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MINERALOGY-GEOCHEMISTRY-GENESIS AND METALLOGENETIC SIGNIFICANCE OF LAMPROPHYRES FROM THE STRATONI-OLYMPIAS AREA KERDILIA FORMATION, EASTERN CHALKIDIKI

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ABSTRACT

Thin grayish green, dark green to grayish black dykes occur in the Paleozoic or older Kerdilia Formation of the Servo-Macedonian Massif and cross-cut the metamorphics and the 30 Ma Stratoni granodiorite. On the basis of texture, mineralogy, mineral chemistry and geochemistry they are classified as lamprophyres (minettes). REE, HYG element normalized patterns and LFS/HFS ratios indicate a most likely derivation from mantle-crust magma interaction. Moreover, an indirect participation of these lamprophyres in the eastern Chalkidiki sulfide mineralization process is indicated, whereas a primary one deserves further investigation.

ΣΥΝΟΨΗ

Λεπτές φλέβες γκρίζου-πράσινου, σκούρου πράσινου έως και γκριζόμαυρου χρώματος απαντούν στον Παλαιοζωικής ή παλαιότερης ηλικίας Σχηματισμό των Κερδυλίων της Σερβο-Μακεδονικής Μάζας και διατέμνουν τα μεταμορφωμένα πετρώματα της περιοχής καθώς και τον ηλικίας 30 εκ. έτη γρανοδιορίτη του Στρατωνίου. Με βάση τον ιστό, την ορυκτολογία,ορυκτοχημεία και γεωχημεία τους ταξινομούνται ως λαμπροφύρες (μινέττες). Σπάνιες γαίες, υγρομαγματόφιλα στοιχεία καθώς και οι λόγοι των LFS/HFS στοιχείων υποδηλώνουν μια πιθανή προέλευση των λαμπροφυρών από μάγμα μανδύα-φλοιού. Πρόσθετα φαίνεται ότι οι λαμπροφύρες έχουν έμμεσα συμμετάσχει στη μεταλλογενετική πορεία δημιουργίας των θειούχων κοιτασμάτων της Ανατολικής Χαλκιδικής, ενώ μια πρωτογενής σχέση χρήζει πρόσθετης έρευνας.

INTRODUCTION

In Stratoni (Madem Laccos and Vagionia) and Olympias areas, located in the Paleozoic or older, Kerdilia Formation of the Servo-Macedonian Massif (Kockel et al., 1977), occur thin dykes ranging in colour from grayish green, dark green

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to grayish black. These rocks were initially classified as andesites or dacites (Neubauer, 1957) and later as lamprophyres (Nicolaou, 1960). The dykes cross-cut biotite/hornblende gneisses, amphibolites and marbles whereas in the Stratoni area have been observed to cross-cut the 29.6 Ma (Papadakis, 1971) Stratoni granodiorite and in places the ore along NE-SW trending faults (Nicolaou, 1960). In addition, Nebel (1989) has described hypabysall andesite and rhyodacite dykes from the Madem Laccos mine also controlled by NE-SW trending faults.

Streckeisen (1979) divided lamprophyres into alkaline (camptonites, monchiquites) melilitic (alnoites, polzenites) and calc-alkaline groups. The latter are widely distributed in both space and time from Archean to Pliocene (Sims and Mudrey, 1972; Desio, 1977; Rock, 1984) occurring over island arcs, active or newly stabilized orogens and the peripheries of orogens (Rock, 1984) and they are generally associated with gold mineralization (Rock et al., 1987).

The present paper is a contribution to the study of the eastern Chalkidiki lamprophyres utilizing mineralogical, major, trace and rare-earth element (REE) data in order to elucidate genetic and metallogenetic aspects of these rocks. All the samples studied are from drill holes.

CLASSIFICATION

On the basis of form (dykes), texture (panidiomorphic, porphyritic), mineralogy (phlogopite dominant), mineral chemistries and chemistry of the studied rocks they can be classified as calc-alkaline lamprophyres (Fig. 1) and particularly as minettes rather than kersantites (see subsequent sections), whereas those described by Nicolaou (1960) could be classifed on the basis of their mineral paragenesis as vogesites or spessartites.

