South Aegean Volcanic Arc: Geochemical Variations and Geotectonic Implications

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ABSTRACT

The Aegean volcanic arc is one of the most important geological structure of the Mediterranean area. It is a belt of volcanic centers consisting of products ranging from basaltic, andesitic, dacitic to rhyolitic in composition, all of them displaying a typical calc-alkaline chemical character.

The most abundant rock types are represented by andesites and dacites. Minor amounts of basalts and rhyolites occur mainly in the central-eastern sector of the arc. The REE, Rb, Sr, Ba, Th, Ta, Hf, Zr, Ni, Co, V and Cr abundances determined in 27 representative samples from different centers suggest that: 1) the intermediate and acidic terms are products of crystal/liquid fractionation processes starting from basic parent magmas; 2) large variations in incompatible elements occur in the most basic samples that are interpreted as evidence for heterogeneously LIL element-enriched mantle source; 3) plagioclase played a role in the evolution of the volcanic centers of the eastern and central arc different from that played in the volcanoes of the western sector.

Along the arc, the differences in the distribution of lithological types, in the volumes of erupted material, in the volcanological characteristics of the different centers as well as in the patterns of trace element distribution in the volcanites are considered to be connected with the prevailing tectonic regime affecting the various sectors of the arc.

INTRODUCTION

The South Aegean area is the site of an active process of converging plate margins. An arc-trench system and an associated back arc area interpreted as a marginal basin in an early stage of development have been recognized (NINKOVICH and HAYS, 1972; BOCCALETTI *et al.*, 1974).

The active volcanic arc consists of several centres situated along a west-east elongated belt between the gulf of Saronico and the island of Nisyros. The volcanic products have a basaltic to rhyolitic composition displaying a typical island-arc calc-alkaline chemical character (*e.g.*, KELLER, in press).

Several petrological studies have been carried out on these volcanic rocks, whereas geochemical data are still scarce.

In this paper major and trace element data on rapresentative volcanic rocks from the Aegean arc are reported aiming at discussing their genesis and the relationship between petrological and geochemical characteristics of the volcanites and the geotectonic setting of the area.

GEOLOGICAL OUTLINES

The late Pliocene-Quaternary volcanic products of the South Aegean area make up a volcanic front that includes the centers of Sousaki, Aegina, Methana, Poros, Milos, Santorini and Nisyros (Fig. 1). Behind this belt the volcanic outcrops of Likades, Atalanti channel, Antiparos and Kos do also occur. All these have chemical characteristics different from those of the active arc rocks (INNOCENTI *et al.*, 1979) and have been intepreted as an evidence of a double arc structure in the South Aegean (NINKOVICH and HAYS, 1972). However, their location – except for the island of Antiparos – along important transcurrent faults bordering the western and eastern sides of the Aegean microplate, argues against this hypothesis. In addition, the Miocene age determined with K/Ar methods on products from Antiparos (INNOCENTI *et al.*, in prep.) exclude also for this center any direct tectonic and genetic link with the at present active magmatic arc.

The active volcanic centers are located above an amphiteather-shaped seismic zone having the maximum depth of 180 km and dipping 35° on the average (PAPAZACHOS, 1973). The focal depth of earth-

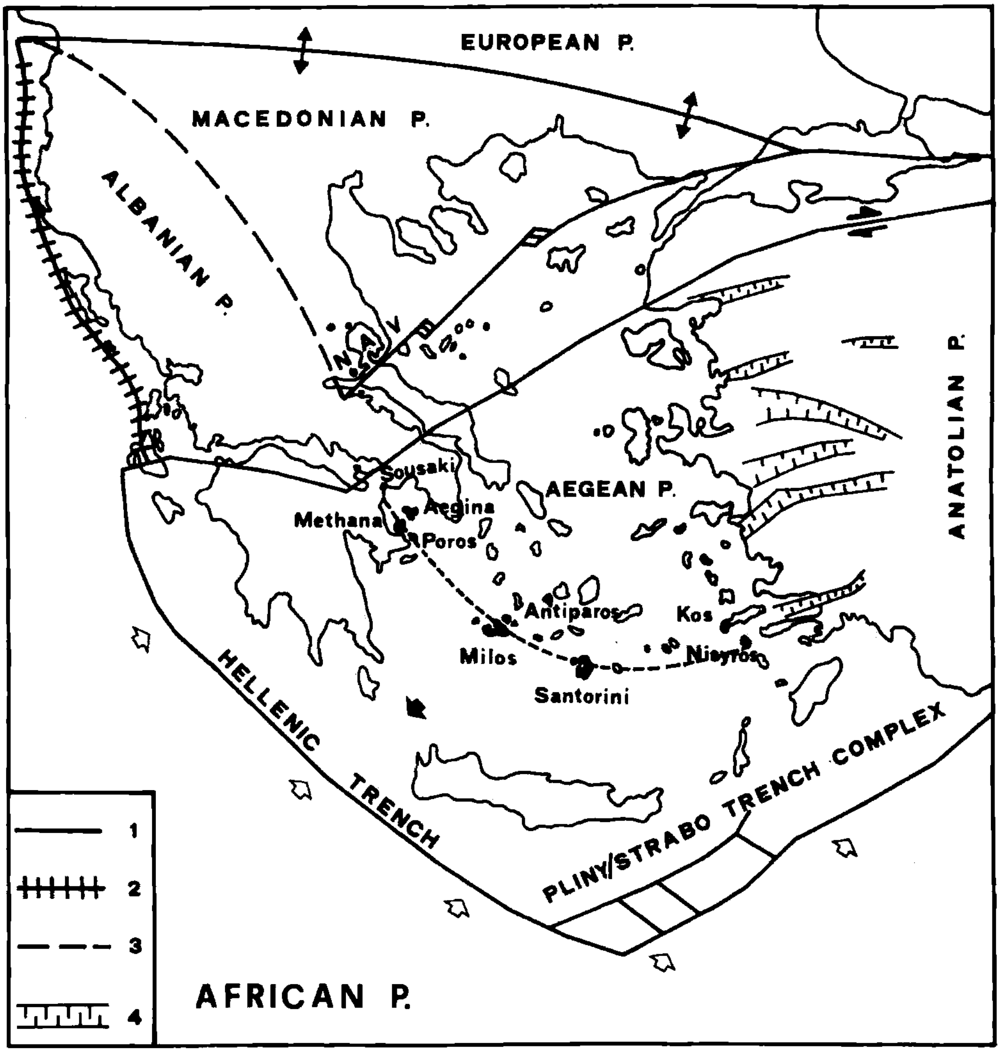


FIG. 1 - Tectonic sketch-map of the Aegean area. (1) Plate limit; (2) limit of Late-Miocene Early-Pliocene thrust in Outer Hellenids; (3) inferred plate limit; (4) graben.

quakes under the volcanic arc averages 150 km (COMNINAKIS and PAPAZACHOS, 1980). The volcanoes lie on a continental crust with thickness of 32-34 km on the western and eastern borders and 23-26 km in the central part of the arc (MAKRIS, 1977). Here the volcanoes lie on a palaeozoic-mesozoic metamorphic basement which has been affected by an important high *P/T* metamorphic phase in Eocene and by a low *P/T* metamorphism in middle-upper Miocene, both accompanied by intrusions of granitic stocks (ANDRIESSEN *et al.*, 1979; DURR *et al.*, 1978).

Tectonically, the volcanic arc develops on an area influenced by a middle Miocene compressional phase followed by a strongly extensional tectonic regime in Pliocene (MERCIER, 1976; ANGELIER, 1979). The volcanism started 3 m.y. B.P. (FYTIKAS *et al.*, 1976) and is still active.

