Δελτίο της Ελληνικής Γεωλογικής Εταιρίας τομ. XXXII/3, 251-258, 1998
Πρακτικά 8ου Διεθνούς Συνεδρίου, Πάτρα Μάιος 1998
Bulletin of the Geological Society of Greece vol. XXXII/3, 251-258, 1998
Proceedings of the 8th International Congress, Patras, May 1998

ELEMENTAL AND Sr-Nd ISOTOPIC EVIDENCE FOR THE ORIGIN AND GEODYNAMIC SIGNIFICANCE OF VOLCANIC ROCKS FROM OXYLITHOS (CENTRAL EUBOEA, GREECE)

M. BARBIERI[1], F. CASTORINA[1], U. MASI[1], P. TUCCI[1], E. AZZARO[3], K. KYRIAKOPOULOS[4], A. MAGGANAS[4], E. BALTATZIS[4] & A. COLLACETO[2]

ABSTRACT

Major- and trace-element contents of 32 samples of Upper Miocene volcanic rocks (mainly dacites, infrequent andesites and shoshonites s.l.) from Oxylithos, central Euboea, have been determined together with selected Sr-and Nd-isotope ratios. The Oxylithos volcanics, that are calc-alkaline of adakitic affinity, show similar elemental and Sr-Nd isotopic (0.70981-0.71012; 0.51223-0.51230 respectively) compositions that indicate both an origin from a common parental magma and magmatic differentiation without significant crustal contamination. The chemical and isotopic compositions suggest a three-component magma source represented by both depleted and enriched mantle and less than 7% of sediments. The enriched mantle was derived from a metasomatic event older than 1.0 Ga. Subduction took place less than 40 Ma.

KEY WORDS: Oxylithos, volcanic rocks, Sr-Nd isotopes, three-component mixing, mantle metasomatism.

1. INTRODUCTION

In the central Aegean vestiges of an Oligocene-Miocene volcanism, show products of calc-alkaline to shoshonitic affinity. The Oxylithos volcano in the central-eastern part of Euboea is probably the most prominent remnant of such volcanism in the area (Fig.1).

Although this volcano has been the subject of many studies (e.g. Fytikas et al., 1976, 1980; Pe-Piper and Piper, 1989, 1994; Pe-Piper, 1994), this paper presents a further contribution, focused on the Sr-Nd isotopic composition of the volcanic products, providing a deeper insight to the origin and geodynamic significance of Oxylithos volcanism in the Tertiary framework of the Aegean area.

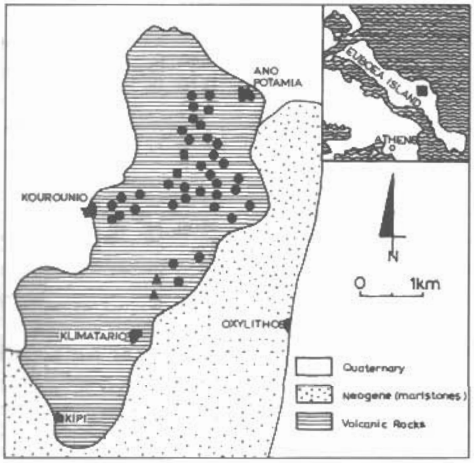


Fig. 1: Geological sketch map of the Oxylithos volcanic area, showing sample locations (andesite, dacite and shoshonite s.l. are represented by full triangle, circle and square, respectively). The inset map shows Oxylithos location in central Euboea.

1 Dipartimento di Scienze della Terra, Universita "La Sapienza", P.le A.Moro 5, I-00185 Roma, ITALY.
2 Via F. Stilicone, 264, I-00175 Roma, ITALY.
3 Istituto di Mineralogia, Petrografia e Geochimica, Via Archirafi 36, I-90123 Palermo, ITALY.
4 University of Athens, Department of Geology, Panepistimiopolis, Gr-157 84 Athens, GREECE.

Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.

2. GEOLOGICAL SETTING AND SAMPLING

The Oxylithos volcano, in the northern part of central Euboea (Fig. 1), is composed of trending NE-SW lava flows and domes. Its products overlie a sedimentary formation consisting mainly of limestones and limestone conglomerates of inferred lacustrine origin and ranging in age from the Aquitanian to the Pontian (Lemeille, 1977). The volcanic rocks show K/Ar radiometric ages of 13.2 ± 0.45 Ma, (Fytikas et al., 1976). According to Pe-Piper and Piper (1994) dacites of porphyritic and subordinately aphyric type occur mainly in the northern and central part of the volcanic complex, whereas andesites occur in the southern part.