MINERALOGY - MINERAL CHEMISTRY

The lamprophyres of this study are holocrystalline panidiomorphic and porphyritic with phenocrysts set in a finer-grained groundmass (Fig. 3). Phenocryst mineralogy consists of phlogopite, biotite, apatite, K-feldspar, Fe-Ti oxides and quartz. Similar mineralogy appears also in the groundmass. Nicolaou (1960) in his study of the lamprophyres describes predominance of plagioclase, hornblende with minor biotite, quartz, apatite and iron oxides. The presence of plagioclase in only one of our samples is inferred by its pseudomorphous alteration to carbonate and sericite. Variable degrees of hydrothermal alteration result in the formation of carbonate, sericite, rutile, sphene, pyrite and quartz. Moreover, dolomite and quartz have also been detected as filling cavities. Selected minerals amenable to reliable microprobe analyses from the primary and the secondary mineral assemblages were analysed in the Jeol superprobe 733 of I.G.M.E. (G.

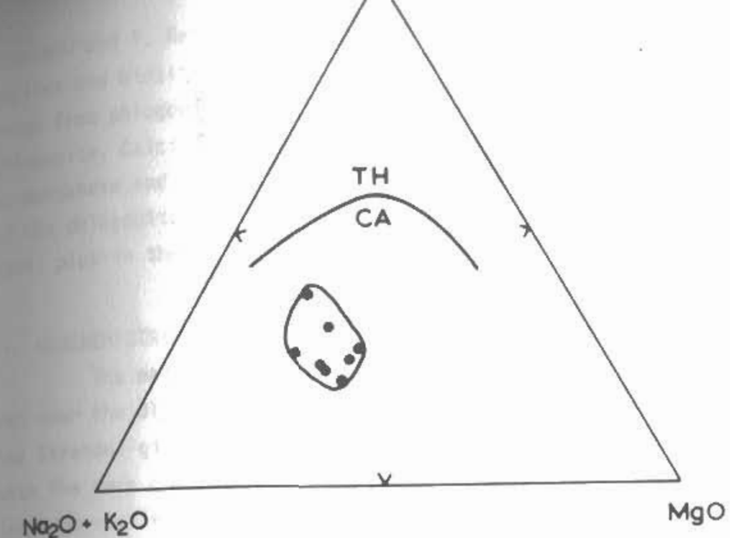

Fig. 1. AFM ternary plot with tholeite (TH)-calcalkaline (CA) fields (Irvine and Baragar, 1971) : Note the calc-alkaline nature of the eastern Chalkidiki lamprophyres.
Εικ. 1. Τριαδικό διάγραμμα AFM ενδεικτικό θολεϊτικών (TH) και ασβεσταλκαλικών (CA) πεδίων (Irvine and Baragar, 1971) : Σημειώνεται ο ασβεσταλκαλικός χαρακτήρας των λαμπροφυρών της ανατολικής Χαλκιδικής.

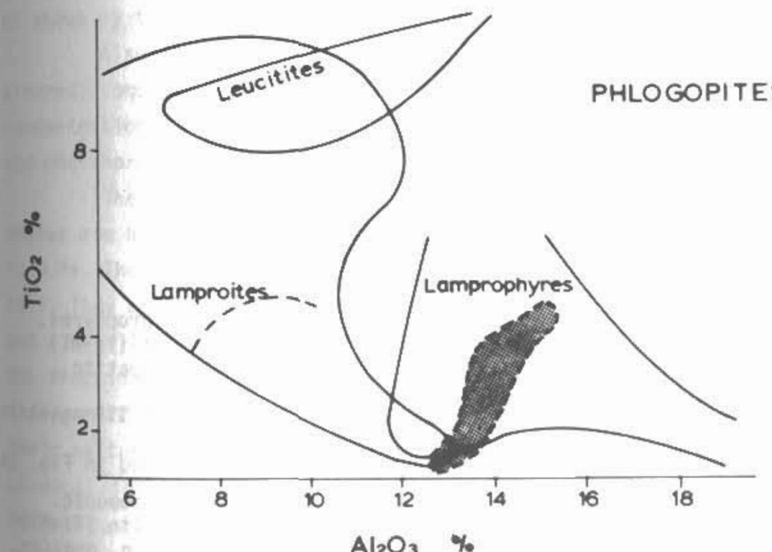

Fig. 2. TiO_2-Al_2O_3 plot for the phlogopites. Note that they plot in the field of lamprophyres. (Rock, 1984).
Εικ. 2. Διάγραμμα TiO_2-Al_2O_3 για τους φλογοπίτες. Σημειώνεται ότι προβάλλονται στο πεδίο των λαμπροφυρών (Rock, 1984).

