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GEOCHEMICAL CHARACTERISTICS OF THE AMPHIBOLITES (OPHIOLITIC METABASITES) FROM THE SERIFOS METAMORPHIC CORE COMPLEX, ATTIC-CYCLADIC METAMORPHIC BELT, CYCLADES, GREECE

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Abstract: Half of the surface outcrop of the Serifos island (NW Cyclades, Attic-Cycladic Metamorphic Belt) is composed of a volcano-sedimentary sequence regionally metamorphosed to greenschists facies. This unit consists of, mainly carbonate-rich metasediments, alternating with silicate-rich layers with chlorite and mica-rich layers and enclose a wide variety of metabasites: amphibolite blocks and mafic schists (with minor relict blueschists facies assemblages, now retrogressed to greenschists). The origin of the amphibolites (ophiolitic metabasites) within the Attic-Cycladic Metamorphic Complex (ACMC) remains enigmatic due to the disrupted occurrence of these rocks that makes difficult to constrain the structural relationship of these rocks with their host rocks and their tectonic significance. This study documents preliminary geochemical data (major-and trace elements) of the amphibolites interlayered within the Serifos Greenschist Unit. A comparative geochemical study of these rocks with other meta-ophiolite rocks from similar structural occurrences in other Cycladic islands, is attempted. On the basis of petrographic and major - trace element bulk chemical data, these rocks can be distinguished in different rock types (basalts/andesites and minor gabbros) with different chemical affinities: a) The relatively LILE-enriched amphibolites resemble typical low- to medium – K calc-alkaline basalts (CAB), comparable to the recent Aegean back-arc volcanics. b) Other amphibolites display chemical affinitities similar to island arc tholeiites (IAT). c) The retrogressesd blueschist – to –greenschists facies metabasites are coarse-grained gabbroic rocks with mixed IAT/MORB chemical affinities. Further geochemical work need to be carried out in order to improve our knowledge on the tectonic setting and emplacement of the Serifos amphibolites.

Keywords: Attic-Cycladic Metamorphic Complex, amphibolites, Serifos, geochemical characteristics

1. Introduction and Setting

Scattered occurrences of ophiolitic rocks are widespread in the upper structural units of Cyclades islands (central Aegean, Greece) and are important for understanding the later Mesozoic ocean spreading and collisional history of the region, which has been obscured by Cenozoic accretionary stacking, metamorphism, plutonism and extension (Pe-Piper and Photiades, 2006). Much work has been done to determine the nature of the protoliths for these rocks on specific islands e.g. Syros (Tinsley and Cheney, 2008, Putlitz et al., 2000, Seck et al., 1996), Sifnos (Schliestedt and Matthews 1987) and Tinos (Katzir et al., 1996). On the island of Serifos earlier workers (e.g. Marinos, 1951; Salemink, 1985) suggested that the higher-grade metamorphic rocks at the intrusive contact, massive skarn and ore deposit formation are related to contact metamorphism.

The ACMC is essentially a pile of accreted tectonic units consisting of predominantly Mesozoic sedimentary and volcanic rocks metamorphosed at various conditions (Feenstra, 1996). The complex consists of two main units (Fig. 1). The upper unit contains various intercalated fragments of ophiolites, sedimentary rocks of Permian age and high-temperature metamorphic rocks. The lower unit is polymetamorphic and consists of a series of thrust sheets containing pre-Alpine basement, Mesozoic marble, metavolcanics and metapelites (Durr et al., 1978, Andriessen et al., 1987, Schliestedt et al., 1987).

