Πρακτικά	4ου Συνέδριου	Μάϊος 1988	
Δελτ. Ελλ. Γεωλ. Εταιρ.	Τομ. XXIII/2	σελ. 413-427	Αθήνα 1989
Bull. Geol. Soc. Greece	Vol.	pag.	Athens

GEOCHEMICAL INVESTIGATION OF AMPHIBOLITES FROM EASTERN AND CENTRAL RHODOPE

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ABSTRACT

Amphibolites apper in the crystalline basement of the Rhodope Zone in the following modes of occurrence: a. in the form of lenses and bands, b. in the form of layers alternating with other rock types (i.e. gneisses, marbles), and c. as large complexes associated with ultramafic bodies. Major and trace element geochemistry reveals that the amphibolites are of magmatic origin and that their protoliths were tholeiites with ocean floor affinities. The metagabbros have also tholeiitic affinities. Some of the amphibolites of Eastern Rhodope have remarkably low HFS elements contents thus showing mixed characteristics with island arc tholeiites while those of Central Rhodope show more uniform, ocean floor, geochemical signatures.

ΣΥΝΟΨΗ

Αμφιβολίτες απαντούν στο κρυσταλλικό υπόβαθρο της Ζώνης της Ροδόπης με τις ακόλουθες μορφές: α. σαν φακοί ή ταινίες, β. σαν στρώματα εναλλασσόμενα με άλλους τύπους πετρωμάτων (π.χ. γνευσίους, μάρμαρα), και γ. σαν μεγάλα συμπλέγματα συνδεδεμένα με υπερβασικά σώματα. Γεωχημική μελέτη των αμφιβολιτικών πετρωμάτων με κύρια στοιχεία και ιχνοστοιχεία έδειξε ότι είναι μαγματικής προέλευσης και ότι οι πρωτόλιθοι τους ήταν θολεϊίτες με χαρακτηριστικά όμοια μ'αυτά ωκεανείων βασαλτών. Οι μεταγάββροι έχουν κι αυτοί θολεϊιτική σύσταση. Μερικοί από τους αμφιβολίτες της Ανατολικής Ροδόπης έχουν ιδιαίτερα χαμηλές περιεκτικότητες σε HFS στοιχεία δείχνοντας έτσι μικτά χαρακτηριστικά με θολεϊιτικούς βασάλτες νησιωτικού τόξου ενώ οι αμφιβολίτες της Κεντρικής Ροδόπης έχουν ομοιόμορφα γεωχημικά χαρακτηριστικά τα οποία προσομοιάζουν σ'αυτά των βασαλτών ωκεάνειου πυθμένα.

1. INTRODUCTION

Amphibolites appear in the crystalline basement of the Rhodope Zone either in form of small bodies (lenses and bands) of a few meters in length or as big layers of some meters up to some tens of meters in thickness. Finally, they occur as large complexes associated with ultramafic bodies. The amphibolites of the Rhodope Zone are distinguished into two types: a. eclogitic amphibolites with eclogite mineral relics and b. common amphibolites. Detailed petrological study (LIATI, 1986, 1988; MPOSKOS, 1987; MPOSKOS & PERDIKATSIS, 1987b) revealed that the amphibolites probably derived by partial or complete amphibolitization of former eclogites. In the present work the geochemical characteristics of the amphibolites from Eastern and Central Rhodope are presented and the results of the geochemistry are discussed.

Ε.ΜΠΟΣΚΟΣ, Β.ΠΕΡΔΙΚΑΤΣΗΣ, Α.ΛΙΑΤΗ - Γεωχημική μελέτη αμφιβολιτών της Ανατολικής και Κεντρικής Ροδόπης.

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GEOLOGIC SETTING

The Greek part of the Rhodope Massif extends from the Strymon fault, to the west, up to the Greek-Turkish boundaries, to the east. Thrust over it in the west, approximately along the Strymon river, is the Sebromacedonian Zone (KOCKEL & WALTHER, 1965; KOUKOUZAS, 1972) while to the east it is bounded by the Circum Rhodope Belt (KAUFFMANN et al., 1976) (Fig. 1).