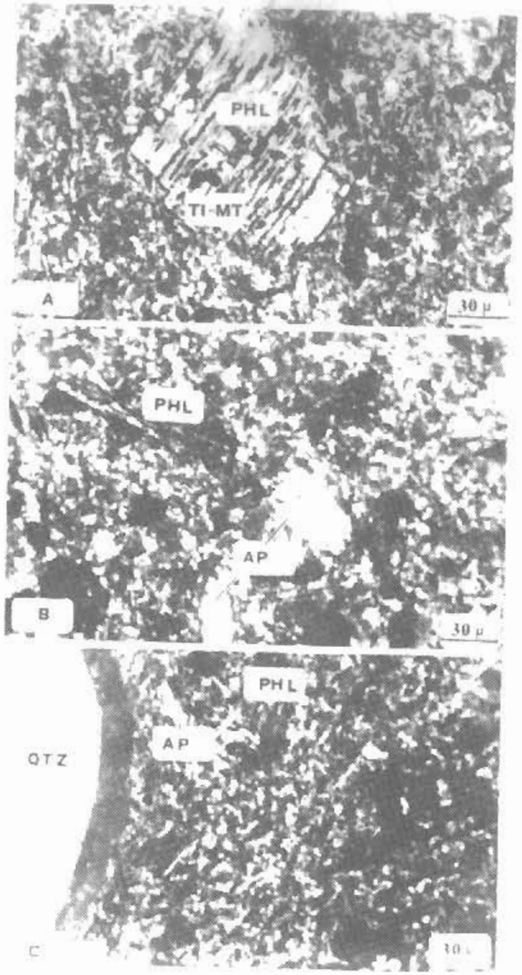

Fig. 3. Microphotographs of porphyritic texture in the studied lamprophyres.
A. Phlogopite (PHL) phenocryst with Ti-magnetite inclusions (Ti-MT) set in a groundmass of K-feldspar, phlogopite/biotite, apatite, Ti-magnetite and quartz.
B. Apatite (AP) phenocrysts with phlogopite laths (PHL) and Ti-magnetite grains set in a groundmass as the one in Fig. 2A.
C. Quartz orbicules (QTZ) set in an overall texture described in Fig. 2A.

Εικ. 3. Μικροφωτογραφίες πορφυριτικού ιστού στους μελετηθέντες λαμπροφύρες.
A. Φαινοκρύσταλλος φλογοπίτη (PHL) με εγκλείσματα Ti-μαγνητίτη (TI-MT) σε κύρια μάζα αποτελούμενη από Κ-άστριο, φλογοπίτη/βιοτίτη, απατίτη, Ti-μαγνητίτη και χαλαζία.
B. Φαινοκρύσταλλοι απατίτη (AP), δοκίδων φλογοπίτη (PHL) και κρυστάλλων Ti-μαγνητίτη σε κύρια μάζα όπως περιγράφεται στην Εικ. 2A.
C. Φαινοκρύσταλλοι σφαιροειδούς χαλαζία (QTZ) μέσα σε γενικότερο ιστό που περιγράφεται στην Εικ. 2A.

Economou and Y. Katsikis, analysts) and the results are given in Table 1. Phlogopites and biotites exhibit chemical zonation from center to rim. The former range from phlogopite to biotite to phlogopite and the latter from biotite to phlogopite. Calcite and dolomite show increased contents in ore elements such as manganese and iron when appropriate (Table 1). In addition the composition of the phlogopites projected on the TiO_2-Al_2O_3 classification diagram (Rock, 1984) plot in the field of lamprophyres (Fig. 2).

GEOCHEMISTRY - GENETIC ASPECTS

The major and trace element data of seven lamprophyres from drill cores near the Olympias mine and the major element data of two lamprophyres from the Stratoni given in Nicolaou (1960) are all summarized in Table 2 together with the mean composition in major and certain trace elements of calc-alkaline lamprophyres (Rock, 1984) for comparative purposes. Analyses were performed by a combination of XRF, ICP and INAA at Arsenal Geotechnical Institute, Vienna by Dr. D. Foliadis and Utrecht University by Dr. J. Baker.

On the basis of the K, Ba, Rb, Cr and Ni concentrations the studied rocks can be classified as semilamprophyres to lamprophyres (Wimmenauer, 1973) and further on the QAPF diagram of Strekeisen (1979) as minettes-kersantites (Fig. 4). The major element analyses reveal the distinctly potassic nature of these lamprophyres - thus, classifing them as minettes rather than kersantites - as shown by the high and variable K_2O/Na_2O ratios which range from ~1 to 7.4.

Also it has to be noted that the eastern Chalkidiki lamprophyres (non-altered) compared to the average calc-alkaline lamprophyres (Table 2) show higher concentrations in silica and potassium and lower in iron, magnesium, titanium and phosphorous.