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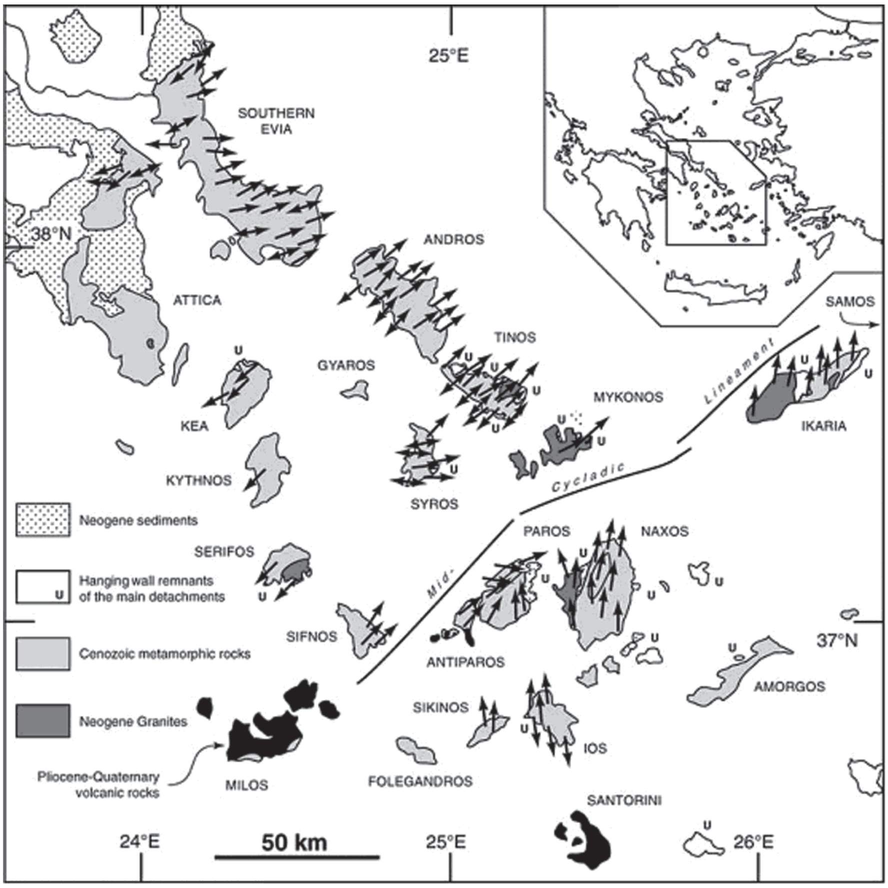

Fig. 1. Simplified geological map of the Cyclades archipelago, after Tirel et . al (2009). Arrows indicate the kinematics of extensional shearing during greenschist facies and locally higher temperature metamorphism, subsequent cooling to the conditions of brittle deformation, and within syn-kinematic intrusions.

The island of Serifos is located in the Western Cyclades within the Attic-Cycladic Metamorphic Complex (ACMC) (Fig. 1). It represents the westward continuation of an arcuate belt of Metamorphic Core Complexes. Within this belt the I-type granitic activity shows overlapping zircon U-Pb igneous crystallisation ages at ~11.5 Ma on both Naxos and Serifos whereas the S-type granitic activity on Serifos appears to be Upper Eocene in age (zircon U-Pb igneous crystallization, Iglseder et al., 2009) with Middle Miocene cooling ages derived from the micas, according to Iglseder et al., 2009 and Grasemann et al., 2006 and Brichau, 2004.

Regarding available age information on the metabasic rocks within the Lower Unit of the Cyclades, recent geochronological work by Bröcker and Pidgeon (2007) on the protolith ages for the main volcanosedimentary succession and for the melange blocks on other Cycladic islands (e.g Sifnos, to the south) indicated a Triassic age for the magmatic precursors of the metatuffaceus and metavolcanic rocks.