The crystalline basement of Rhodope consists of metasedimentary rocks, as biotite-plagioclase gneisses, pelitic gneisses, mica-schists, calc-silicate rocks, and marbles and rocks of magmatic origin as granitic-granodioritic gneisses, serpentinized peridotites and (eclogitic) amphibolites. Syn- to post-metamorphic plutonic and subvolcanic bodies have intruded the rocks of the basemest.

In Eastern Rhodope two major tectonic units can be distinguished on the basis of metamorphic grade (MPOSKOS, 1987):

a. a lower Tectonic Unit (further referred to as LTU)consisting of a leucocratic granite gneiss and a volcanosedimentary series made up of pelitic gneisses, chloritoid-staurolite schists, amphibolites, and rarely marbles. Metadiabasic, metagabbroic and metaaplitic dykes crosscut both the granite-gneiss, and the volcanosedimentary series. Large ultramafic bodies are incorporated in this unit.

b. an Upper Tectonic Unit (further referred to as UTU) which overlies tectonically the LTU. It consists of alternating migmatized pelitic gneisses, amphibolites and marbles and of a metamorphic ophiolite sequence. Pegmatoids are abundant and crosscut all the rock types of the UTU.

As is show in Fig. 1. the above distinction has not been made yet for Central Rhodope.

The Rhodope Zone has been affected by three successive metamorphic episodes (LIATI, 1986; MPOSKOS et al., 1986 a, b; MPOSKOS, 1987, 1988; MPOSKOS & PERDIKATSIS, 1987a, b): a. a high-P, b. a Barrow-type, and c. a low-P (lower greenschist facies) metamorphism. For the Barrovian metamorphism P-T conditions of 6-7 kbar, 650°C (KRONBERG & RAITH, 1977) and 7-9 kbar, 550-650°C (LIATI, 1986), have been determined for Central Rhodope. For the same metamorphic event, an increase in metamorphic grade from the SE part of East Rhodope (P=7-9 kbar, Tmax= 530°C) to the western part of Central Rhodope (Echinos-Thermai region) (T=700°C in the migmatite zone) has been recognized (MPOSKOS, 1987, 1988). The lower greenschist facies metamorphism is well expressed by the growth of retrograde phases, like, for instance, brown-green biotite at the expense of garnet, muscovite and brown biotite, tremolite at the expense of hornblende in the metapelites (MPOSKOS, 1987, 1988), etc.

DESCRIPTION OF THE AMPHIBOLITES

a. Field relations

In the eastern and southern part of the UTU of Eastern Rhodope, the amphibolites constitute parts of a metamorphosed ohpiolithic complex with ultramafic, mafic and intermediate members. Trondjemitic and plagiogranitic dykes crossut the gabbroic and dioritic rocks. In the metagabbros, the primary magmatic layering, expressed as alternated light-and dark-coloured bands, is often preserved. Besides the amphibolites of gabbroic origin, abundant amphibolites appear as layers intercalated in gneisses and/or frequently alternated with pelitic gneisses and marbles. These probably represent either primary dykes or lava flows.

In the LTU of Eastern Rhodope, the amphibolites occur as alternations, of some meters in thickness, in the gneisses. They often show the characteristics