The chondrite normalized REE patterns of the eastern Chalkidiki lamprophyres are highly fractionated. La values range from 140 to 176x and Lu from 7.6 to 9.9x. The chondritic abundances and the $(La/Lu)_N$ ratios range from 17.2 to 19.1. They also show small negative Eu anomaly suggesting that plagioclase was not a significant phase either in the residual solids (partial melt case) or in the fractionated cummulates (Fig. 5). The eastern Chalkidiki lamprophyres bear similar REE pattern to that of the calc-alkaline minettes and lower ΣREE, while, their pattern is identical to that of the Stratoni granodiorite despite major chemical differences, thus suggesting a common origin and processes of formation. Moreover, it should be noted the higher silica and potassium and the lower iron, magnesium, titanium and phosphorous concentrations of the eastern Chalkidiki lamphrophyres compared to the calc-alkaline lamprophyres of Rock (1984) (Table 2). The differences may have a bearing on the rare-earth element concentrations

Table 1. Chemistry of the minerals phlogopite, biotite, calcite and dolomite of lamprophyres from the Kerdilia Formation, Eastern Chalkidiki.

Πίν. 1. Χημική σύσταση των ορυκτών φλογοπίτη, βιοτίτη, ασβεστίτη και δολομίτη λαμπροφυρών, από τον Σχηματισμό Κερδυλίων, Ανατολική Χαλκιδική.

	Phlogopite n=36			Biotite n=16			Calcite n=5			Dolomite (Cavity filling) n=2	Highly Altered Lamprophyre Dolomite n=3
	x	σ	Range	x	σ	Range	x	σ	Range	x	x
SiO2	38.8	1.1	36.3-40.5	37.0	0.5	36.2-37.7	0.46	0.24	0.31-0.86		0.72
Al2O3	13.7	0.6	12.9-15.0	14.1	0.4	13.3-14.6					
FeO	9.1	3.5	3.5-13.8	16.4	2.0	14.2-19.9	0.15	0.26	0.0 -0.61	3.47	1.69
MgO	20.1	2.9	16.2-24.2	14.2	1.4	11.5-15.9	0.21	0.16	0.0 -0.44	19.64	12.60
CaO	0.04	0.06	0.0- 0.17	0.05	0.09	0.0- 0.31	51.39	0.80	50.35-52.13	30.30	33.20
Na2O	0.9	0.24	0.3- 1.4	0.9	0.23	0.4- 1.3					
K2O	9.2	0.4	8.7-10.1	9.2	0.3	8.8- 9.8					
TiO2	2.8	1.1	1.3- 4.5	3.8	0.2	3.6- 4.5					
MnO	0.14	0.07	0.0- 0.3	0.22	0.09	0.09-0.4					
							0.33	0.47	0.0 -1.13	0.60	3.80
Total	94.8	5.2	92- 97.2	95.9	1.1	93.6-97.2	52.54	1.93		54.01	52.01
Si	5.664	0.117	5.435-5.806	5.552	0.036	5.503-5.649					
Al(iv)	2.336	0.118	2.190-2.560	2.448	0.037	2.398-2.570					
X	8.000			8.000							
Al(vi)	0.031	0.027	0.0 -0.104	0.056	0.028	0.018-0.110					
Fe	1.491	2.383	0.434-1.733	2.056	0.271	1.733-2.500					
Mg	4.353	0.598	3.584-5.310	3.176	0.292	1.903-3.483					
Ti	0.310	0.121	0.144-0.492	0.413	0.022	0.400-0.495					
Mn	0.018	0.008	0.0---0.037	0.028	0.011	0.011-0.048					
Y	6.203			5.747							
Ca	0.006	0.009	0.0--0.028	0.088	0.015	0.0 -0.051					
Na	2.254	0.069	0.085-0.389	0.257	0.065	0.110-0.377					
K	1.724	0.068	1.634-1.899	1.766	0.072	1.641-1.858					
Z	1.984			2.031							
Mg/(Mg+Fe)	0.794	0.087	0.676-0.924	0.607	0.053	0.507-0.664					

Table 2. Chemical analyses of major and trace elements of lamprophyres from the Kerdilia Formation, Eastern Chalkidiki.

Πίν. 2. Χημισμός κυρίων στοιχείων και ιχνοστοιχείων λαμπροφυρών από το Σχηματισμό Κερδυλίων, Ανατολική Χαλκιδική.