On the island of Serifos three tectonic-metamorphic units are distinguished (Fig. 2): The lower unit is made mostly of gneisses with intercalations of quartzite layers and minor marble lenses (Fig. 2). Marbles tectonically overlie the gneisses. Transition zones occur at the lower contact with the gneisses as well as at the upper contact with the greenschists. The upper structural unit is dominated by greenschists. This unit consists of a volcanosedimentary sequence, mainly of carbonate-rich metasediments which enclose a wide variety metabasites: orthoamphibolites (metavolcanics), mafic schists and metagabbros (with minor relict blueschists assemblages, now retrogresed to greenschists) (Fig. 3). Metabasic rocks constitute about one third or more of the the surface outcrop of the Serifos accretionary units. In the northern part of the island the calc-schists form alternating bands of carbonate-rich and silicate-rich layers with chlorite

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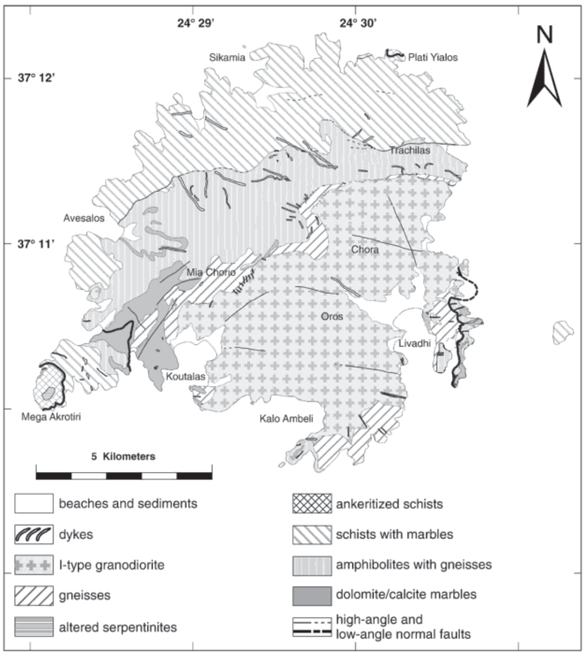

Fig. 2. Geological map of Serifos (modified after Iglseder et al., 2009).

and mica-rich layers. Ophiolitic melange blocks are widespread in the uppermost structural levels of the Serifos structural pile consisting of carbonate-rich schists, dolomites, amphibolites and serpentinite blocks (SE- and SW-end of the island) (Fig. 3).

This study focus on the scattered metabasite (blocks or dykes) outcrops within the volcanosedimentary sequence (Greenschist-facies unit) in the northern part of the island and not those within the ophiolite melange outcrops at the uppermost structural levels.

2. Materials and Methods

Ten (10) samples selected for analysis (Tab.1). They were jaw crushed and ground to a fine flour in an agate mortar prior to analysis by XRF techniques. Major elements were determined on fused discs using Rh anode excitation, and the trace elements Sc, V, Cr, Ni, Zn, Ga, Rb, Sr, Y, Zr, Nb, La, Ce, Nd and Ba on pressed powder briquettes using either Rh or W excitation on the Phillips PW1600 X-ray fluorescence spectrometer at Leicester University (for techniques see Marsh et al. 1983).

3. Results

3.1. Major- and trace-element geochemical data

Preliminary geochemical evaluation on Serifos matabasites shows that there is a variety of compositions. Because these rocks are metamorphosed /altered and could have been affected by major fluid-induced chemical interchange with the associated metasediments, only the immobile major and trace elements, Ti, Zr, Nb, Y and V were utilised in discrimination diagrams. Any spread of mobile major elements such as Na, K and Mg, Ca and trace elements, such as Ba, Rb, and Sr could be attributed to metasomatic exchange of these elements within the oceanic crust due to seafloor hydrothermal alteration, or metamorphism (Seyfried & Mottl, 1982; Floyd & Tarney, 1979).