VOLCANOLOGY

Variable volcanological characteristics are shown by the different centers along the arc. Large composite volcanoes generally associated with caldera structures occur in the central-eastern sector (*i.e.* Nisyros, Santorini, Milos), whereas a complex system mainly consisting of lava domes (Sousaki, Aegina, Methana, Poros) developed in the western part of the arc.

The island of Nisyros is a composite active volcano with a summit caldera. Three eruptive phases have been recognized. The first products are represented by few submarine basaltic andesites cropping out in the NW side of the island. During the second mainly andesitic phase, the strato-volcano was built up whereas the products of the third phase are represented by domes and small lava flows of dacitic-rhyolitic composition emplaced after the caldera collapse (DAVIS, 1967, DI PAOLA, 1974).

Santorini is the remnant of a series of central volcanoes broken up by the «Minoan» explosive eruption, which was followed by the formation of a large caldera (PICHLER and KUSSMAUL, 1980). Before the caldera collapse, the island was made up by a series of centers, the oldest of which erupted also submarine lavas giving K/Ar ages of 1.6 m.y. (FERRARA *et al.*, 1980). After the «Minoan» eruption, the activity has been essentially intracalderic with the outpouring of the dacitic products of the islets of Palea Kameni and Nea Kameni (GEORGALAS, 1962).

In the island of Milos, the volcanic activity started in Pliocene (2.6 m.y. ago) and extended also over the adjoining island of Kimolos and Antimilos. The products consist of prevailing pumice, tuffites and ignimbrites overlain by a volcanic series made up of basaltic, andesitic to dacitic lava flows and domes associated with a few pyroclastic products. The latest (0.48 m.y. B.P.) mainly rhyolitic activity produced some tuff-cones with associated perlitic lava flows (FYTIKAS *et al.*, 1976; ANGELIER *et al.*, 1977). The volcanic sequence rests on a basement consisting of metamorphic rocks and Neogene sediments which crop out sporadically in the southern part of the island.

At Methana, volcanic rocks lie on a Mesozoic sedimentary basement, and consist of lava domes with associated lava flows and minor agglomerates. The age of the oldest outcropping volcanites is 0.9 m.y., and the latest activity dates back to 250 y. B.P. (GEORGALAS, 1962).

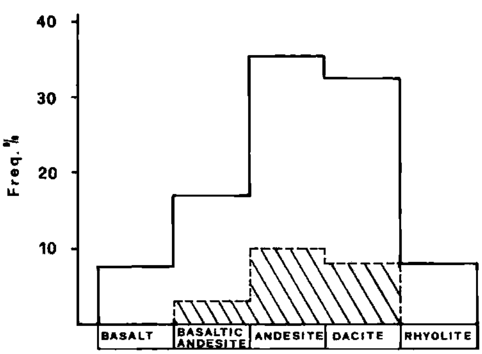


FIG. 2 - Frequency distribution of the different rock types in the Aegean arc based on 352 major element analyses. Dashed area: frequency distribution of rocks in the western arc sector.

The centers of Aegina, Poros and Sousaki are characterized alike by the presence of lava domes with a composition ranging from basaltic andesite to dacite (PE, 1972, 1973). Apparently the products of Sousaki are the oldest of the entire arc having the K/Ar age of 2.7 m.y. (FYTIKAS *et al.*, 1976; BELLON *et al.*, 1979).

PETROGRAPHY AND CHEMISTRY

Several major element analyses and petrographical data are available on the volcanic rocks from the Aegean arc. The following discussion is based on 270 major element analyses taken from the literature (BURRI and SOPTRAJONOVA, 1967; DI PAOLA, 1974; NICHOLLS, 1971; PE, 1972, 1973; PICHLER and KUSSMAUL, 1972; PUCHELT *et al.*, 1977), and on 82 new analyses.

The volcanic products of the Aegean arc form a typical basalt-andesite-dacite-rhyolite calc-alkaline suite. The frequency distribution of the lithological types shown in Fig. 2 indicates a predominance of andesitic and dacitic terms that represent about 35% and 32% of the arc products, respectively. An uneven distribution of the different rock types along the arc is observed, the westernmost centers being characterized by a scarcity or the absence of basic and acidic types.

Petrographically the rocks show mainly a porphyritic texture. In the most basic types the phenocryst mineralogy is dominated by clinopyroxene, generally partially resorbed olivine, plagioclase and Ti-magnetite, whereas orthopyroxene occurs only occasionally. In the intermediate rocks clinopyroxene, plagioclase and Ti-magnetite and, at a lesser extent, orthopyroxene are the main phenocryst phases. Hornblende phenocrysts often occur in the rocks from Methana, Aegina and Milos. Hornblende and orthopyroxene tend to increase in the most evolved terms. Biotite, sanidine and rare quartz are found in the rhyolites. Groundmasses consist of the same phases as the phenocrysts and glass, that is sometime very abundant. Obsidians and perlites occur in Milos and Nysiros.

Chemically, basalts and basaltic andesites display high Al_2O_3 (generally higher than 18%), TiO_2 ranging between 0.8-0.9% and relatively low K_2O that shows values close to that of island arc tholeiitic series as defined by PECCERILLO and TAYLOR (1976). The Mg_v are around 60.

Within the most evolved rocks CaO, MgO and FeO decrease whereas FeO_T/MgO ratio slightly increases. K_2O/Na_2O ratio tends to increase reaching values close to unity in the rhyolites. On the whole, the K_2O/Na_2O ratio keeps close to the values of the islands arc type rather than to those of the Andean type calc-alkaline rocks (EWART, 1979; JAKEŠ and WHITE, 1972). In Fig. 3 the K_2O *vs* SiO_2 relationships are shown. Except for Methana volcanic rocks that have the lowest correlation coefficient, the rate of increase of K_2O with silica is about the same for the different centers and on the whole it is intermediate between that observed in island arc and in active continental margin suites matching closely those displayed by calc-alkaline series

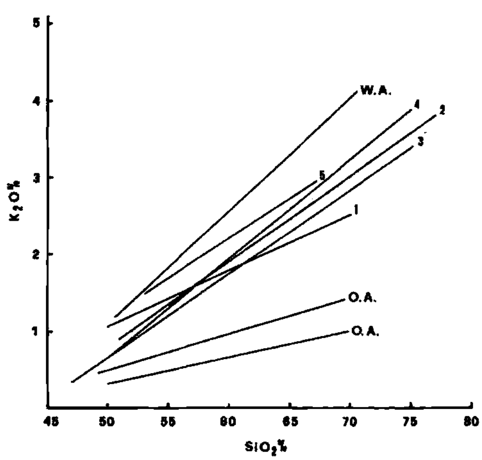


FIG. 3 - K_2O versus SiO_2 correlation lines for suites from different volcanic centers of the Aegean arc. (1) Methana; (2) Milos; (3) Santorini; (4) Nisyros; (5) Aegina. The lines of the Volcanites from oceanic arcs (O.A.) and Western Andes (W.A.) are from ROGERS and NOVITSKY-EVANS (1977).

TABLE 1 - Chemical composition of volcanic rocks from South Aegean Arc.