Wt%	G118-500	G118-570	G209-406A	G109-338	G118-603	G209-406B	Vagionia	GAl. 173	G109-565.	X1	S1	X2	S2	
SiO2	54.76	53.59	52.39	53.31	50.88	54.91	59.94	60.52	39.74	55.04	3.45	51.54	3.29	
TiO2	0.83	0.85	0.73	0.66	0.65	0.71	0.48	0.45	0.74	0.67	0.15	1.31	0.59	
Al2O3	13.64	14.32	14.76	12.26	12.11	12.91	15.01	14.25	20.85	13.66	1.12	14.29	5.23	
Fe2O3	3.78	4.24	4.08	4.01	4.27	3.93	5.75	6.03	1.75	4.51	0.87	8.43	5.54	
MnO	0.13	0.12	0.12	0.08	0.11	0.09	0.14	0.11	1.46	0.11	0.02	0.14	0.11	
MgO	5.41	3.05	4.08	3.97	4.33	4.08	3.95	2.52	2.52	3.92	0.86	6.69	2.57	
CaO	6.85	8.54	7.19	6.29	7.01	5.82	3.45	5.85	9.97	6.37	1.47	6.44	2.11	
K2O	5.44	5.28	5.65	4.35	4.81	5.21	3.74	2.81	8.13	4.66	0.98	3.88	1.99	
Na2O	2.53	2.08	1.73	1.12	0.65	0.71	3.04	3.26	0.41	2.06	0.89	2.68	0.97	
P2O5	0.38	0.41	0.36	0.42	0.41	0.42	0.36	0.52	0.48	0.41	0.05	0.72	0.57	
LOI	5.98	6.71	8.19	10.66	12 18	8.23	4.32	3 81	13.36	7.51	2.92	4.13	2.36	
TOTAL	99.73	99.19	99.28	97.13	97.41	97 02	100.18	100.13	99.41	98.92		100.25		
PPM		n = 3 - 6										A	B	C
Sc	11.00	11.00	12.00			13.00				11.75	0.96	17+-3		
V	75.00	96.00	73.00	95.11	94.36	101.53			73.00	89.17	12.03	210+-60	145+-60	
Cr	129.00	140.00	145.00	98.21	145.16	97.82			101 00	125.87	22.36	495+-177		60
Co	16.00	19.00	19 00	28.71	19.21	45.80			19.00	24.62	11.21	42+-13		
Ni	52.00	58.00	52.00	63.97	55 43	68.26			46.00	58.28	6.62	307+-17	254+-132	60
Cu	26.00	29.00	27.00	19.65	17.09	23.99			28.00	23 79	4.57	63+-6	20--329	
Zn	51.00	42.00	52.00	54.07	56.24	52.19			101.00	51.25	4.90	103+-6		
Pb	33.00	45.00	33.00						66 00	37.00	6.93		53--598	
As				3.00	7.91	2.40				4 44	3.02		32--2508	
Rb	118.00	115.00	108.00	186.00	218.00	185.00			155.00	155.00	46.92	187+-21		200
Sr	235.00	382.00	193.00	220.00	390.00	420.00			106.00	306.67	101.03	1160+-42	17--75	1300
Y	24.00	25.00	22.00	21.35	21 10	22.83			19 00	22.72	1.54		127--1645	
Zr	251.00	319.00	209.00	360.00	390.00	420.00			278.00	324.83	81.78	16+-6	509--5146	
Nb	28.00	31.00	25.00						10.00	28.00	3.00	383+-55		
Ba	1216.00	1194.00	1078.00	1000.00	840.00	2000.00			297.00	1221.30	405.50	2700+-116		1500
W	5.00	5.40	‹ 2	119.00	64.80	162.00			149.00	71.24	69.43			
Sb				5.80	19.30	‹ 0.70				12.55	9.55			
Be	4.50	4.30	4.70	3.90	4.60	4.70			1.70	4.45	0.31			
Th	26.00	10.00	25.00	20.00	20.00	21.50			14.00	20.42	5.70	51+-20	5--66	
U	10.00	12.00	11.00	9.80	10.40	9.30			6.00	10.42	0.96		12+-3	
Li	34.00	25.00	38.00	25.80	21.00	22.80			7.00	27.77	6.72			
Au				‹ 0.02	‹ 0.02	‹ 0.05								
Cs	8.60	7.10		11.50	11.20	14.60				10.60	2.89			
Ga	9.00	10.00	11.00	‹ 30.00	‹ 19.00	‹ 30.00				10.00	1.00	20+-0	20+-3	
La	55.81	58.10		46.30	47.20	49.40			5.00	51.36	5.29			
Ce	100.00	121.00		103.00	103.00	108.00			31.00	107.00	8.34			
Nd	‹ 40.40	‹ 65.70		‹ 70.00	‹ 70.00	‹ 70.00								
Sm	9.16	9.47		7.40	7.70	8.10				8.37	0.91			
Eu	2.00	1.80		1.49	1.55	1.58				1.69	0.21			
Tb	0.62	0.56		0.63	0.57	0.63				0.60	0.03			
Yb	2.07	1.98		1.60	1.43	1.49				1.71	0.29			
Lu	0.34	0.31		0.26	0.26	0.28				0.29	0.03			
Hf	7.87	14.00		11.50	11.80	12.30				11.49	2.24			
Ta	1.40	1.35		1.13	1.04	1.43				1.27	0.17			