In the AFM diagram (Fig. 4) the majority of Serifos metabasites follow the tholeiitic trend: a) high content of Al_2O_3 (> 15.5, up to 20%) and b) display a trend towards higher Fe/Mg ratios. Yet few samples display a scatter. These samples are metasomatised greenschists which have biotite-rich

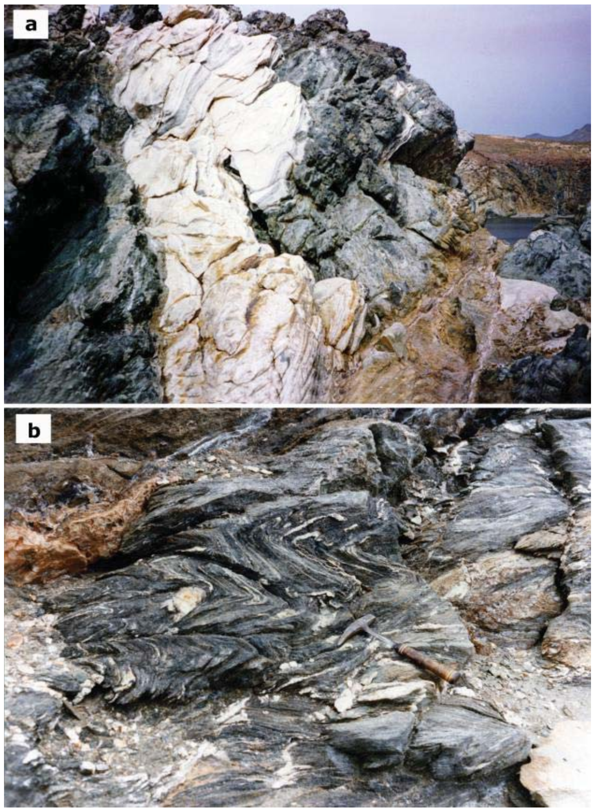

Fig. 3. Field photographs. (a) Marble lense intercalated within amphibolites, from tectonic mélange formation in SE Serifos (Loc. Tsilipaki).Note that marble exhibit high ductility, as depicted from the tight isoclinal fold in the central part, (b) Calcareous schists from the Greenschist unit (Sykamia, N. Serifos). Note the competency contrast between calcite and quartz veins: ptygmatic ductile folding of calcite, chevron folding of quartz veins.

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Table 1. Sample description.

Region	*Sample No.*	*Locality*	*Tectonic Unit*	*Rock type*	*Classification*
Serifos isl.	SER-76	Troulos	Greenschist-facies Unit	Fine-grained meta-volcanic	IAT/MOR Basalt
	SER-94	Tsilipaki, SE peninsula	Greenschist-facies Unit	Greenschist	IAT/MORB
	SER-K2	Kentarchos	Greenschist-facies Unit	amphibolite	IAT
	SER-101	Trachilas	Greenschist-facies Unit	amphibolite	CAB
	SER-99	Galani	Greenschist-facies Unit	Low-grade greensch-ist	
	SER93-20	Playia	Greenschist-facies Unit	Amphibolite (fine grained basalt)	CAB
	SER93-21	Troulos	Greenschist-facies Unit (contact zone)	amphibolite	CAB
	SER93-39	Sykamia	Greenschist-facies Unit	Retrogressed Blue-schist (gabbroic)	IAT/MORB
	SER94-10	Tsilipaki	Greenschist-facies Unit	amphibolite	CAB
	SER92-27b	Tsilipaki	Tectonic melange	Retrogressed Blue-schist	IAT/MORB

(#Ser93-21) and epidote-rich (Ser93-39) compositions respectively. Figure 5 shows MgO vs TiO_2 variation and classifies the amphibolites into compositional fields of ophiolite complexes of known tectonic environment. Serifos metabasites are subdivided into two groups of low MgO (< 4 %) and high MgO (> 7%) content. Some of the high MgO amphibolites (e.g. Ser-K2, Ser-101, Ser-76, Ser-99) resemble that of gabbroic rocks from Northern Aegean (e.g. Lesvos, Gartzos et al., 2009) and ophiolite complexes in the Alps and Appenine and into the field of foliated gabbros from the Mid-Atlantic ridge fracture zone (Bonatti et al., 1975).