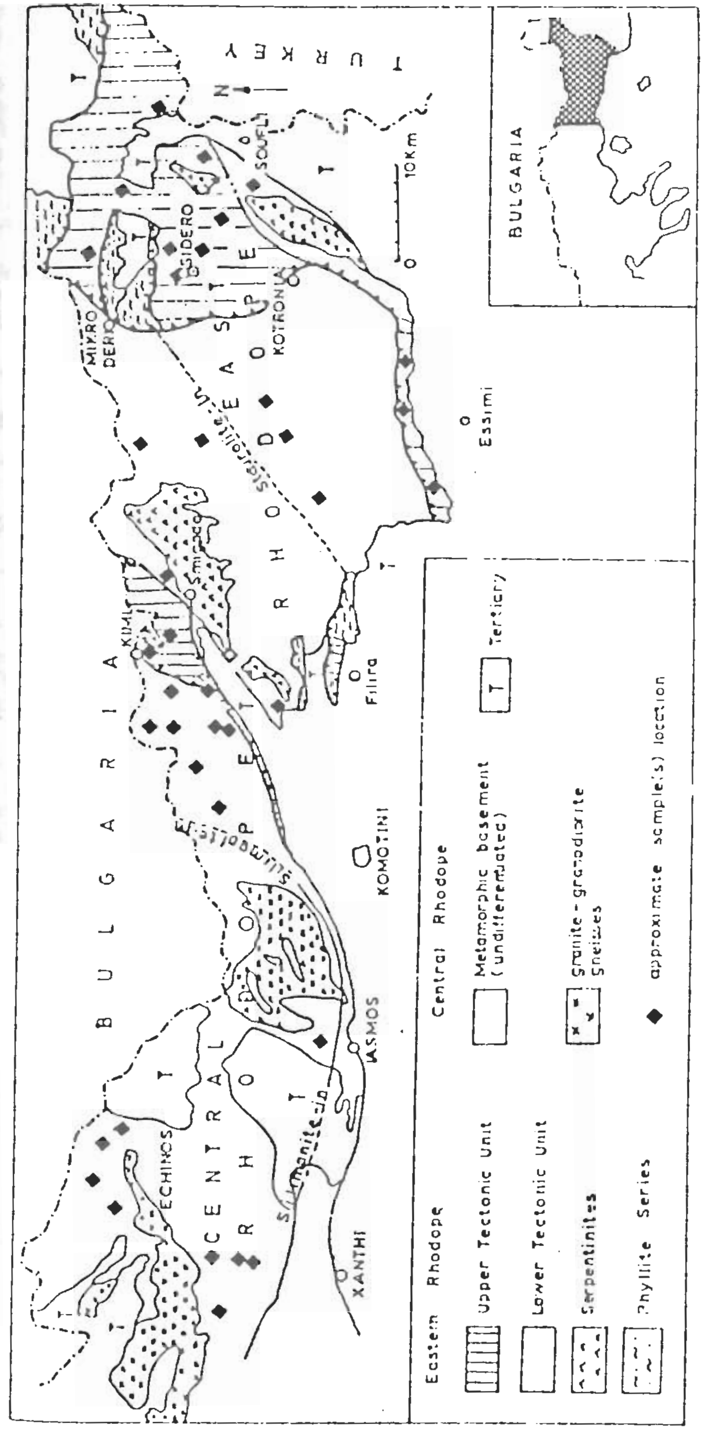


Fig. 1: Geologic sketch-map of Central and Eastern Rhodope with sample location

Σχήμα 1: Γεωλογικό σκαρίφημα της Κεντρικής και Ανατολικής Ροδόπης με τις θέσεις δειγματοληψίας.

of dykes since they appear oblique to the schistosity. In small metagabbroic bodies, with a maximum thickness, of 40m, magmatic minerals, such as plagioclase and augite are preserved as relics.

In the area SW of Mirtiski, amphibolites overlie pelitic schists and have a thickness of more than 100m. In the eastern part of Central Rhodope, Drymi-Sarakini area, amphibolites alternating with pelitic gneisses are of great extent. In the upper parts of the amphibolite layers, a transition to "gneisses-amphibolite-marble" alternations is observed.

In the western part of Central Rhodope the amphibolites appear as intercalations in gneisses, migmatites and marbles. They also occur in from of blocks or lenses from some decimeters up to a few meters, in gneisses.

The field observetions indicate a magmatic origin for the amphibolites. However, it is possible that some of the amphibolites, especially these intercalated with marbles and calc-silicate rocks, could have a sedimentary origin. The geochemical data will contribute to the resolution of this problem.

b. Petrography

The amphibolites of the Rhodope Zone are distinguished into two types: the eclogitic amphibolites and the common amphibolites.

1. The eclogitic amphibolites are characterized by the following mineral assemblage:
   Hornblende-plagioclase-omphacite (or sodic augite)-rutile±garnet±clinozoisite/zoisite±biotite±quartz±sphene.
   In eclogitic amphibolites plagioclase-clinopyroxene symplectites occur sometimes in the place of omphacite.
2. The common amphibolites are characterized by the mineral assemblage: Hornblende-plagioclase-rutile±garnet±biotite±clinozoisite/zoisite±sphene±quartz±cpx(salite). The common amphibolites at least in their majority, derive from preexisting eclogites. They are more abundant probably because the amphibolitization process has considerably proceeded.