X1, S1 = Mean, SD of all values of drill cores except the highly altered lamprophyre (G109-565.5)
X2, S2 = Mean (n=574), SD of calc-alkaline lamprophyres from Rock (1984)

A, B, C [illegible] USA, Devon U.K. and Kos Greece respectively (Rock, 1984)
[illegible] to varing number of analyses, concentrations, means, SDs or ranges are given

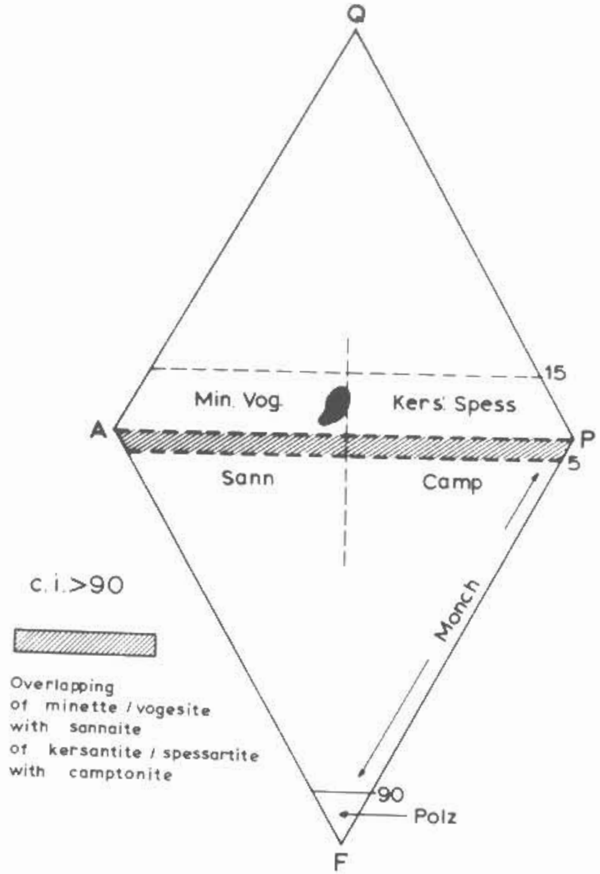

Fig. 4. QAPF plot for the classification of lamprophyres (Streckeisen, 1979). Note that the eastern Chalkidiki lamprophyres plot in the field for minettes-kersantites.

Εικ. 4. Διάγραμμα QAPF ταξινόμησης των λαμπροφυρών (Streckeisen, 1979). Σημειώνεται ότι οι λαμπροφύρες της ανατολικής Χαλκιδικής προβάλλονται στο πεδίο των μινεττών-κερσαντιτών.