In the binary Ti/1000 vs V diagram of Shervais (1982) the majority of the samples plot in the Ocean floor Basalt field and in particular the field

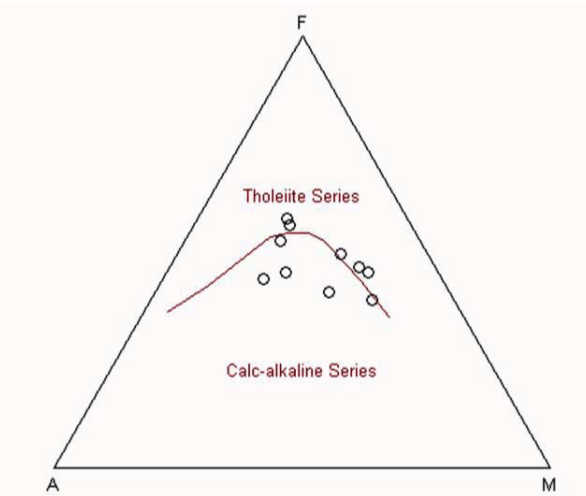

Fig. 4. AFM (Na_2O+K_2O – Fe_2O_3t – MgO) plot of Serifos metabasites which exhibit trend of tholeiitic series.

of MORB (N- and E-type) (Fig. 6). Only one sample has a Ti/V ratio of less than 20 and falls in the field of Island Arc Tholeiites.

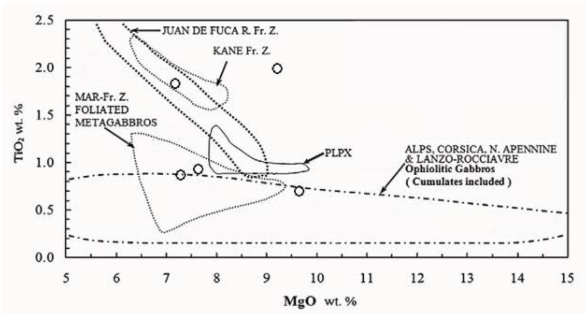

Fig. 5. TiO_2 *vs* MgO variation diagram for the Serifos metabasites. The outlined fields indicate the variation of gabbros and basalts from Alpine ophiolite complexes (Beccaluva et al., 1977, 80, Betrtand et al., 1987) and from oceanic fracture zones, equivalent to transform faults (Bonatti et al., 1975; Miyashiro and Shido, 1980; Honnorez et al., 1984; Langmuir and Bender, 1984), compliled after Gartzos et al. (2009).

3.2. Spidergram patterns

The majority of the metavolcanics display significant enrichment in alkalies, Rb, K and Na as well as enrichment in alkaline earth elements Sr and Ba, relative to N-MORB compositions (Fig. 7). These can partly be attributed to secondary processes e.g., seafloor alteration prograde metamorphism, K-metasomatism with biotite formation during contact metamorphism, but some primary characteristics may remain. The patterns of the multi-element diagrams normalised to N-MORB and primordial mantle show distinct enrichment in

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LILE (Sr, Ba, K) and LREE relative to High Field Strength Elements (HFSE – Nb, Ti, P) (Fig. 7). There are distinct Nb, Ti and P anomalies typical of arc rocks. The compositional group of the relatively more LILE-enriched amphibolites (#Ser93-20, #Ser94-10) resemble typical low- to medium-K calc-alkaline basalts and are comparable to the recent Aegean back-arc volcanics (Stouraiti, 1995). The relatively less LILE- enriched fine-grained amphibolites (metabasalts) e.g. #Ser-K2, Ser-101, Ser-76, resemble arc thoileiites (IAT).

wide, but the fluid sources and processes of mass transfer are controversial.

In the conventional discrimination diagrams according to tectonic setting (Pearce & Cann, 1973; Wood, 1980) Serifos amphibolites are grouped into two compositional groups (Fig. 8 a-c). The most common compositional type display mixed Island Arc Tholeiites (IAT) and Calc-alkaline Basalt affinities (CAB). The second and more rare compositional group includes amphibolite samples with mixed MORB – Island Arc Tholeiite affinities and represented by the retrogressed blueschist/greenschist samples. Amphibolite with typical MORB affinities was not identified in this study.