	SN72	TH13	TH27	SN75	NY39ˆ	MH40	NY21ˆ	TH25	TH20	M24	SN82	MH38	K33
SiO_2	49.00	51.14	51.52	53.93	54.85	54.90	55.80	56.90	57.16	57.78	58.56	60.02	60.39
TiO_2	0.85	0.88	0.81	0.77	0.73	0.79	0.77	0.78	1.19	0.82	1.26	0.63	0.82
Al_2O_3	19.09	19.30	19.19	17.33	17.10	17.45	18.22	18.18	16.36	16.86	15.98	17.16	16.54
Fe_2O_3	2.42	2.87	1.80	1.73	3.98	2.05	3.94	1.59	1.73	2.23	3.63	1.88	2.08
FeO	6.24	5.42	6.30	5.60	1.44	4.14	2.44	4.68	6.54	4.56	5.00	3.32	3.54
MnO	0.17	0.16	0.16	0.14	0.08	0.15	0.06	0.12	0.17	0.13	0.19	0.14	0.11
MgO	6.54	5.78	5.64	6.90	6.75	5.53	4.73	3.72	3.70	3.96	2.68	3.63	2.85
CaO	11.17	9.80	9.83	8.26	9.53	8.93	8.55	7.12	6.86	7.54	5.95	6.38	5.61
Na_2O	2.61	3.03	3.11	3.33	3.18	2.87	3.62	3.64	3.66	2.94	4.24	3.54	3.39
K_2O	0.36	0.70	0.65	1.26	1.18	1.45	1.14	2.09	1.32	1.33	1.58	1.98	2.90
P_2O_5	0.05	0.09	0.10	0.12	0.17	0.13	0.22	0.12	0.15	0.08	0.18	0.16	0.15
L.O.I.	0.45	0.03	0.87	0.35	0.81	1.61	0.71	1.05	1.16	1.76	0.76	0.68	1.62
Mg_v°	61.4	59.7	59.3	66.4	73.4	65.4	61.8	55.5	48.4	55.3	39.9	59.7	51.9

	MH18	MH6	M52	D2L	TH8	MH46	TH4	TH38	MH15	TH35	TH36	T1	TH40	K99
SiO_2	60.86	62.33	62.55	64.24	64.57	64.84	65.29	65.67	66.05	66.79	67.85	69.28	70.54	74.80
TiO_2	0.56	0.52	0.77	0.58	0.64	0.51	0.78	0.62	0.43	0.70	0.38	0.40	0.30	0.13
Al_2O_3	17.67	15.83	16.64	17.35	15.30	16.28	15.71	16.10	15.41	15.75	15.92	15.03	14.64	12.68
Fe_2O_3	1.85	2.03	3.05	3.35	3.98	1.36	1.27	0.65	1.94	0.61	1.29	1.70	0.56	0.38
FeO	2.91	2.63	1.96	0.84	0.44	2.88	3.86	3.86	1.57	3.52	1.54	1.28	1.60	0.70
MnO	0.14	0.13	0.09	0.04	0.13	0.12	0.15	0.10	0.12	0.08	0.05	0.01	0.05	0.06
MgO	3.15	3.25	2.25	1.33	1.24	1.96	1.51	1.00	1.97	1.04	1.76	1.11	0.65	0.18
CaO	6.20	6.04	5.31	5.60	3.12	5.02	3.72	2.60	4.71	3.66	3.59	2.75	2.14	0.94
Na_2O	3.71	3.82	3.46	2.99	5.21	3.16	5.13	5.34	3.34	4.47	4.15	2.64	4.41	3.80
K_2O	2.07	2.00	2.51	1.93	1.75	2.28	1.72	2.60	2.44	2.56	2.45	3.27	2.99	3.57
P_2O_5	0.14	0.12	0.14	0.15	0.13	0.14	0.13	0.17	0.12	0.13	0.10	0.09	0.07	0.02
L.O.I.	0.74	1.30	1.27	1.60	3.49	1.45	0.73	1.39	1.90	0.76	0.92	2.44	1.85	2.74
Mg_v°	58.5	59.9	49.5	41.4	38.7	49.5	38.2	32.0	54.9	34.4	57.2	44.7	45.3	26.1

° $Mg/Mg+Fe^{++}$ atomic ratio calculated using an assumed oxidation ratio $Fe_2O_3/FeO=0.15$ (GREEN et al.,1974); ˆdata from DI PAOLA (1974). All elements (except MgO by AAS and Feo by titration) analyzed by XRF with full matrix correction after FRANZINI et al. (1972). Analyst: M.SAITTA -Istituto di Mineralogia-Pisa and L.TODARO- C.S. per la Mineralogia e Geochimica dei Sedimenti-Florence

SN72-Santorini,Oia; TH13-Santorini cape Skaros; TH27-Santorini,W flank of Megalo Vouno; SN75-Santorini,Akrotiri; NY39-Nisyros, Mandraki; MH40-Methana,W of Kameno Vouno; NY21-Nisyros,southern slope of caldera rim; TH25-Santorini,N flank of Mikro Profitis Elias; TH20-Santorini, cape Skaros; M24-Milos,NW part of island; SN82-Santorini,cape Kulumbo; MH38-Methana,Kameno Vouno; K33-Milos,Kimolos; MH18-Methana,Kameno Vouno; MH6-Methana,Profitis Elias; M52-Milos ,near Aghios Marina; D2L-Aegina; TH8-Santorini, Nea Kameni,lava of Mikra Kameni; MH46-Methana,Kosona; TH4-Santorini,Nea Kameni,1951 lava; TH38-Nisyros,NE rim of caldera; MH15-Methana,Kosona; TH35-Santorini,Fira,upper part of caldera wall; TH36-Nisyros,W rim of caldera; T1-Sousaki; TH40-Nisyros, Nikia; K99-Milos,Kimolos.

occurring in magmatic arcs associated with thin continental crust (ROGERS and NOVITSKY-EVANS, 1977).

The calc-alkaline character of the Aegean volcanites is also shown by the AFM trends (Fig. 4) which are characterized – with the exception of the rocks of the Main Series of Santorini (NICHOLLS, 1971) – by the typical lack of iron enrichment.

TRACE ELEMENTS

Twenty seven representative samples have been selected for trace element analyses. Their major element composition is reported in Table 1; trace element data are reported in Table 2.

The basaltic rocks come all from Santorini and show ferromagnesian element contents higher than the average values quoted by TAYLOR (1969), PERFIT *et al.* (1980) and WHITFORD *et al.* (1979) for island-arc calc-alkaline basalts. However, both the ferromagnesian element contents and the Mg_V (ca. 59-61) indicate that these rocks have suffered fractionation of mafic minerals as it was demonstrated also by NICHOLLS (1978).

The abundance of large ion lithophile (LIL) elements (Sr, Ba, Rb) and of high field-strenght (HFS) elements (Th, Zr, Hf, Ta) is comparable with the abundance average values found in island arc basalts with the exception of Th and Sr that display higher and lower abundances, respectively. The ΣREE ranges between 62 ppm and 45 ppm, the lowest values being shown by sample Sn 72 displaying also the lowest K_2O content. The REE patterns (Fig. 5 a) are fractionated for LREE with La/Sm ratio ranging from 2.2 to 3.2 and unfractionated for HREE. All the samples have a small Eu anomaly that stresses out the role of plagioclase fractionation also in these basic rocks.

The basaltic andesites and andesites have incompatible element contents higher than those in the basalts and, with the exception of V, lower ferromagnesian element abundances whose mean values are still higher than the andesite averages quoted by TAYLOR (1969). The LREE fractionation increases (Fig. 5 b,c) with the $[La/Sm]_N$, displaying large range of values (2.2-5.2).