The samples studied were collected mainly from the best exposures in the central-northern part of the volcano. The rocks display a porphyritic texture with zoned labradorite phenocrysts and minor ortho- and clino-pyroxene microphenocrysts; orthopyroxene is sometimes mantled by clinopyroxene; biotite is common, often totally altered to leucoxene and chlorite; hornblende is rare as well as quartz, and, finally, the groundmass is usually microgranophyric.

3. EXPERIMENTAL RESULTS

Geochemistry

Table 1 shows average major- and trace-element contents of the studied rocks, obtained by XRF analysis except for FeO (by titrimetric method) and LOI; Table 2 shows the Sr- and Nd-isotope ratios of selected samples. The experimental procedure of the isotopic analysis is given in Table-2 note.

TABLE 1. Average major (wt%) and trace (ppm) element contents of Oxylithos volcanic lithotypes (dacite A and B characterised by LOI < and > 2 wt%, respectively); standard deviation in brackets.

sample (*)	*Andesite* (2)		*Dacite A* (10)		*Dacite B* (18)		*Latite* (1)	*Shoshonite* (1)
SiO_2	60.79	(0.23)	64.86	(0.93)	63.28	(0.93)	55.79	53.09
TiO_2	0.44	(0.00)	0.44	(0.02)	0.44	(0.03)	0.58	1.07
Al_2O_3	14.47	(0.05)	15.16	(0.42)	15.11	(0.65)	19.79	16.17
Fe_2O_3	3.15	(0.48)	3.55	(0.31)	3.64	(0.32)	4.21	5.94
FeO	1.06	(0.36)	0.53	(0.21)	0.46	(0.19)	0.41	0.97
MnO	0.09	(0.01)	0.11	(0.02)	0.09	(0.02)	0.12	0.17
MgO	5.71	(0.01)	3.17	(0.32)	3.67	(0.62)	2.96	7.09
CaO	5.55	(0.23)	4.69	(0.45)	4.84	(0.32)	4.82	7.29
Na_2O	2.96	(0.08)	3.36	(0.10)	3.29	(0.08)	4.14	2.89
K_2O	2.12	(0.04)	2.39	(0.14)	2.29	(0.08)	3.88	3.43
P_2O_5	0.14	(0.01)	0.14	(0.02)	0.14	(0.01)	0.16	0.17
LOI	3.42	(0.05)	1.25	(0.23)	2.75	(0.19)	3.1	1.71
Total	**99.87**	**(0.03)**	**99.99**	**(0.08)**	**99.9**	**(0.06)**	**99.96**	**99.99**
Rb	63.5	(0.7)	73.4	(27.0)	65.7	(12.5)	115	105
Sr	876.5	(55.9)	718.1	(67.1)	705.0	(112.4)	100	272
Ba	950.0	(35.4)	924.7	(29.4)	913.8	(154.6)	473	472
La	30.5	(3.5)	28.2	(4.1)	31.2	(9.5)	29	30
Ce	40.0	(5.7)	43.8	(9.3)	45.8	(6.6)	58	53
Y	13.0	(2.8)	14.2	(2.0)	14.4	(3.3)	29	23
Zr	144.5	(2.1)	135.3	(14.0)	135.7	(18.7)	269	173
Nb	7.8	(0.5)	8.5	(0.6)	8.2	(0.6)	13.6	6.2
Ni	40.2	(1.6)	26.0	(1.0)	24.3	(0.9)	14	33.8
Cu	34.9	(0.5)	27.1	(1.0)	25.2	(0.8)	47.4	29.9
Zn	55.5	(0.2)	55.0	(0.4)	51.3	(0.9)	98.1	60.6
Cr	122.0	(15.6)	78.2	(22.0)	101.3	(33.5)	9	219
V	90.5	(17.7)	82.3	(15.4)	81.1	(18.3)	38	159

(*) number of analysed samples

Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.