Table 2. Representative whole-rock analysyes (XRF) of major elements (wt. %) and trace elements (ppm) of the Serifos metabasites.

Sample no.	SER93-20	SER93-21	SER93-39	SER94-10	SER92-27b	SER-76	SER-K2	SER-101	SER-99	SER-94
Rock type	Amphibolite	Metasom. Amphibolite (bit-rich)	Greenschist (epidote-rich)	Amphibolite	Greenschist (melange)	Amphibolite	Amphibolite	Amphibolite	Greenschist (low-grade)	Greenschist
SiO_2	48,4	59,5	51,2	48,7	51	46,8	48,6	48,3	49,2	49,7
TiO_2	1,15	1,11	1,57	1,25	1,02	1,99	0,87	0,92	0,69	1,83
Al_2O_3	19	17	16,6	18,2	17	15,4	16,3	16,2	15,5	15,5
Fe_2O_3	10,8	6,1	8,3	10,3	10,4	11,4	12,2	10,3	9,4	9,3
MnO	0,17	0,06	0,14	0,13	0,06	0,19	0,16	0,15	0,11	0
MgO	3,34	2,55	3,93	2,89	3,42	9,22	7,31	7,65	9,66	7,19
CaO	12,24	7,63	7,73	12,76	11,95	11,89	10,91	13,5	10,2	7,51
Na_2O	3,14	1,64	3,59	2,93	4,37	2,97	2,82	2,63	2,89	4,51
K_2O	1,11	2,83	1,46	0,93	0,61	0,25	1	0,4	0,67	0,44
P_2O_5	0,17	0,19	0,4	0,5	0,25	0,11	0,09	0,17	0,15	0,24
LOI	0,4	0,6	5,15	1,68	0,6	0,4	0,5	0,33	2	4
Total	99,92	99,2	100,1	100,3	100,68	100,62	100,76	100,55	100,47	10,3
Sc	28	24	30	n.d	45	39	41	n.d	29	29
V	268	165	195	n.d	215	260	291	n.d	192	207
Cr	35	168	671	n.d	522	445	177	n.d	540	218
Co	24	22	48	n.d	32	45	51	n.d	48	35
Ni	23	49	148	n.d	66	175	56	n.d	192	71
Cu	16	34	23	n.d	37	52	318	n.d	14	14
Zn	55	44	83	n.d	45	120	18	n.d	112	112
Ga	20	24	17	n.d	15	15	13	n.d	16	16
Rb	43	126	31	n.d	9	11	29	n.d	15	15
Sr	357	250	452	n.d	337	179	188	n.d	345	163
Y	37	36	28	n.d	27	36	16	n.d	17	30
Zr	180	284	98	n.d	51	130	35	n.d	59	175
Nb	8	23	5	n.d	2	<1	<2	n.d	0	7
Ba	203	539	253	n.d	54	40	112	n.d	172	39
La	16	28,6	11	n.d	5,4	5	4,6	n.d	8,3	3
Ce	39	62	18	n.d	9,3	10,6	7,7	n.d	19,7	13,5
Nd	23,7	25	10,2	n.d	12	12,7	7	n.d	15	13,3
Th	1	12	3	n.d	3	1	2	n.d	1	2

4. Discussion

Elevated concentrations of certain large-ion-lithophile elements (LILE; e.g., Ba, K, Rb, Cs, Ca, Sr), U, and Pb in arc magmas relative to high-field-strength elements (e.g., Ti, Th, Hf, Nb, Zr) are considered key indicators of fluid addition to arc magma source regions world-