Large variation are also observed in the abundances of both light and heavy REE. The HREE patterns are constantly flat

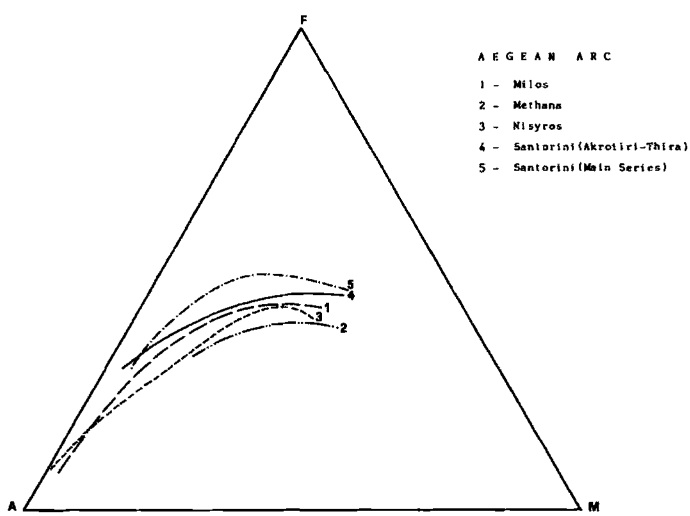


FIG. 4 - AFM curves for rock suites from different Aegean arc centers. (1) Milos; (2) Methana; (3) Nisyros; (4) Santorini (Akrotiri-Thira series); (5) Santorini (main series) (NICHOLLS, 1971).

TABLE 2 - Trace element composition.

	SN72	TH13	TH27	SN75	NY39	MH40	NY21	TH25	TH20	M24	SN82	MH38	K33	MH18	MH6	M52	D2L	TH8	MH46	TH4	TH38	MH15	TH35	TH36	T1	TH40	K99
Rb	10	17	20	9	18	50	28	66	52	44	67	79	109	85	67	67	55	62	71	59	63	85	93	73	157	91	119
Ba	85	171	151	239	320	343	411	483	255	254	259	478	730	484	421	1116	697	388	468	384	717	518	524	684	480	801	660
Sr	201	212	180	187	815	286	525	268	174	187	201	311	226	363	267	595	440	148	209	160	310	249	129	466	218	253	84
Th	1.6	3.1	3.7	6.9	2.5	6.2	3.2	9.6	10.2	5.3	9.9	9.6	13.6	10.4	9.2	11.7	8.8	11.9	93	12.2	8.4	11.2	16	9.3	14.6	11	14.2
Zr	80	90	93	75	118	106	153	187	189	149	213	122	262	140	101	164	149	223	140	215	262	103	316	166	188	230	112
Hf	2.3	2.2	2.1	3.2	2.9	0.56	2.8	3.3	4.6	3.7	4.6	2.9	5.5	3.2	2.6	3.9	4.0	5.6	3.7	5.6	5.7	2.8	7.0	4.1	4.8	5.0	2.3
Ta	0.16	0.35	n.d.	0.51	0.54	0.56	0.59	0.60	1.0	1.2	0.6	0.72	1.0	0.68	0.65	1.5	0.80	0.6	0.98	0.72	1.5	0.73	1.2	1.2	3.1	1.4	1.3
Cr	80	123	102	266	147	117	46	58	78	90	90	47	72	31	93	5	6	5	14	5	3	16	5	8	70	5	2
V	259	246	257	201	160	172	175	153	212	193	192	102	148	89	92	157	120	30	58	56	15	66	33	54	40	25	43
Sc	37	33	36	32	22	26	20	16	28	25	22	14	17	14.2	13	13.9	12	17	11.3	17	5.7	9	15	6.5	7.1	4	1.3
Ni	40	44	41	99	71	44	32	24	23	27	7	24	17	16	20	8	6	4	7	5	4	10	4	10	43	5	3
Co	34	31	31	33	26	23	19	17	23	20	16	14	16	13.7	13	13.6	7.5	7	8.5	10	4.2	8.2	8	8.4	5	4	1
La	5.5	11	8.4	15	13.6	17.1	19.1	26	19	15	20	21	27	24	20	34	24	25	27	24	38	27	31	29	34	34	31
Ce	13	20	16	33	32	29	39	41	37	31	42	38	55	44	38	63	51	48	48	51	63	45	66	52	64	55	41
Nd	8.0	11	9	16	16	14	16	16	18	15	22	16	21	18	15	22	24	20	19	22	25	18	30	17	26	18	12
Sm	2.5	3.4	3.2	4.0	3.2	3.2	3.6	4.8	5.8	4.2	5.9	3.4	5.1	3.3	2.7	5.3	4.6	5.9	4.2	5.7	6.1	2.9	6.9	2.9	5.4	2.9	2.6
Eu	0.94	0.83	0.85	0.90	1.02	0.89	1.06	0.79	1.25	0.95	1.31	0.88	0.92	0.91	0.77	1.20	1.05	1.33	0.92	1.47	1.25	0.77	1.4	0.69	1.00	0.61	0.32
Tb	0.5	0.6	0.8	0.6	0.5	0.5	0.6	0.6	1.0	0.8	1.0	0.5	0.9	0.4	0.4	0.7	0.7	1.2	0.6	1.2	1.0	0.4	1.2	0.4	0.6	0.42	0.4
Yb	2.6	2.3	2.3	2.8	1.08	2.14	2.3	2.4	4.2	3.1	4.2	0.95	3.0	2.0	1.8	2.0	2.0	4.2	2.4	4.8	3.7	1.8	6.0	1.6	1.8	1.9	1.6
Lu	0.38	0.50	0.50	0.40	n.d	0.36	0.36	0.4	0.8	0.5	0.8	0.33	0.56	0.38	0.32	0.38	0.39	0.9	0.4	0.9	0.7	0.3	n.d.	0.3	0.27	0.41	0.31
Σ REE	45	62	55	87	83	80	98	108	110	87	120	94	133	105	90	143	126	130	118	138	163	109	173	113	153	118	101
$[La/Sm]_N$	1.5	2.2	1.8	2.5	2.9	3.5	3.7	3.7	2.2	2.4	2.3	4.3	3.6	5.0	5.2	4.3	3.7	4.3	4.3	2.9	4.2	6.3	3.0	6.8	4.1	7.7	8.4
La/Yb	2.1	4.8	3.6	5.3	7.6	7.9	8.3	10.8	4.5	4.8	4.7	10.7	9.0	12.0	11.0	17.0	12.0	5.9	11.2	5.0	10.2	15.4	5.1	18	19	20	19
$[Tb/Yb]_N$	0.85	1.10	1.30	0.78	1.07	0.96	1.09	1.10	1.00	1.00	0.95	1.02	1.20	0.87	0.85	1.40	1.43	1.20	0.98	1.00	1.10	0.96	0.80	1.00	1.33	1.00	1.02
Eu/Eu*	1.08	0.94	0.75	0.81	0.98	0.94	0.97	0.60	0.69	0.71	0.74	1.03	0.58	1.12	1.00	0.79	0.75	0.81	0.77	0.79	0.69	1.00	0.67	0.85	0.75	0.75	0.43

Th, Hf, Ta, Co, Sc and REE by INAA (POLI et al. 1977); Rb, Sr, Ni, Cr, V, Zr by XRF (LEONI and SAITTA, 1976). The precision (1 sigma) is better than 15% for Lu and Tb, better than 10% for Ta, Yb, Ni, Cr, V and better than 5% for La, Ce, Nd, Sm, Eu, Th, Hf, Sc, Co, Rb, Sr, Ba, Zr.

with $[Tb/Yb]_N$ around unity. The andesites from Milos and Nisyros display a significant negative Eu anomaly that increases in the acidic terms, whereas the andesites from Methana do not display any Eu depletion (Fig. 5 c). The Eu behaviour in basalts and andesites suggests that a low pressure plagioclase fractionation played an important role in the evolution of some volcanic centers, especially of those of the central and eastern sectors of the arc.