TABLE 2. Sr- and Nd-isotope ratio of Oxylithos volcanic rocks.

sample	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr^{(a)}$	$^{87}Sr/^{86}Sr^{(b)}$	$^{143}Nd/^{144}Nd^{(c)}$
Andesite						
L-1	3	837	0.218	0.70952	0.70952	0.51223
L-2	64	916	0.200	0.70937	0.70950	0.51225
Dacite						
K-1	72	728	0.286	0.70955	0.70950	0.51228
K-23	70	743	0.273	0.70948	0.70944	0.51229
O-2	66	810	0.236	0.70935	0.70931	0.51227
Latite						
K-26	115	100	3.328	0.71012	0.70933	0.51224
Shoshonite						
0-14	105	272	1.117	0.70981	0.70948	0.51223

Samples were analysed with Finnigan MAT 262 RPQ mass spectrometer at Centro di Studio per il Quaternario e l'Evoluzione Ambientale, CNR, Rome. Sr and Nd were analysed after separation by matrix following standard procedures.

(a) Errors on $^{87}Sr/^{86}Sr$ ratio = 0.00001 as mean standard error; measured 87Sr/86Sr ratio normalised to $^{86}Sr/^{88}Sr$ = 0.1194. NBS 987 Sr Standard analysed during the course of this study yielded $^{87}Sr/^{86}Sr = 0.71026\pm1$ (2σ; n =6).

(b) Initial ratios calculated at 13 Ma.

(c) Errors on $^{143}Nd/^{144}Nd$ ratio = 0.00001 as mean standard error; measured $^{143}Nd/^{144}Nd$ ratio normalised to $^{144}Nd/^{146}Nd$ ratio =0.7219. La Jolla Nd Standard analysed during the course of this study yielded $^{143}Nd/^{144}Nd = 0.51186\pm1$ (2σ; n = 5).

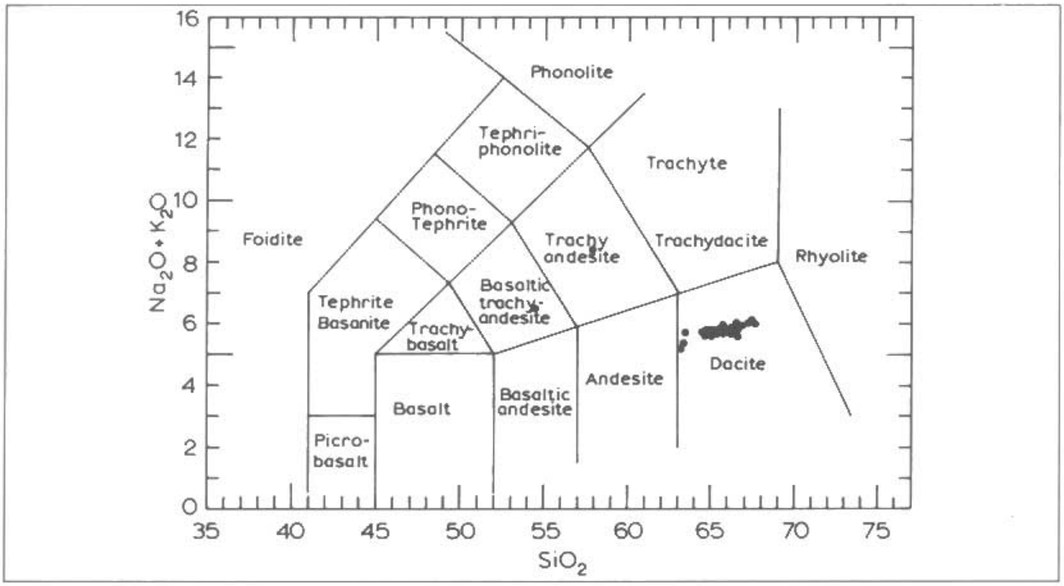


Fig. 2: Alkalies vs. SiO_2 classification diagram for Oxylithos volcanic rocks (after Le Bas et al., 1986).

Major- and trace-elements

10 samples show LOI contents less than 2 wt.%, whereas 22 samples show higher (however < 3.6 wt.%) contents. Comparison of the chemical compositions of the two groups of rocks shows no significant differences for major e[...] both groups are considered here as one.

Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.

The petrographic distinction of the samples into dacite and andesite is confirmed by the alkali-silica relationship (Fig. 2). Apart from SiO_2 and alkalies, the rocks generally show similar contents of the major elements. On the basis of the values (≤ 0.70) of the K_2O/Na_2O ratio all the samples are moderately potassic calc-alkaline except two, that are alkaline (shoshonitic): sample K-26 is a latite (K_2O/Na_2O = 0.94) and sample O-14 is a shoshonite s.s. (K_2O/Na_2O = 1.19).