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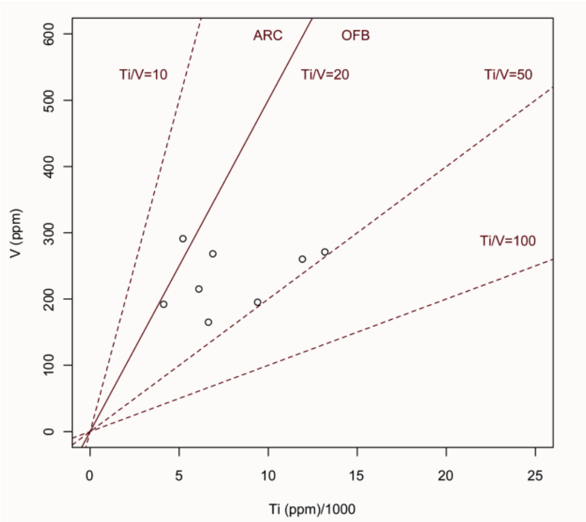

Fig. 6. Vanadium versus Ti/1000 discrimination diagram of Shervais (1982) for the Serifos metabasites. The straight lines discriminate the fields for Island Arc Tholeiites (IAT) from supra subduction zones, Ocean Floor Basalts (N- and E-type Mid-Ocean Ridge Basalts). N-type MORB range in Ti/Zr ratios from 20-30 and E-type MORB from 30-50.

4.1. Review of geochemical studies on Cyclades metabasites

Metabasic rocks from similar structural levels in the adjacent island of Syros show comparable geochemical characteristics. Based upon mineralogy, the metabasic rocks of Syros are commonly interpreted as metamorphosed volcanics inter-layered with shallow carbonates or as metamor-phosed ocean-floor igneous rocks (Tinsley, 2008). Coarse-grained omphacite-bearing rocks and eclogites are metamorphosed gabbros whereas associated felsic rocks may have formed from residual melts of these gabbros (Schumacher, 2004).

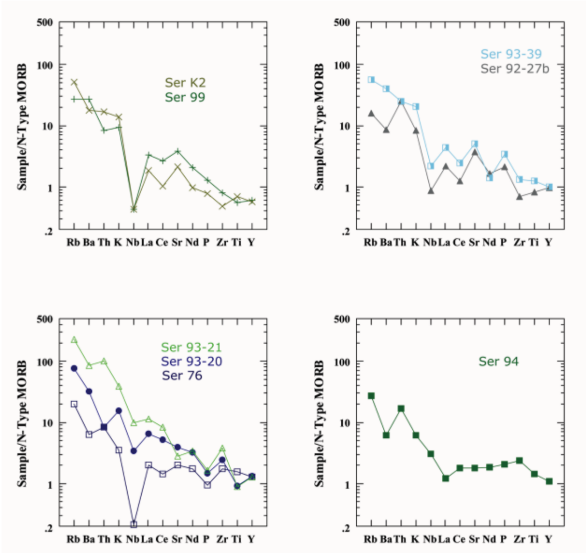

Fig. 7. Spidergram patterns of Serifos metabasites normalized to N-type MORB (after Sun & McDonough, 1989) : a) and b) amphibolites.

Recent work by Baziotis et al. (2009) on the metabasitic rocks from the Upper Tectonic Unit of the Lavrion area (south Attica, mainland Greece) reported similar occurrence of metabasites as greenschists and blueschists. Major and trace element relations against Mg# showed that blueschists always exhibit a more evolved basaltic composition

