by way of a « detached piece of a formerly continuous slab, which continues to sink with very steep inclination into the mantle ». As these island arc dynamics should have occurred in less than 1 m.y. (Barberi et al., 1974; Keller, 1974), an

TABLE 5

Average of trace element and rare earth data of andesites and quartz-andesites (column I) and quartz-latiandesites (III) from Lipari, Salina, Filicudi and Alicudi in comparison with andesites, quartz-andesites and plagiodacites from the Tonga-Kermadec island arc (To-Ke) and with quartz-latiandesites from the central Andes (An).

	I	To-Ke	III	An
Rb	24	11	75	64
Sr	620	254	659	648
Ba	247	198	674	914
Sc	30	32	20	39
Cr	101	29	78	35
Co	32	23	34	19
Ni	40	21	40	32
Zr	93	38	113	197
La	20	2.9	40	n.d.
Ce	37	6.2	73	40
Pr	4.6	1.1	6.3	n.d.
Nd	20	5.0	32	22
Sm	4.1	1.8	5.8	4.7
Eu	1.2	0.6	1.6	1.2
Gd	3.9	2.2	5.0	4.2
Tb	0.6	0.4	0.7	0.6
Dy	3.3	2.8	4.2	n.d.
Ho	0.7	0.7	0.8	n.d.
Tm	0.3	n.d.	0.3	0.3
Er	2.2	1.9	2.4	n.d.
Yb	1.6	2.0	2.2	1.6
Hf	1.5	0.9	3.1	n.d.
Th	2.5	0.3	8.1	12
U	1.1	n.d.	2.2	2.4

unusually high annual sinking rate of the slab of more than 10 m/year would result. This high annual sinking rate should be connected with unusual high seismicity in the Tyrrhenian area. In that region, however, only some deep- but no intermediate-focus earthquakes are listed.

Ad 2): The average chemical compositions of the calc-alkaline group within the Aeolian archipelago, i.e. of the islands Lipari (period I), Salina, Filicudi, Alicudi, and Panarea, are compiled in Tables 4 and 5. There are obvious discrepancies with regard to some major element contents in comparison with a typical island arc association, e.g. the Tonga-Kermadec volcanic rocks (Table 4). The most striking discrepancy concerns the potassium level which is threefold higher in the Aeolian volcanics than in the Tonga-Kermadec rocks. Great differences exist also for the K_2O/Na_2O ratios and the sigma values. The petrochemical discrepancy between this Pacific and the Aeolian archipelago is particularly remarkable with respect to the trace element and rare earth element abundances (Table 5). Among these data Rb, Sr, Cr, Ni, Zr, La, Ce, Pr, Nd, Sm, Eu, and Th differ significantly. Because of these strong petrochemical discrepancies between the Aeolian volcanic rocks and a typical island arc assemblage, a relation of the Aeolian islands to such an island arc system is not supported. This incompatibility is evidenced also diagrammatically, e.g. by way of the STRECKEISEN double-triangle plot (figs 14 *a-c*). Significant differences are clearly visible between the Aeolian islands on the one hand and the Tonga-Kermadec group on the other. The Aeolian calc-alkaline volcanic rocks show a quite different distribution in the double-triangle, which is not comparable with island arc associations. There exists, however, a similarity with typical continental « andesites », e.g. those from the Central Andean area (Figs. 14 *a* and 14 *c*). This similarity is also reflected in the average chemical composition (Tables 4 and 5), especially the K_2O, Al_2O_3, Rb, Sr, Th, U, and the rare earth contents.

Because of these facts the existence of a seismic Benioff and of a subduction zone in the Tyrrhenian and the adjoining Calabrian area, and the origin of the Aeolian volcanic magmas from a down-going lithospheric slab can not be supported. It seems that the Aeolian calc-alkaline rocks resemble more closely the continental type of « andesites » that may have been formed in the upper mantle under low pressure but high H_2O conditions. Parts of these subcrustal melts could have been contaminated by crustal material. With regard to the magma genesis of the acidic rocks of Lipari (periods III and IV) an origin by anatexis of crustal rocks cannot be ruled out. A similar magma genesis indicated by Sr isotope data was also suggested for the shoshonitic association within the Aeolian islands (Vulcano, Stromboli; KLERKX et al., 1974). It should be remembered, that up to the Miocene the area of the present Tyrrhenian Sea was occupied by the Tyrrhenian Block. Since that time the Tyrrhenian Block was eliminated. Great parts of its crust may have been carried off by way of « corroding » processes at the base of the crust. Due to this « oceanisation » the continental crust of the southern Tyrrhenian was replaced by oceanic crust (MENARD, 1967; VAN BEMMELEN, 1969). The orign and the evolution of Aeolian magmas seems closely connected with these processes and can be understood without the postulation of a steep-inclined subduction zone. A similar style of tectonics and magma formation seems to exist in the Aegean area, where the Cycladean volcanic arc represents neither a typical island arc structure nor is connected with a subduction zone. The ingenious model of plate tectonics is not a geoscientific panacea and should in each case be applied carefully and in strict coincidence with the facts. Dogmatical interpretations of some plate tectonic functions, e.g. DICKINSON's K-h relation for Southern Italy and Greece by NINKOVICH and HAYS (1972), or creation of similar functions (Rb-h and Zr-h relations [h = curves of equal earthquake focal depth]) by these authors may lead to serious errors.

ISTITUTO INTERNAZIONALE DI VULCANOLOGIA - C.N.R.

CARTA GEOLOGICA DELL' ISOLA DI LIPARI
GEOLOGIC MAP OF THE ISLAND OF LIPARI (AEOLIAN ISLANDS)

HANS PICHLER