A characteristic feature of all the rocks studied is their high MgO content, that is not explained by the presence of crystal cumulates, because there is no such microscopic evidence, as already noted by Pe-Piper and Piper (1994); thus, the high MgO contents appear to be an intrinsic characteristic of the parental magmas, which are of adakitic affinity (Defant and Drummond, 1990).

The compositions of the studied rocks are consistent with these results presented by Pe-Piper and Piper (1994). Moreover, the Oxylithos rocks are compositionally similar to analogous in age volcanic rocks from Skyros (Fytikas et al., 1980; Pe-Piper, 1991), though MgO and K_2O are higher and lower respectively, in the Oxylithos rocks.

Sr-Nd isotope ratios

The measured Sr-isotope ratios range narrowly from 0.70981 to 0.71012 and are not related to various lithotypes; the isotopic ratios corrected for age also vary narrowly, as expected because of both the young age and the moderate Rb/Sr ratios of the rocks.

The isotopic ratios are similar to the values measured by Pe-Piper and Piper (1994) in analogous lithotypes from both Oxylithos and Skyros.

As well as the Sr-isotope ratios, the Nd-isotope ratios range narrowly from 0.51223 to 0.51230, being irrespective of the various lithotypes.

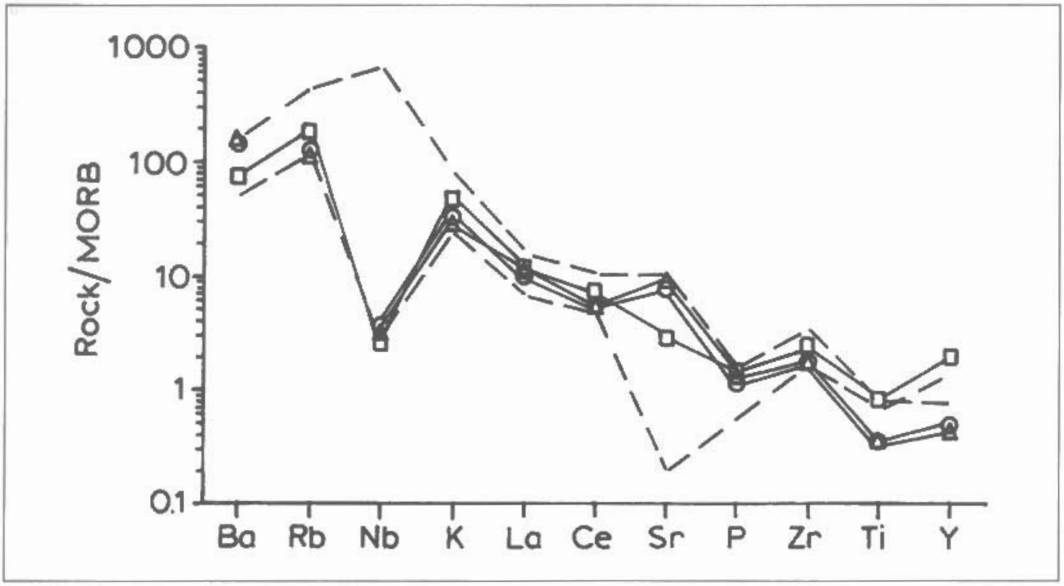
4. DISCUSSION

The broadly similar chemical and isotopic compositions suggest an origin of Oxylithos rocks from a common parental magma and rule out that crustal assimilation controlled magmatic evolution from andesite to shoshonite. Moreover, the calc-alkaline signature along with other chemical characteristics such as high Zr/Y ratios, high LIL/HFSE ratios and negative Nb, Ti and P anomalies (Fig 3) indicate an affinity of the Oxylithos rocks to volcanic rocks of active continental margins (Atherton et al., 1984). However, their adakitic affinity distinguishes Oxylithos rocks from common arc products and sets some constraints on both the characteristics of the magma source(s) and the age of the subduction. In fact, as other adakites (e.g. Kay, 1978; Yogodzinski et al., 1995 ; Stern and Kilian, 1996;), Oxylithos rocks are not derived from parental basaltic magmas, whose lack or outcrop exposure is thus explained. With respect to the timing of subduction, since adakites are genetically related to subduction of young (< 25 Ma) oceanic crust (Defant and Drummon; 1990), then, at Oxylithos subduction took place later than 40 Ma and most likely during collision between the African and Eurasian plates, which occurred in the Early Tertiary (e.g. Innocenti et al., 1981).