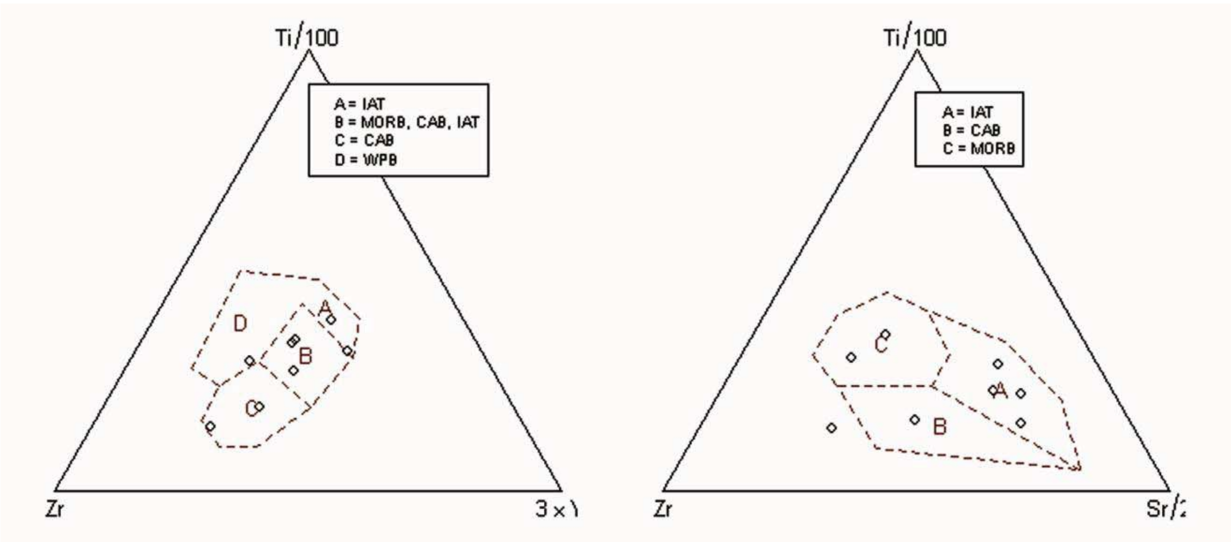

Fig. 8. Ternary classification diagrams of Pearce & Cann (1973): a) Ti/100 – Zr – Y*3 diagram, b) Ti/100 – Zr – Sr/2 diagram, and c) Zr/117 – Th – Nb/16 classification diagram of Wood (1980). Note that the majority of amphibolites display mixed Island Arc Tholeiites and Calcalkaline Basalt affinities whereas retrogressed blueschists metagabbroic rocks plot within the MORB field.

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(Baziotis et al., 2009). Both types of the metabasites share common geochemical features like HFSE flat patterns slight positive Nb anomalies with La/Nb<1. According to Baziotis et al., 2009 the protoliths of the metabasites seem to evolve through fractional crystallization processes following a normal tholeiitic trend, similar to the Serifos amphibolites. Based on the REE patterns of the studied metabasites Baziotis argued that fractional crystallization alone cannot explain the observed patterns. Therefore it is argued out that either partial melting of a heterogeneous mantle source or interaction/assimilation of sedimentary (gneissic) material can produce the observed REE pattern, with the former process being the dominant. Concluding the same authors interpret the protoliths of the metabasites as products of a mature back-arc basin similar to that occurring in Syros, Sifnos and Tinos islands, all parts of the ACCB.

5. Conclusions

On the basis of geochemical (major - trace element bulk rock data), the studied metabasites from the volcanosedimentary sequence can be distinguished in different rock types (mostly fine-grained basalts and andesites and less gabbros) with different chemical affinities: a) The relatively LILE-enriched amphibolites resemble typical low- to medium – K calc-alkaline basalts (CAB), similar to the recent Agean back-arc volcanics. b) Other amphibolites display chemical affinitities similar to island arc tholeiites (IAT). c) The retrogressesd blueschist – to –greenschists facies metabasites display mixed IAT/MORB chemical affinities. Comparable geochemical data are documented for the metabasites from similar structural levels in the Lavrion area. Further geochemical work need to be carried out in order to improve our knowledge on the tectonic setting of the amphibolites in the western part of the Attic Cyclades Metamorphic Complex.

Geochemical data exclude an intra-plate or a depleted MORB-type (N-type) mantle source for the various types of metabasites and rather indicate a subduction-related *(e.g.* arc type) geotectonic setting.

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