The incompatible element abundances still increase in the dacites, whereas a strong depletion of ferromagnesian elements is observed. The overall REE fractionation increases and, except for the rocks from Methana, a significant negative Eu anomaly appears together with a decrease in Sr values. A slight HREE fractionation appears in some samples with $[Tb/Yb]_N$ ratios reaching the value of 1.43.

A large variation in HREE absolute abundances (Fig. 5 d) is observed where the Santorini dacites are the most HREE rich rocks among the analyzed samples.

The rhyolites display the highest REE fractionation with $[La/Sm]_N$ values of ca. 8 and La/Yb ca. 20. Sample K99 shows a negative Eu anomaly (Fig. 5 e) coupled with low Sr contents. Instead, the absolute abundances of REE, Zr, and Hf decrease. This, together with the lowest P_2O_5 contents, suggests that in the late stages of differentiation an important role was played by accessory phases such as zircon and apatite.

DISCUSSION

The calc-alkaline volcanic suite of the Aegean arc has a composition variable from basaltic to rhyolitic passing through andesitic and dacitic terms. Basalts and basaltic andesites occur mainly in the central-eastern sector of the arc. Trace element distribution shows continuous trends through the suite suggesting that crystal/liquid fractionation processes played an important role in the genesis of the most evolved terms.

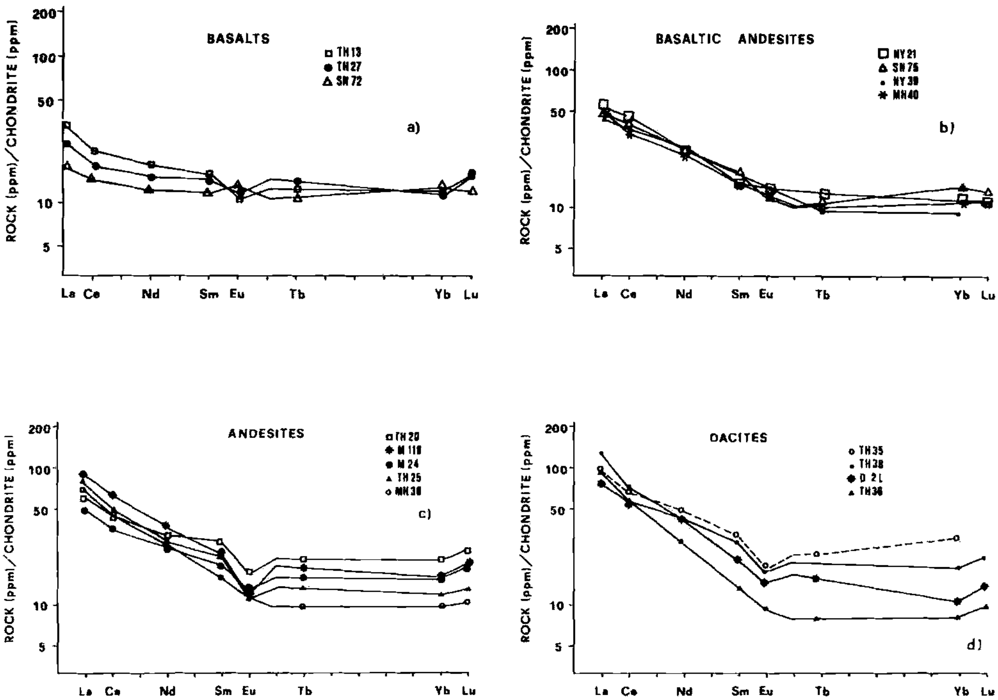
The high-Al basalts and basaltic andesites have relatively high ferromagnesian elements with respect to other island arc basic calc-alkaline rocks (TAYLOR, 1969; PERFIT *et al.*, 1980). However, the abundances of these elements suggest that even the most primitive of the analyzed rocks cannot be considered as derived from liquids in equilibrium with the mantle but as the products of magmas which have suffered a small degree of olivine and spinel fractionation that, for the Santorini rocks, has been estimated to be about 6-13% (NICHOLLS, 1978). The occurrence of Eu anomalies in the REE pattern of the basic samples also indicate that these liquids suffered a plagioclase fractionation during their ascent to the surface.

The REE distribution evidenced a flat REE pattern and a variable degree of LREE fractionation for rocks with comparable D.I. and ferromagnesian element contents. This, together with the large range of values of the other incompatible elements (Rb, Sr, Zr, Hf, ecc.), calls for the occurrence of several geochemically distinct primary magmas along the arc.

The transition to andesites and dacites is characterized by an increase of $\sum$ REE, LREE fractionation and LIL element abundances. Instead, the Sr abundances together with Eu/Eu* values tend to decrease, showing that plagioclase fractionation played a major role in the genesis of these rocks. It is worth noting that among the andesites, those from Methana do not show any significant Eu anomaly.

The variation of LREE abundances and fractionation is shown in the $[La/Sm]_N$ *vs.* La_N diagram (Fig. 6). All the samples define a positive general trend suggesting an evolution process governed by a clinopyroxene fractionation. The scattering shown by the rock samples of intermediate composition can be attributed to an increasing role of plagioclases over clinopyroxenes in the course of fractionation, as already evidenced by the Eu/Eu* decrease and/or by primary geochemical differences.

Several genetic models have been proposed for the Aegean calc-alkaline rocks. These include lower crust melting (PICHLER and STENGELIN, 1968; PICHLER and KUSSMAUL, 1972), derivation from the



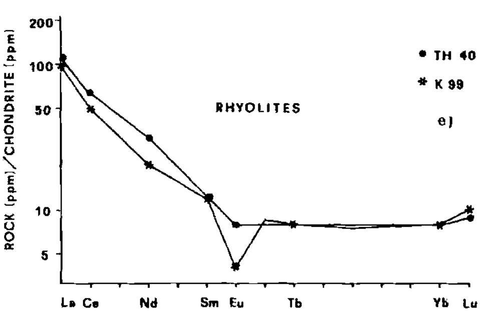


FIG. 5 - Condrite-normalized REE patterns for representative Aegean arc volcanites.

melting of a subducting oceanic slab (PUCHELT and HOEFS, 1971) and melting of the mantle peridotitic wedge overlaying the Benioff zone (NICHOLLS, 1978; PUCHELT, 1978).

The paucity of rhyolites, however, and the relatively low $^{87}Sr/^{86}Sr$ values found even in the most acidic volcanic rocks from different parts of the arc (GALE, 1981; PE, 1975; PE and GLEDHILL, 1975; PUCHELT and HOEFS, 1971) argue against the crustal melting hypothesis. In addition, geochemical data favour a derivation of the acidic products from basic-intermediate magmas by a crystal/liquid fractionation mechanism.

Also the hypothesis of a genesis by melting o a subducting oceanic slab is not supported by petrological and geochemical data. In fact, a total melting of the source rock should be necessary in order to explain the major element chemistry of the most primitive rocks of the studied area (NICHOLLS, 1978). However, the incompatible trace element abundances found in these samples do not match those observed either in N-type or E-type oceanic basalts (WOOD, 1979; PERFIT *et al.*, 1980).

In addition, the lack of a conspicuous HREE fractionation in the analyzed samples testifies the absence of residual garnet during the melting processes. This conflicts with the hypothesis of the provenance of the Aegean calc-alkaline magmas from a subducting slab at a depth of about 150 km such as that reached by the Benioff zone under the active volcanoes.