However, if the Oxylithos magmas can be considered as mantle liquids derived by mantle and slab melt interaction, similar to other adakitic rocks (e.g., Stern and Kilian, 1996), such a process does not explain their high Sr and low Nd isotopic values. In this respect, the high Sr and low Nd isotopic ratios might indicate some crustal contribution to the adakitic parental magmas (Fig.4a). Crustal contamination may also be suggested by the presence of small gneiss xenoliths found in the Oxylithos rocks. Calculations show that AFC processes require the involvement of more than 30 wt.% of S-type crust (Stern and Kilian, 1996) to explain the isotopic values of those rocks, and that is unrealistic. Moreover, AFC processes would likely have removed most Mg, Cr, Sr, V and associated elements from the magmas, and that is not apparent from the chemical composition of the rocks. The Sr-isotope compositions of Oxylithos rocks also rule out mere assimilation of Aquitanian limestone, which represents the basement rock-type of the volcanic edifice, because this rock has a Sr isotopic ratio lower than Oxylithos volcanic rocks (Hodell et al., 1991).

Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.

Fig. 3: Spiderdiagram of incompa-tible elements for Oxylithos volcanic rocks normalised to N-MORB (Sun and McDonough, 1989); andesite, dacite and shoshonite are represented by open triangle, circle and square, respectively. The field between the dashed lines represents mixtures of metasedimentary materials and granitoids (Mason et al., 1996).



Therefore, the high Sr and low Nd isotopic compositions must be an intrisic characteristic of the magma source(s).

According to Pe-Piper (1994), the Pb isotopic compositions of Oxylithos volcanic rocks suggest magma derivation from mantle source(s) enriched because of an old (> 1.0 Ga) metasomatic event. Nd - model ages, varying between 900 and 1100 Ma, support such a conclusion, that is also suggested by the negative correlation between Sr/La and Sr-isotope ratios and trend towards the EM II component (Zindler and Hart, 1986) (Fig 4a); Moreover, the Sr-Nd isotope ratios of Oxylithos rocks are similar to those of K-rich volcanic rocks from the eastern Aegean (e.g. Robert et al., 1993), and Roman province (e.g. Roger et al., 1985), as well as from other subduction-related areas (e.g. White and Dupre, 1986; Wheller et al., 1987), where the role played by an old metasomatic mantle component in the petrogenesis has been inferred.

As a whole, the significant correlation between the Sr-Nd isotope ratios and trace-element contents indicates to the existence of a three-component magma source, represented by the depleted ($^{87}Sr/^{86}Sr$ = 0.7032; $^{143}Nd/^{144}Nd$ = 0.5131) and metasomatic mantle ($^{87}Sr/^{86}Sr$ = 0.7048 - O.7085; $^{143}Nd/^{144}Nd$ = 0.51237 - 0.5123), and sediments. Graphical modelling of the three-component mixing process is shown in Fig. 4b. As a potential sedimentary source in the calculations a mixture of old metasedimentary materials and granitoids ($^{87}Sr/^{86}Sr$ = 0.7234; $^{143}Nd/^{144}Nd$ = 0.51212; Mason et al., 1996) was chosen on the base of each trace element similarity to Oxylithos rocks (Fig.3), instead of the local crust under Euboea, whose characteristics are not well known. Mixing calculations show that adding to the magma source(s) up to 7% of such sediments yields the Sr-Nd isotope ratios of Oxylithos rocks. The relatively large amount of sediments involved, however falling within the range inferred for subduction processes (Ellam and Hawkesworth, 1988), is realistic. This is also constrained by the high Ba/La ratios of the studied rocks, which suggest elevated fluxes of fluids from the subducted slab carrying sediments. On the contrary, AFC processes acting on the magma produced from the enriched mantle might explain the chemical and isotopic characteristics of all the rocks except the shoshonites, which, however are geochemically and isotopically indistinguishable from other Oxylithos rocks (Fig.3).

Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.