GEOCHEMISTRY

In order to characterize the amphibolites chemically, 90 whole rock analyses for major and trace elements were performed (21 of these are from metagabbros). Of these samples, 46 were collected from the UTU of Eastern Rhodope (21 are metagabbros), 16 from the LTU of Eastern Rhodope, 15 from the Eastern part of Central Rhodope and 13 from the Western part of Central Rhodope. The approximate location of the collected samples is given in the map of Fig.1.

The mean value and the standard deviation of the chemical analyses for each of these four groups are listed in Table 1.

a. Analytical techniques

Bulk chemical X-Ray fluorescence analyses for major and trace elements were carried out for 90 specimens by a Philips semi-automatic XRF-spectrometer using powder pellets. For the major elements the correction method of BROWN et al. (1973) was applied. Cr tube was used for the major and Mo and W for the trace element determination.

b. The nature of the protoliths

The magmatic nature of the protoliths is indicated by the correlation of incompatible elements, with similar chemical bahaviour, with one another (i.e. TiO_2 vs. Zr, Cr vs. Ni) (Fig. 2, 3).

The magmatic origin of the protoliths is confirmed by the correlation of some incompatible elements with the M-value ($MgO/MgO+FeO^*$, molecular) indi-

TABLE 1: CHEMICAL ANALYSES OF THE AMPHIBOLITES

	CENTRAL RHODOPE: EASTERN PART $\bar{x}$*	CENTRAL RHODOPE: EASTERN PART s	CENTRAL RHODOPE: WESTERN PART $\bar{x}$	CENTRAL RHODOPE: WESTERN PART s	EASTERN RHODOPE: UTU $\bar{x}$	EASTERN RHODOPE: UTU s	EASTERN RHODOPE: LTU $\bar{x}$	EASTERN RHODOPE: LTU s	Metagabbros $\bar{x}$	Metagabbros s
SiO_2	51,4 (51,3)	2,5 (1,0)	48,9 (48,6)	4,4 (1,1)	50,0 (49,8)	3,8 (1,1)	49,6 (49,5)	3,3 (1,0)	50,8 (50,4)	6,0 (1,1)
TiO_2	0,95 (0,82)	0,54 (1,7)	1,66 (1,56)	0,58 (1,37)	0,99 (0,84)	0,53 (1,8)	1,32 (1,27)	0,39 (1,3)	0,60 (0,53)	0,26 (1,8)
FeO^*	10,10 (9,8)	2,4 (1,2)	12,2 (11,9)	2,7 (1,2)	10,9 (10,7)	1,7 (1,2)	11,5 (11,3)	2,0 (1,2)	11,6 (11,2)	3,0 (1,3)
Al_2O_3	16,11 (15,7)	3,4 (1,2)	14,6 (14,4)	2,4 (1,2)	16,2 (16,0)	2,4 (1,2)	16,2 (15,9)	3,1 (1,2)	15,5 (15,3)	2,2 (1,1)
MnO	0,19 (0,19)	0,04 (1 [illegible])	0,21 (0,21)	0,04 (1,1)	0,18 (0,18)	0,04 (1,27)	0,22 (0,19)	0,14 (1,16)	0,22 (0,21)	0,08 (1,4)
MgO	7,7 (7,5)	1,8 (1,2)	6,40 (6,3)	0,96 (1,15)	8,26 (8,0)	2,1 (1,2)	6,7 (6,6)	1,0 (1,1)	8,2 (7,6)	3,0 (1,5)
CaO	9,81 (9,70)	1,4 (1,1)	10,7 (10,6)	1,5 (1,1)	10,5 (10,3)	2,1 (1,7)	10,1 (9,9)	1,7 (1,1)	10,7 (10,5)	2,0 (1,2)
Na_2O	3,0 (2,9)	0,9 (1,3)	2,70 (2,57)	0,9 (1,6)	2,30 (2,03)	1,0 (1,72)	3,4 (3,3)	0,9 (1,3)	2,0 (1,9)	0,6 (1,3)
K_2O	0,39 (0,16)	0,42 (5)	0,99 (0,93)	0,4 (1,4)	0,59 (0,31)	0,56 (3,8)	0,49 (0,42)	0,25 (1,8)	0,19 (0,13)	0,13 (2,0)
P_2O_5	0,12 (0,09)	0,07 (2)	0,30 (0,25)	0,2 (1,7)	0,17 (0,09)	0,22 (3,5)	0,20 (0,23)	0,10 (1,5)	0,08 (0,05)	0,09 (2,8)
Cr	262 (222)	170 (2)	216 (132)	139 (2)	227 (185)	142 (2)	197 (180)	71 (2)	168 (73)	260 (4)
Ni	95 (84)	43 (2)	57 (52)	27 (2)	73 (61)	39 (2)	66 (58)	32 (2)	33 (19)	35 (3)
Rb	11 (8)	8 (2)	21 (18)	14 (2)	14 (9)	13 (2)	11 (8)	6 (2)	5 (5)	3 (2)
Sr	230 (197)	149 (2)	252 (222)	158 (2)	161 (141)	86 (2)	196 (183)	71 (2)	108 (83)	73 (2)
Zr	63 (53)	34 (2)	83 (70)	54 (2)	59 (40)	45 (2)	87 (80)	43 (2)	22 (15)	19 (2)
Nb	5 (4)	3 (2)	8 (6)	8 (2)	8 (6)	6 (2)	6 (6)	2 (2)	6 (5)	6 (3)
Y	25 (21)	14 (2)	36 (31)	17 (2)	28 (23)	14 (2)	36 (35)	8 (1)	30 (22)	25 (2)