The genetic hypothesis proposed by NICHOLLS (1978) for the basic rocks of Santorini seems more satisfactory. According to this author the calc-alkaline high-Al basalts are the final products of a multistage process started with the partial melting of a subducting oceanic slab. The formed LILE and water-rich liquids react with the upper mantle wedge overlying the Benioff zone. The subsequent melting of this LILE-enriched hydrous peridotite gives rise to basaltic magmas displaying calc-alkaline chemical characteristics. Finally, these magmas undergo a modification during their ascent to the surface by crystal/liquid fractionation processes controlled by olivine separation. This hypothesis can explain the geochemical characters of most of the analyzed rocks, although the assumption of a LILE enrichment is not always necessary. If we accept the theoretical models calculated by NICHOLLS (1978) according to which the primitive calc-alkaline basalts in equilibrium with the mantle have a Ni abundance of about 220-200 ppm, we have indeed to admit that the most basic of the analyzed samples (Sn 72) has suffered a fractionation of about 20% olivine, assuming for this mineral a Ni solid/liquid partition coefficient of 10. Since olivine has very low $D_{s/l}$ for most of the LIL elements, its separation caused also an indirect enrichment in these elements whose abundances have been calculated to be about 20% lower in the parent magma than that of sample Sn 72. The LREE and other LIL element abundance of such parent magma can be modelled assuming an equilibrium partial melting of about 15% of a primordial mantle composition (WOOD, 1979). These figures are somewath lower but not much different from the 20% calculated by NICHOLLS (1978) for the high-Al basalts from Santorini on the basis of the major element chemistry. Instead, if we consider the other basalts and basaltic andesites from Santorini, Nisyros and Methana we find that, in order to model the incompatible element contents of their mantle-equilibrated parents, it is necessary to assume a variable, but much lower, degree of partial melting that, in some cases, reaches 3% if a primordial mantle composition is assumed as the source rock. Such figures are considered too low in the light experimental petrology data (GREEN, 1973).

Accordingly, on the basis of quantitative modelling it can be concluded that some

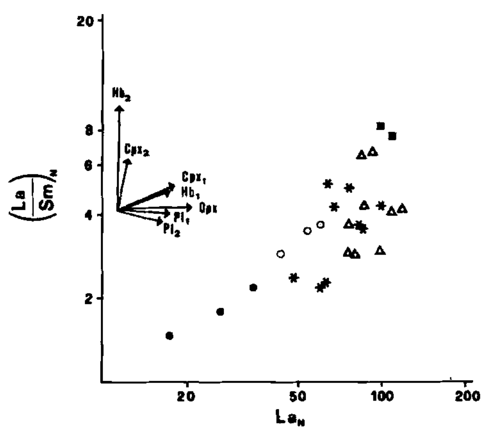


FIG. 6 - $[La/Sm]_N$ versus La_N relationship for the analyzed samples. The arrows indicate changes of the two parameters for the 20% separation of solid, except $horn_2$ (= 5% separation). The partition coefficients of minerals for basic (1) and acidic (2) liquids used for calculations are from NAGASAWA and SCHETZLER (1971), ARTH and HANSON (1975), and ARTH (1976).

degrees of LIL element enrichment of the source has to be assumed for most but not all the analyzed rocks. This, in turn, is considered as an evidence for a marked geochemical heterogeneity in the upper mantle under the Aegean arc.

The LILE enrichment of a mantle wedge overlying the Benioff zone can tentatively be attributed either to magmas generated by subducting slab melting (NICHOLLS, 1978) or to hydrous fluids derived by the slab dehydration or to addition of crustal materials (possibly represented by sediments dragged down by the subducting slab (ARMSTRONG, 1971) to the mantle. However, the involvement of crustal materials should determine higher Rb/Ba and Ba/La ratio with respect to those observed in our rocks (KAY, 1980). Also, the relatively low $^{87}Sr/^{86}Sr$ found in basic rocks from the Aegean Arc (Nisyros: $^{87}Sr/^{86}Sr$ = 0.7037, and Santorini: $^{87}Sr/^{86}Sr$ = 0.7054; PE and GLEDHILL, 1975) exclude a conspicuous participation of crustal material in the generation of geochemical anomalies in the Aegean mantle.

Also, the addition of magmas coming from the melting of the undergoing slab to the mantle (NICHOLLS, 1978) is not supported by our data. As a matter of fact, as discussed by APTED (1981), the liquids formed by the melting of a slab transformed into eclogite have strongly fractionated HREE with $[Tb/Yb]_N \gg 1$. The reaction of such liquids with peridotite increases sharply the $[Tb/Yb]_N$ of the source rock of the calc-alkaline liquids that should inherit this geochemical characteristic. Instead, $[Tb/Yb]_N$ values significantly higher than unity have not been found in all the analyzed basalts and basaltic andesites.

The trace element patterns normalized against a primordial mantle composition (Fig. 7) suggest that hydrous fluids could have been responsible for the hypothesized geochemical anomaly causing a preferential enrichment in the more mobile LIL elements with respect to HFS elements. In addition, the relatively low values of Ti, P and Ta with respect to geochemically similar elements (Fig. 7) may show that, during partial melting,

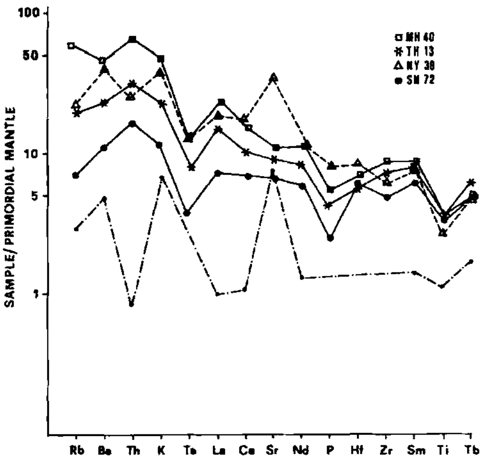


FIG. 7 - Trace element distribution normalized against a «primordial» mantle composition (WOOD, 1979) for some of the analyzed basalts and basaltic andesites. Dot-and-dash lines: pattern of island arc tholeiite from New Britain reported by PERFIT *et al.* (1980).

some accessory phases such as ilmenite, sphene and apatite have been left as residual phases. The presence of these minerals in the residuum might be favoured by high fO_2 and fH_2O connected with the presence of hydrous fluids coming from the subducting slab as proposed by SAUNDERS *et al.* (1980). The absence of a HREE fractionation in all the analyzed samples indicates that melting occurred at relatively low pressure, outside the stability field of garnet.

Finally, it has to be pointed out that the sample from Nisyros has an incompatible element distribution markedly different from those observed in the basic rocks of Santorini, Milos and Methana. It is possible, indeed, to observed (Fig. 7) a Th depletion with respect to Ba and K and Sr enrichment with respect to Ce and Nd. Such features, not observed in the other rocks, have been recognized in many island-arc basalts (PERFIT *et al.*, 1980) and have been interpreted as evidences for a mantle heterogenity under volcanic arcs.

The variable $^{87}Sr/^{86}Sr$ values found in the basic rocks from different volcanic centers (PE, 1975; PE and GLEDHILL,

1975) can be related to this supposed mantle heterogenity.

GEODYNAMIC IMPLICATIONS

Petrological and geochemical data on the calc-alkaline rocks from the Aegean arc suggest a genesis of the suite by crystal/liquid fractionation processes from basic parent magmas formed by the melting of an heterogeously LILE-enriched garnet-free peridotitic mantle. The distribution along the arc of the different lithological types of the suite is characterized by the presence of the basic terms mainly in the central-eastern arc, whereas these are scarce or lacking in the western sector. The Eu/Eu* ratio also displays lower values in the rocks from Milos, Nisyros and, partially, from Santorini than in the samples from Methana. This has been interpreted as an evidence for a more important role of a low-pressure plagioclase fractionation in the evolution of the central-eastern arc suites than in that of the rocks from Methana. This, in turn, could indicate that low-pressure fractionation processes were more effective in the central-eastern sector of the Aegean arc than in the western one. In addition to these geochemical and petrological variations, prominent volcanological differences do also exist. In fact, in the central-eastern arc large composite volcanoes occur. They are often associated with summit calderas connected with large explosive eruptions suggesting the presence of shallow level magma chambers. Instead, in the western sector the volcanic centers generally constist of dome swarms mainly made of intermediate to acidic lavas.