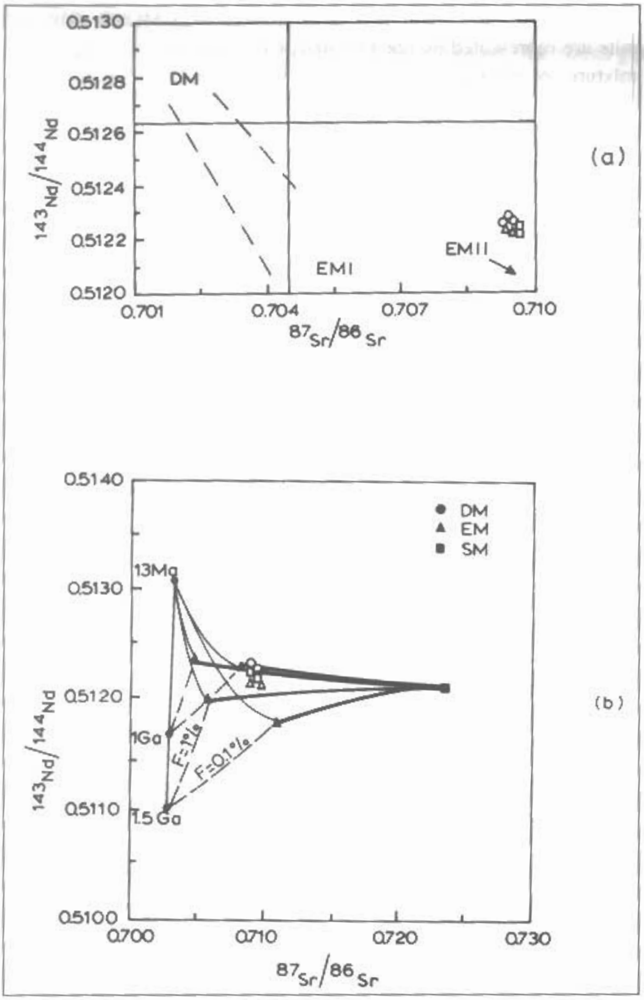


Fig. 4:
Sr-Nd isotope plot of the Oxylithos volc rocks.

(a) Initial $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{14}$ diagram showing composi-tional range the studied rocks at 13 Ma. The between the dashed lines represents MO and OIB fields, DM corresponds to depl mantle, while EMI and EMII indicated locations of enriched mantle (Zindler Hart, 1986); symbols as in figure 2.

(b) Schematic modelling showing possible isotopic derivation of Oxyli magmas. Filled circles represent the isot compositions of the depleted mantle (I at 13 Ma, 1.0 and 1.5 Ga, respectively. F triangles represent the isotopic com tions of enriched mantle (EM) compor produced by 0.1 - 1.0% melting of a dep mantle source. Curves connecting DM and sediments show the evolution of m processes at 13 Ma; Oxylithos sar symbols as in Fig. 2.

Parameters used in the modellization:

- DM: $^{87}Sr/^{86}Sr$ = O.7032, Rb/Sr = 0. $^{143}Nd/^{144}Nd$ = 0.51311, Sm/Nd = 0.293;
- Sediments: $^{87}Sr/^{86}Sr$ = O.7234, Sr = 7 $^{143}Nd/^{144}Nd$ = 0.51212, Nd = 24 ppm.
- Bulk distribution coefficients: Rb = 0 Sr = 0.075, Sm = 0.0487, Nd = 0.0223;

Data source of isotopicand ele composition of DM and distri coefficients from McKenzie and O' (1991, 1995); Mason et al., (1996).

Finally, the high Sr-isotope ratios of the Oxylithos volcanic rocks are not unique among volcanic rocks of the Aegean area, since they are imilar to these magnesian andesites of Skyros (Pe-Piper and Piper, 1994) and they are also analogous to the ra younger (3.4-0.5 Ma), more mafic and shoshonitic volcanic rocks from the Volos-Atalanti area (PE Innocenti et al., 1979). As a whole, a volcanic province exists extending from Euboea, to Skyros to Thessaly (ESET), whose activity developed from Middle Miocene to Pleistocene and was character the emplacement of rocks of high MgO and high Sr-isotope ratios; volcanic activity migrated throu from the east to the northwest becoming progressively more shoshonitic and basic. All volcani from this province seem to have been derived from a mantle wedge characterised by the presence o metasomatic component.