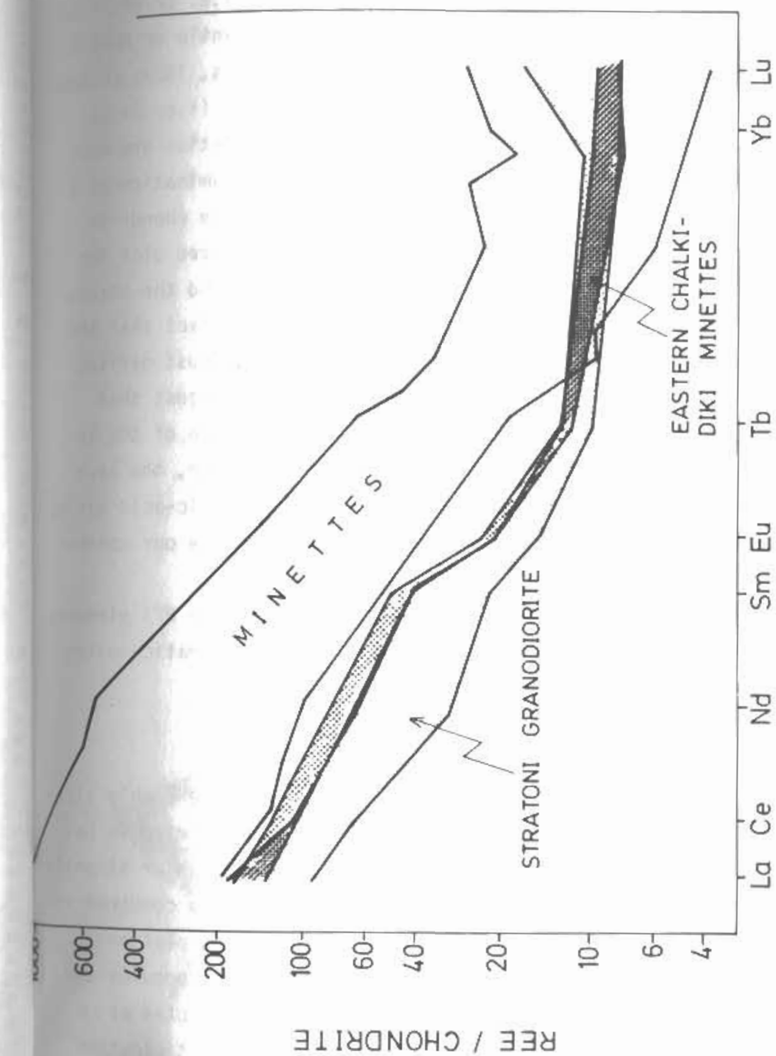

Fig. 5. Chondrite normalized rare-earth element patterns for the eastern Chalkidiki lamprophyres, together with those for calc-alkaline minettes (Rock, 1984) and the Stratoni granodiorite (unpubl. data). Data for chondrites are from Frey et al. (1968).

Εικ. 5. Διαγράμματα σπανίων γαιών σε σχέση με τους χονδρίτες για τους λαμπροφύρες της ανατολικής Χαλκιδικής, ασβεσταλκαλικούς μινέττες (Rock, 1984) και το γρανοδιορίτη του Στρατωνίου (αδημ. στοιχεία). Οι χονδρίτες είναι από Frey et al. (1968).

and all in turn on the particulars of the genesis of these rocks.

The genesis of the calc-alkaline lamprophyres associated with granites is assigned either to exclusively mantle materials and processes (Bachinski and Scott, 1979; 1980; Jahn et al., 1979) or to mantle-crust interaction (Rock, 1980; 1984). The participation of mantle to the genesis of the studied lamprophyres is indicated by the ratios of certain incompatible trace elements (i.e. Zr/Hf, Y/Tb) and the mg ≠ values which are comparable to those of primitive mantle or MORB'S (Jagoutz et al., 1979; Paritsis, 1985; Kalogeropoulos and Paritsis, 1989; Le Roex et al., 1983). Concurrently, a series of other HFS element ratios (i.e. Zr/Ce, Ce/Ta etc.) are distinctly different and the LFS to HFS element ratios are much higher. These contrasting features can be assigned to either contamination of a mafic magma by an aqueous fluid or to mantle-crust interaction. The chondrite normalized REE patterns (Fig. 5) and the primordial mantle normalized plot for the HYG elements (Fig. 6) of the eastern Chalkidiki lamprophyres and the Stratoni granodiorite point to a common origin. This, combined with the fact that the latter is postulated to represent a hybrid product of mantle and crust derived components (Kallogeropoulos et al., 1988; Gerouki et al., 1989) suggest that mantle-crust magma interaction is a likely process for the formation of the lamprophyres with the former being the predominant component. However, the lack to date of radiogenic isotope data and chemistries of potential mafic-acid mixing end members do not allow us to completely and quantitatively justify our contention.

Moreover the La/Ta (~40) ratios, the decoupling of LFS from HFS elements and the Ta-Nb trough (Fig. 6) are all indicative of arc-related magmatic suites (Wood et al., 1980; 1981; Saunders et al., 1980; 1981).

RELATION TO METALLOGENY

A point of significance that stems from Table 2 is that the highly altered lamprophyre sample is enriched in K, Ca, Al, Mn, Pb, Zn and depleted in Na, Mg, La, Ce, Ba, Li, U, Sr, Nb, Y, Ni and Cr relative to the unaltered or slightly altered samples. Concomitantly, the marbles hosting the sulfide ores compared to barren marbles are systematically enriched in elements which show depletion in the hydrothermally altered lamprophyre (e.g. Ce, Ba, U etc., Kalogeropoulos et al., 1989). These data suggest that the lamprophyres have variably acted as a source for these elements, which in turn supports their indirect participation in the ore-forming process.