*$\bar{x}$: MEAN VAL., S: STD. DEV. ($\bar{x}$): GEOM. MEAN, (S): GEOM. DEV.

The analyses have been recalculated on an anhydrous basis (without H_2O and CO_2).

Symbols: Circles: Eastern Rhodope; filled circles: Upper Tectonic Unit, open circles: Lower Tectonic Unit. Triangles: Central Rhodope; filled triangles: eastern part, open triangles: western part.

Fig.2 : Correlation between TiO_2 and Zr. The linear trend is indicative of an igneous protolith.

Σχήμα 2: Συσχέτιση μεταξύ TiO_2 και Zr. Η γραμμική τάση υποδηλώνει ότι οι πρωτόλιθοι ήταν μαγματικά πετρώματα.

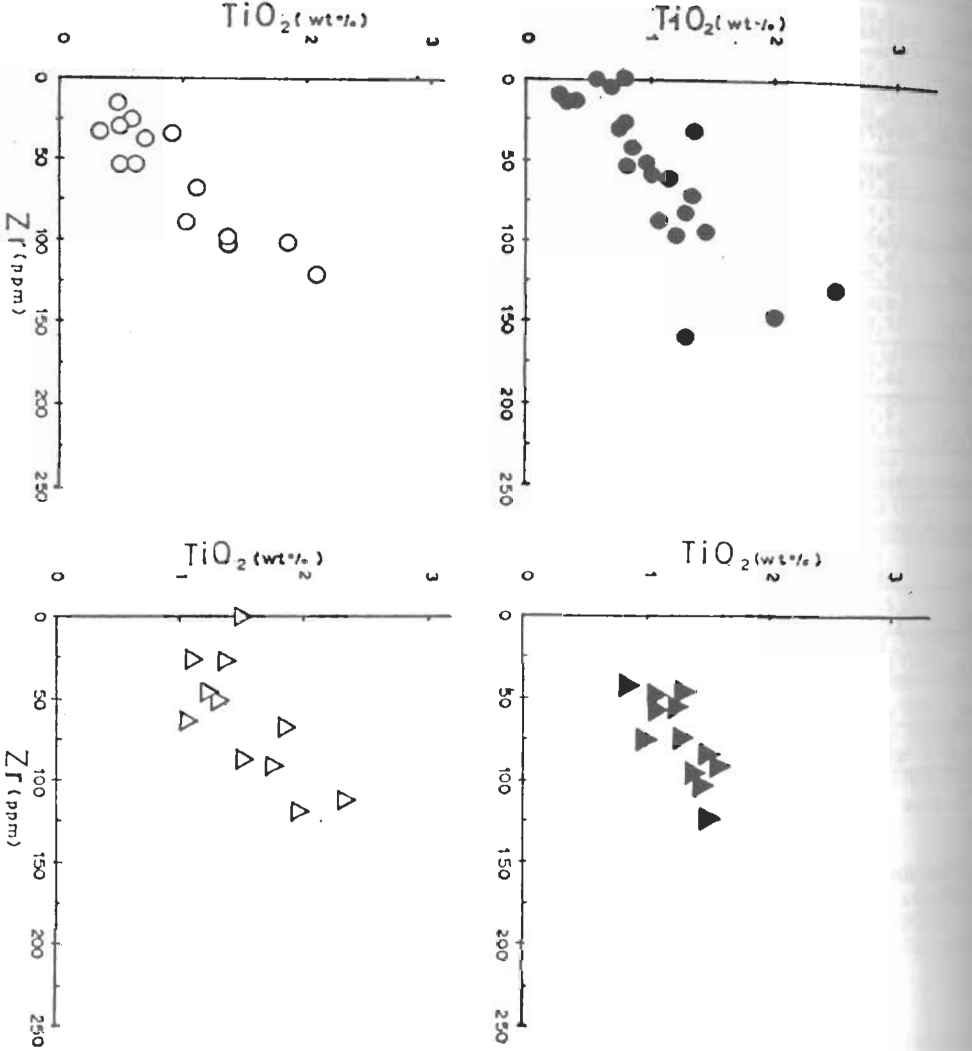
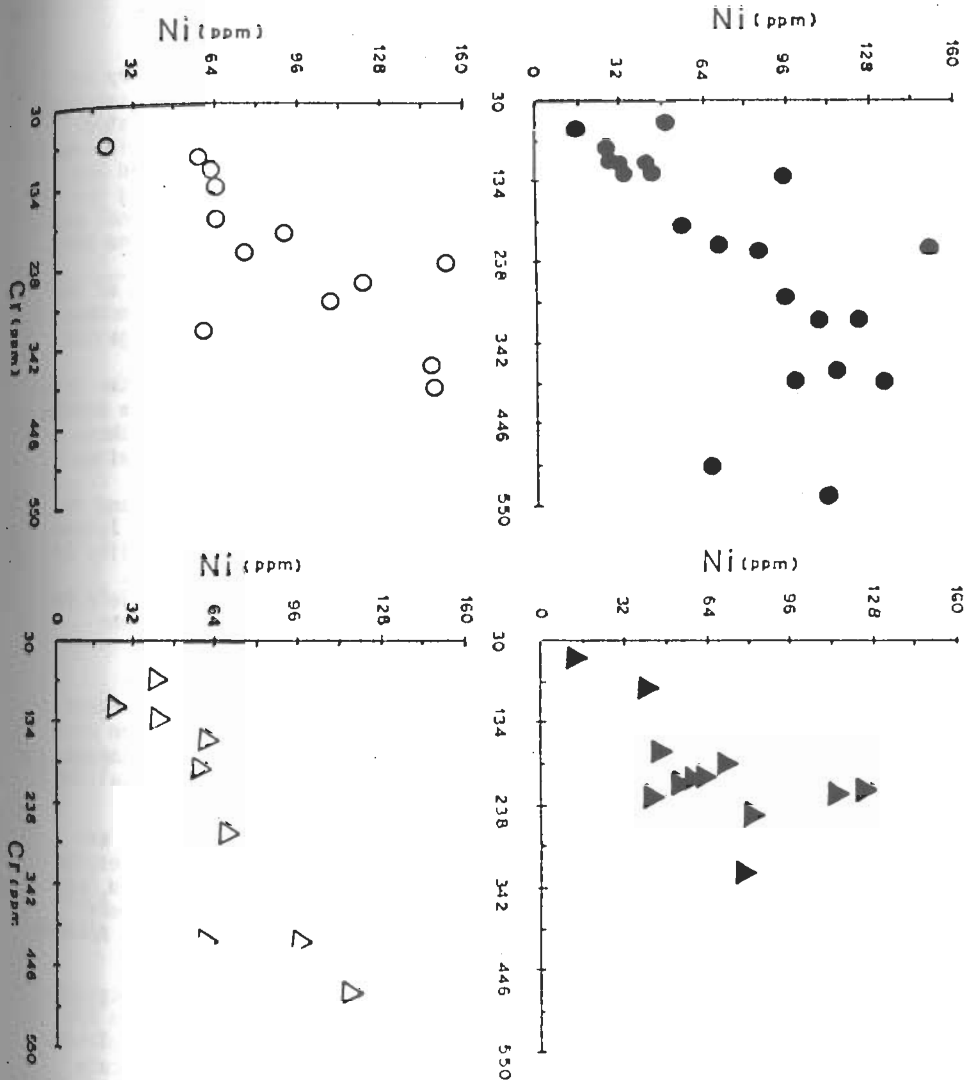