These volcanological, petrological and geochemical differences can be interpreted as related to differences in the tectonic regime prevailing in the various sectors of the arc. Geophysical and geological data (ANGELIER, 1979; LE PICHON and ANGELIER, 1979; MCKENZIE, 1978; MERCIER, 1976) suggest that the entire Aegean area has been affected by rather intense spreading movements with a consequent lithospheric thinning that has been particularly intensive in the eastern-central sector of the arc. The deformation patterns and fault plane solution are also consistent in showing a differential kynematic behaviour of the western arc with respect to the central-eastern sector which, according to DEWEY and SENGOR (1979) is characterized by a slow eastward motion relative to the Central Aegean and Peloponnesian blocks. This peculiar tectonic situation finds a physiographic expression in the wedge-shaped geometry of the arc-trench system where the convergence movement of the African block passes from the normal to the front-arc in the western sector, to the parallel to the arc one in the central-eastern side of the arc (LE PICHON and ANGELIER, 1979).

We suggest that the eruption of larger volumes of basic magmas in the central-eastern arc together with the differences in volcanic structure and evolutionary history of the magmas observed between eastern and western sector are directly related to the mentioned differences in the tectonic regime along the arc. The tensional tectonics affecting the eastern aegean area favoured the formation of large central volcanoes with shallow magma chambers, where a plagioclase-controlled fractionation played an important role in the evolution of the magmas. Instead, in the western sector of the Aegean Volcanic arc the tectonic regime was less markedly tensional. This prevented a rapid uprise of magma from the depth, so that smaller volumes of material were erupted and the fractionation started at higher pressure thus preventing an abundant plagioclase separation.

In conclusion, the main factor controlling the observed volcanological, petrological and geochemical differences is believed to be the different behaviour of magma during its ascent to the surface as a response to the variable tectonic regime along the arc. This, in its turn, is directly related to the complex interaction of lithospheric blocks occurring in this zone of convergence between the African plate and the south European border.

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REFERENCES

ANDRIESSIEN, P. A. M., BOELRIJK, N. A. I. M., HEBEDA, E. H., PRIEM, H. N. A., VERDURMEN, E. A. Th. and VERSCHURE, R. H., 1979, *Dating the Events of Metamorphism in the Alpine Orogen of Naxos (Cyclades, Greece).* Contrib. Mineral. Petrol., *69*, p. 215-225.

ANGELIER, J., 1979, *Recent Quaternary Tectonics in the Hellenic Arc: Examples of geological Observation on Lands.* Tectonophysics, *52*, p. 267-275.

———, CANTAGREL, J. M. and VILMINOT, J. C., 1977, *Neotectonique cassante et volcanisme plio-quaternaire dans l'arc égéen interne: l'île de Milos (Grèce).* Bull. Soc. Géol. France, *19*, p. 119-124.

APTED, M. J., 1981, *Rare Earth Element Systematics of Hydrous Liquids from Partial Melting of Basaltic Eclogite: a Re-evaluation.* Earth Planet. Sci Letters, *52*, p. 172-182.

ARMSTRONG, R. L., 1971, *Isotopic and Chemical Constraints on Models of Magma Genesis in Volcanic Arcs.* Earth Planet. Sci. Letters, *12*, p. 137-142.

ARTH, J. G., 1976, *Behaviour of Trace Elements during Magmatic Processes. - A Summary of Theoretical Models and Their Applications.* J. Res. U. S. geol. Surv., *4*, p. 47-67.

——— and HANSON, G. N., 1975, *Geochemistry and Origin of Early Precambrian Crust of Northeastern Minnesota.* Geochim. Cosmochim. Acta, *39*, p. 325-362.

BELLON, H., JARRIGE, J. J. and SOREL, D., 1979, *Les activités magmatique égéennes de l'Oligocene à nos jours et leur cadre géodinamiques. Données nouvelles et synthése.* Rev. Géol. Dynam. Géogr. Phys., *21*, p. 41-55.

BOCCALETTI, M., MANETTI, P. and PECCERILLO, A., 1974, *The Balkanides as an Instance of Back-arc Thrust Belt: Possible Relation with the Hellenids.* Geol. Soc. Am. Bull., *85*, p. 1077-1084.

BURRI, C. and SOPTRAJANOVA, G., 1967, *Petrochemie der jungen vulkanite der Inselgruppe von Milos (Griechenland) und deren stellung im Rahmen der Kykladenprovinz.* Vierteljahresschr. naturforsch. Ges. Zürich, *112*, p. 1-27.

COMNINAKIS, P. E. and PAPAZACHOS, B. C., 1980, *Space and Time Distribution of the Intermediate Focal Depth Easthquakes in the Hellenic Arc.* Tectonophysics, *70*, p. T35-T47.

DAVIS, E. N., 1967, *Zur geologie und petrologie der Inseln Nisyros und Jali (Dodecanes).* Praktica Acad. Athens, *42*, p. 235-252.

DEWEY, J. F. and SENGOR, A. M. C., 1979, *Aegean and Surrounding Regions: Complex Multiplate and Continuum Tectonics in a Convergent Zone.* Geol. Soc. Am. Bull., *90*, p. 84-92.

DI PAOLA, G. M., 1974, *Volcanology and Petrology of Nisyros island (Dodecanese, Greece).* Bull. Volcanol., *38*, p. 944-987.

DURR, St., ALTHERR, R., KELLER, J., OKRUSCH, M. and SEIDEL, E., 1978, *The Median Aegean Crystalline Belt: Stratigraphy, Structure, Metamorphism, Magmatism.* In: *Alps, Apennines, Hellenides* (eds. CLOSS, H., ROEDER, D. and SCHMIDT, K.), IUCG Sci. Rep. *38*, p. 455-477, Stuttgart.

EWART, A., 1979, *A Review of the Mineralogy and Chemistry of Tertiary-recent Dacitic, Latitic, Rhyolitic and Related Salic Volcanic Rocks.*, In: *Trondhjemites, dacites and related rocks* (ed. BAKER, F.), p. 14-121, Elseveir Sci. Publ. Comp., Amsterdam.

FERRARA, G., FYTIKAS, M., GIULIANI, O. and MARINELLI, G., 1980, *Age of the Formation of the Aegean Active Volcanic Arc.* In: *Thera and Aegean World* (ed. DOUMAS, C.), *II*, p. 37-42, London.

FRANZINI, M., LEONI, L. and SAITTA, M., 1972, *A Simple Method to Evaluate the Matrix Effects in X-ray Fluorescence Analysis.* X-Ray Spectrom., *1*, p. 151-154.

FYTIKAS, M., GIULIANI, O., INNOCENTI, F., MARINELLI, G. and MAZZUOLI, R., 1976, *Geochronological Data on Recent Magmatism of the Aegean Sea.* Tectonophysics, *31*, p. T29-T34.

GALE, N.H., 1981, *Mediterranean Obsidian Source Characterisation by Strontium Isotope Analysis.* Archaeometry, *23*, p. 41-51.

GEORGALAS, G. C., 1962, *Catalogue of the Active Volcanoes of the World. Part XII-Greece.* Intern. Ass'n Volcanology, Rome, 40 pp.