5. CONCLUSIONS

The Upper Miocene volcanic rocks of Oxylithos range from andesite through dacite to shosh dacite is the most common lithotype. Geochemically, the rocks show broad homogeneity of chem isotopic compositions. They are characterised by high MgO, Cr, V contents and high Sr init (0.70981- O.71012) and low Nd (0.51223 to 0.51230) isotopic ratios that indicate derivation common parental magma of adakitic affinity and subsequent magmatic differentiation with significant of crus gmatophile-element

Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.

similar to arc magmas. The adakitic affinity sets the timing of the subduction less than 40 Ma during collision between the Eurasian and African plates and attributes the origin of Oxylithos rocks to the interaction between mantle-melts and mantle-wedge melts. However, the adakitic affinity does not explain the high Sr and low Nd isotopic ratios of these rocks. The Sr-Nd isotopic ratios cannot also be explained by AFC processes because they would require an unrealistic (> 30%) amount of upper crustal material to be involved. The Sr and Nd isotopic compositions can be explained by the contribution from an enriched mantle. To summarise, the Sr-Nd isotopic and other elemental signatures indicate that Oxylithos magmas were derived from a composite source involving both depleted and enriched mantle and less than 7% of sediments, in a subduction-related environment. The Nd-model ages support the hypothesis that the enriched mantle was derived by a metasomatic event older than 1.0 Ga, as suggested by the Pb-isotope composition of the studied rocks by Pe-Piper (1994).

Finally, the Oxylithos volcanic rocks share with similar coeval rocks from Skyros and younger, more mafic and K-rich rocks from eastern Thessaly many elemental and isotopic characteristics, thus identifying a volcanic province (ESET) in central Aegean of converging magmatism underlain by a segment of old metasomatic enriched mantle.

AKNOWLEDGEMENTS

The field work has been carried out with the financial support provided by the agreement between the University of Rome "La Sapienza" and the National University of Athens. Isotopic analyses have been carried out by means of the facilities of CNR, Centro di Studio per il Quaternario e l'Evoluzione Ambientale. Moreover, thanks are due to two anonymous referees for constructive criticism of the manuscript.

REFERENCES

ATHERTON M.P., MCCOURT W.J., SANDERSON L.M. AND TAYLOR W.P. (1979). The geochemical character of the segmented Peruvian coastal batholith and associated volcanics. In : Atherton M.P. and Tarney J.(eds.): origin of granitic batholiths: geochemical evidence, Shiva Publishing Orpington, Kent, 45-64.

DEFANT M.J. AND DRUMMOND M.S. (1990). Derivation of some modern arc magmas by melting of young subducted lithosphere. *Nature* 347, 662-665.

ELLAM R.M. AND HAWKESWORTH C.J. (1988). Elemental and isotopic variations in subduction related basalts: evidence for a three component model. *Contrib. Mineral. Petrol.* 98, 72-80.

FYTIKAS M., GIULIANI O., INNOCENTI F., MARINELLI G. AND MAZZUOLI R. (1976). Geochronological data on recent magmatism of the Aegean sea. *Tectonophysics* 31, 29-34.

FYTIKAS M., GIULIANI O., INNOCENTI F., MANETTI P., MAZZUOLI R. , PECCERILLO A. AND VILLARI L. (1980). Neogene volcanism of the northern and central Aegean regions. *Ann. Geol. Pays Hell.* 30, 106-129.

HODELL D.A., MUELLER P.A. AND GARRIDO J.R. (1991). Variations in the strontium isotopic composition of seawater during the Neogene. *Geol.* 19,24-27.

KEY R.W. (1978) Aleutian magnesium andesites: melts from subducted Pacific oceanic crust. *J. Volcanol. Geothermal Res.* 1, 117-132.

INNOCENTI F., MANETTI P., MAZZUOLI R. , PASQUARI G. AND VILLARI L. (1981). Neogene and Quaternary volcanism in the eastern Mediterranean. Time-space distribution and geotectonic implication. In: Sedimentary basins of Mediterranean margins, Wezel F.C. (ed.), Tecnoprint Bologna, 369-385.

LE BAS M.J., LE MAITRE R.W., STRECKEISEN A. AND ZANETTIN B. (1986). A chemical classification of volcanic rocks on the Total Alkali-Silica diagram. *J. Petrol.* 27, 745-750.

LEMEILLE F. (1977). Etudes néotectoniques en Grece centrale nord orientale (Eubée centrale, Attique, Béotie, Locride) et dans les Sporades du Nord (île de Skyros). These 3ème Cycle. Univ. Paris XI, 173 pp.

Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.

MASON P.R.D., DOWNES H., THIRLWALL M.F., SEGHEDI I., SZAKACS A., LOWRY D. AND MATTEY D. (1996). Crustal assimilation as a major petrogenetic process in the East Carpathian Neogene and Quaternary continental margin arc, Romania. *J. Petrol.* 37, 927-959.

MCKENZIE D. AND O'NIONS R.K. (1991). Partial melt distributions from inversion of rare earth element concentrations. *J. Petrol.*32, 5, 1901-1991.

MCKENZIE D. AND O'NIONS R.K. (1995).The source regions of ocean island basalts. *J. Petrol.* 36, 1, 133-159.

PE G. (1975). Strontium isotope ratios in volcanic rocks from the northwestern part of the Hellenic arc. *Chem. Geol.* 15, 53-60.

PE-PIPER G. (1991). Magnesian andesites from the island of Skyros, Greece: geochemistry and regional significance. *Geol. Mag.* 128, 585-593.

PE-PIPER G. (1994). Lead isotopic compositions of Neogene volcanic rocks from the Aegean extensional area. *Chem. Geol.* 118, 27-41.

PE-PIPER G. AND PIPER D.J.W. (1989). Miocene magnesian andesites and dacites, Evia, Greece: adakites associated with subducting slab detachment extension. *Lithos*, 125-140.

PE-PIPER G. AND PIPER D.J.W. (1994). Miocene magnesian andesites and dacites, Evia, Greece: adakites associated with subducting slab detachment extension. *Lithos*, 125-140.

PE-PIPER G., PIPER D.J.W., KOTOPOULI C.N. AND PANAGOS A.G. (1994). Neogene volcanoes of Chios, Grece: the relative importance of subduction and back-arc extension. In :J.L. Smellie (Editor), Volcanism associated with extension at Consuming Plate margins. J. Geol. Soc. London Spec. Publ.

ROBERT V., FODEN J. AND VARNE R. (1993). The Dodecanese province: a model for tectonic control on potassic magmatism. *Lithos* 28, 241-260.

ROGER N.W., HAWKESWORTH C.J., PARKER R.J. AND MARSH J.S. (1985). The geochemistry of potassic lavas from Vulsini, central Italy and implications for mantle enrichment processes beneath the Roman region. *Contrib. Mineral. Petrol.* 90, 244-257.

STERN C.R. AND KILIAN R. (1996). Role of the subducted slab, mantle wedge and continental crust in the generation of adakites from the Andean Austal Volcanic Zone. *Contrib. Mineral. Petrol.* 123, 263-281.

SUN S.S. (1980). Lead isotopic study of young volcanic rocks from mid-ocean ridges, ocean islands and island arcs. *Philosophical transactions of the Royal Society of London*, Series A 297, 409-445.

SUN S.S. AND MCDONOUGH W.F. (1989). Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In : A.D. Saunders and M.J. Norry (Eds): Magmatism in the ocean basins. J. Geol. Soc. London Spec. Publ. 42, 313-345.

TAYLOR S.R. AND McLENNAN S.M. (1985). The Continental Crust: its composition and evolution. Blackwell Sci.Pub. Oxford, 312p.

WHELLER C.E., VARNE R., FODEN J.D. AND ABBOTT M.J. (1987). Geochemistry of Quaternary volcanism in the Sunda-Banda arc, Indonesia, and three component genesis of island arc basaltic magmas. *J.Volcan.Geotherm.Res.*32, 137-160.

WHITE W.M. AND DUPRE B. (1986). Sediment subduction and magma genesis in the Lesser Antilles: isotopic and trace element constraints. *J.Geophys.Res.*91,5927-5941.

WHITFORD D.J., WHITE W.M. AND JEZEK P.A. (1981) Neodymium isotopic composition of Quaternary arc lavas from Indonesia. *Geochim. Cosmoch. Acta* 45, 989-995.

YOGODZINSKI G.M., KAY R.W., VOLYNETS O.N., LOLOSKOV A.V. AND KAY S.M.(1995). Magnesian andesite in the western Aleutian Komandorsky region: implications for slab melting and processes in the mantle wedge. *Geol. Soc. Am. Bull.* 107, 505-519.

ZINDLER A. AND HART S.R.,(1986). Chemical geodynamics. *Annu.Rev.Earth Planet. Sci. Lett.* 14, 493-571.

Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.