Moreover, the lead isotopes of the ores ($^{206}Pb/^{204}Pb = 18.781 \pm 0.016$; $^{207}Pb/^{204}Pb = 15.661 \pm 0.013$; $^{208}Pb/^{204}Pb = 38.855 \pm 0.042$; Kalogeropoulos et al. 1989) are similar with those of the lamprophyres ($^{206}Pb/^{204}Pb = 18.770 \pm 0.015$;

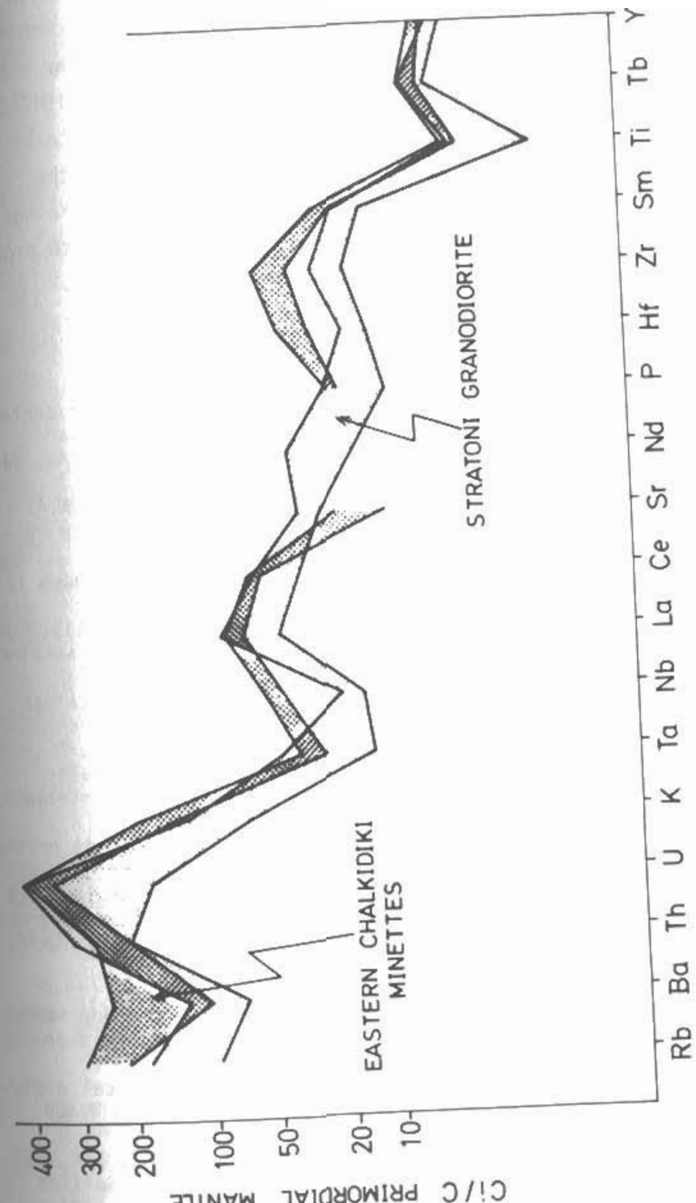

Fig. 6. Primordial mantle normalized HYG element patterns for the eastern Chalkidiki lamprophyres and the Stratoni granodiorite (unpubl. data). Data for primordial mantle are from Wood et al. (1979) and Jagoutz et al. (1979).

Εικ. 6. Διαγράμματα των υγρομαγματόφιλων στοιχείων σε σχέση με primordial μανδύα για τους λαμπροφύρες της ανατολικής Χαλκιδικής και τον γρανοδιορίτη του Στρατωνίου. Στοιχεία για τον primordial μανδύα είναι από τους Wood et al. (1979) και Jagoutz et al. (1979).

$^{207}Pb/^{204}Pb$ = 15.674 ± 0.015; $^{208}Pb/^{204}Pb$ = 38.916 ± 0.020; R. Frei, pers. comm., 1989) regardless of alteration degree of the latter. This evidence suggests that the lead in the lamprophyres and the ore largely originate from a common source. As the lead isotopes show a crustal affinity this source for the lamprophyres should be sought in its crustal contaminant. The data referred to above combined with the potassic/hydrous-rich nature of the lamprophyres which is similar with that of the ore-forming hydrothermal fluids, the fact that Rock et al. (1987) indicate a close genetic association of the ternary system lamprophyres/calc-alkaline granitoids/gold mineralizations and the gold-bearing nature of the eastern Chalkidiki base metal sulfide ores (Nicolaou and Kokonis, 1980; Kalogeropoulos, et al., 1989) suggest that a further study is needed in order to prove if a primary participation of the lamprophyres in the ore genesis exists.

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