GREEN, D. H., 1973, *Experimental Melting Studies on a Model Upper Mantle Composition at High Pressure under Water-satured and Water-unsatured Conditions.* Earth Planet. Sci. Letters, *19*, p. 37-53.

GREEN, D. H., EDGAR, A. D., BEASLEY, P., KISS, E. and WARE, N. G., 1974, *Upper Mantle Source for Some Hawaiites, Mugearites and Benmoreites.* Contrib. Mineral. Petrol., *48*, p. 33-43.

INNOCENTI, F., MANETTI, P., PECCERILLO, A. and POLI, G., 1979, *Inner Arc Volcanism in NW Aegean Arc: Geochemical and Geochronological Data.* N. Jh. Miner. Mh., *4*, p. 145-158.

———, KOLIOS, N., MANETTI, P., RITA, F. and VILLARI, L. in prep., *Acid and Basic Late Neogene Volcanism in Central Aegean Sea: Its Nature and Geotectonic Significance.*

JAKES, P. and WHITE, J. R., 1972, *Major and Trace Element Abundances in Volcanic Rocks of Orogenic Areas.* Geol. Soc. Am. Bull., *83* p. 29-40.

KAY, R. W., 1980, *Volcanic Arc magmas: Implications of a Melting-Mixing Model for Element Recycling in the Crust-Upper Mantle System.* J. Geol., *88*, p. 497-522.

KELLER, J., (in press). *Mediterranean Island Arcs.* In: *Orogenic Andesites and Related Rocks* (ed. THORPE, R. S.), John Wiley and Sons, New York.

LEONI, L. and SAITTA, M., 1976, *X-ray Fluorescence Analysis of 29 Trace Elements in Rocks and Mineral Standards.* Rend. Soc. Ital. Min. Petrol., *32*, p. 497-510.

LE PICHON, X. and ANGELIER, J., 1979, *The Hellenic Arc and Trench System: a Key to the Neotectonic Evolution of Eastern Mediterranean Area.* Tectonophysics, *60*, p. 1-42.

MAKRIS, J., 1977, *Geophysical Investigations of the Hellenides.* Hamburger Geophysikalische Einzelschriften, *33*, pp. 128.

MCKENZIE, D., 1978, *Active Tectonics of Alpine-Himalayan Belt: the Aegean Sea and Surrounding Regions.* Geophys. J. R. astr. Soc., *55*, p. 217-254.

MERCIER, J. L., 1976, *La néotectonique, ses méthods et ses buts. Un exemple: l'arc égéen (Mediterranée Oriental).* Rev. Géograph. Phys. Géol. Dynam., *18*, p. 323-346.

NAGASAWA, H. and SCHNETZLER, C. C., 1971, *Partioning of Rare Earth, Alkalic and Alkaline Earth Elements between Phenocrysts and Acidic Igneous Magma.* Geochim. Cosmochim. Acta, *35*, p. 953-968.

NICHOLLS, I. A., 1971, *Petrology of Santorini Volcano-Cyclades, Greece.* Jour. Petrol., *12*, p. 67-119.

———, 1978, *Primary Basaltic Magmas for the Pre-caldera Volcanic Rocks of Santorini.* In: *Thera and Aegean World* (ed. DOUMAS, C.), *I*, p. 109-120, London.

NINKOVICH, D. and HAYS, J. D., 1972, *Mediterranean Island Arcs and Origin of High Potash Volcanoes.* Earth Planet Sci. Letters, *16*, p. 331-345.

PAPAZACHOS, B. C., 1973, *Distribution of Seismic Foci in the Mediterranean and Surrounding Area and Its Tectonic Implications.* Geophys. J. R. astr. Soc., *33*, p. 421-430.

PE, G. G., 1972, *Geochemistry and Chemical Mineralogy of the Lavas of Crommyonia.* Ann. Géol. des Pays Hell., *24*, p. 257-275.

———, 1973, *Petrology and Geochemistry of Volcanic Rocks of Aegina, Greece.* Bull. Volcanol., *37*, p. 491-514.

———, 1975, *Strontium Isotope Ratios in Volcanic Rocks from the Northwestern Part of the Hellenic Arc.* Chem. Geol., *15*, p. 53-60.

——— and GLEDHILL, A., 1975, *Strontium Isotope Ratios in Volcanic Rocks from the South-eastern Part of the Hellenic Arc.* Lithos, *8*, p. 209-214.

PECCERILLO, A. and TAYLOR, S. R., 1976, *Geochemistry of Eocene Calc-alkaline Volcanic Rocks from the Kastamonu Area, Northern Turkey.* Contrib. Mineral. Petrol., *58*, p. 63-81.

PERFIT, M. R., GUST, D. A., BENCE, A. E., ARCULUS, R. J. and TAYLOR, S. R., 1980, *Chemical Characteristics of Island-arc Basalts: Implications for Mantle Sources.* Chem. Geol., *30*, p. 227-256.

PICHLER, H. and KUSSMAUL, S., 1972, *Calc-alkaline Volcanic Rocks of the Santorini Group (Aegean Sea, Greece).* N. Jh. Miner. Abh., *116*, p. 268-307.

——— and ———, 1980, *Comments on the Geological Map of the Santorini Islands.* In: *Thera and Aegean World,* (ed. Doumas, C.), *II*, p. 413-427, London.

——— and STENGELIN, R., 1968, *Petrochemische und nomenclaturische revision der vulkanite des süd-agäischen raumes (Griechland).* Geol. Rund., *57*, p. 795-810.

POLI, G., MANETTI, P., PECCERILLO, A. and CECCHI, A., 1977, *Determinazione di alcuni elementi del gruppo delle terre rare in rocce silicatiche per attivazione neutronica.* Rend. Soc. Ital. Min. Petrol., *33*, p. 755-763.

PUCHELT, H., 1978, *Evolution of the Volcanic Rocks of Santorini.* In: *Thera and Aegean World,* (ed. DOUMAS, C.), *I*, p. 131-146, London.

——— and HOEFS, J., 1971, *Preliminary Geochemical and Strontium Isotope Investigations on Santorini Rocks.* In: *Acta Internat. Sci. Congr. on the Volcano of Thera, I,* p. 318-327.

———, MURAD, E. and HUBBERTEN, H. W., 1977, *Geochemical and Petrological Studies of Lavas, Pyroclastics and Associated Xenoliths from Christiana Islands, Aegean Sea.* N. Jb. Miner. Abh., *131*, p. 140-155.

ROGER, J. J. W. and NOVITSKY-EVANS, J. M., 1977, *The Clarno Formation of Central Oregon, USA. - Volcanism on a Thin Continental Margin.* Earth Planet. Sci. Letters, *34*, p. 56-66.

SAUNDERS, A. D., TARNEY, J. and WEAVER, S. D., 1980, *Transverse Geochemical Variations across the Antartic Peninsula: Implications for the Genesis of Calc-alkaline Magmas.* Earth Planet. Sci. Letters, *46*, p. 344-360.

TAYLOR, S. R., 1969, *Trace Element Chemistry of Andesites and Associated Calc-alkaline Rocks.* In: *Proceedings on the Andesite Conference*, (ed. MCBIRNEY, A. R.), Bull. State Oregon Dep. Geol. Miner. Ind., *65*, p. 43-63.

WOOD, D. A., 1979, *A Variably Veined Suboceanic Upper Mantle-Genetic Significance for Mid-ocean Ridge Basalts from Geochemical Evidence.* Geology, *7*, p. 499-503.

WHITFORD, D. J., NICHOLLS, I. A. and TAYLOR, S. R., 1979, *Spatial Variations in the Geochemistry of Quaternary Lavas across the Sunda Arc in Java and Bali.* Contrib. Mineral. Petrol., *70*, p. 341-356.

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