Fig. 3: Correlation between Cr and Ni. The linear trend is indicative of an igneous protolith.

Σχήμα 3: Συσχέτιση μεταξύ Cr και Ni. Η γραμμική σχέση υποδηλώνει ότι οι πρωτόλιθοι ήταν μαγματικά πετρώματα.



cating that differentiation processes took place (Fig. 4, 5). Thus, the concentration of TiO_2 increases with advanced fractionation (lower M-value) whereas that of Cr decreases. Fig. 6 shows clearly that the amphibolites of Rhodope follow a tholeiitic trend.

The same figure shows that the metagabbros also follow a tholeiitic trend.

c. Geotectonic setting of the protoliths

The great number of recent studies dealing with the geochemistry of (meta) basaltic rocks revealed that any conclusion about the tectonic setting of the protoliths based only on geochemical criteria have to be integrated with other, geological and petrographic, evidence. Most of the discrimination diagrams proposed over the last years have been derived empirically and are based on statistics, often leading to contradictory results for one and the same rock type (e.g. HOLM, 1982; DUNCAN, 1987) especially in transitional environments. Therefore, such diagrams should be regarded with suspicion and their extensive use is avoided in the frame of the present work.

Because of element mobility during alteration and metamorphism of the protoliths, emphasis is given to the use of the so-called "immobile" incompatible elements (Ti, P, Zr, Nb, Y, Cr) which are relatively resistant against alteration processes.

The absolute abundance of "immobile" incompatible elements in the investigated amphibolites resembles that of ocean floor basalts (MORB). The mobile elements (e.g. K, Rb) have in most cases increased values relative to those reported from MORB but this is probably due to enrichment during alteration and/or metamorphism.

Some samples have remarkably lower contents of Zr, P_2O_5, TiO_2 and Nb, a characteristic of basaltic rocks erupted in an island arc environment. Island arc tholeiites have also increased alkalies contents but the high mobility of these elements doesn´t permit the use of this criterion as distinctive.

In Fig. 7, the amphibolites from Central Rhodope fall in the field for OFB whereas some samples from Eastern Rhodope (those with low HFS element contents) are projected in the field for island arc tholeiites(IAT).

Therefore, for Eastern Rhodope, two alternatives arise:

1. The protoliths of the amphibolites represent both arc and spreading ridge basalts. In that case, the initial magmas are considered to have been erupted in two distinct tectonic environments, an island arc and an adjacent back-arc basin. Due to subsequent metamorphism and tectonics the resulting metamorphic rocks (the amphibolites) appear now in the same area.
2. The protoliths of the amphibolites were erupted in a spreading ridge environment but mixed geochemical features resulted, to some extent, despite the uniform tectonic framework. It should be stressed here that mixed geochemical characteristics are not rare especially in magmatic enviroments such as marginal basins and attenuated continental margins (compare ARCULUS 1987; MAGGETTI et al., 1987; DUNCAN, 1987).

Field observations favor the second view since there is no indication for a separation of the initial magma packages into two types erupted in two distinct tectonic environments. The frequent alternations of the amphibolites, that were formerly lavas with other rock types (gneisses, marbles) indicate a uniform tectonic framework of eruption. Of interest is the fact that all of the amphibolites that occur in the broad area between Xanthi and Echinos show close affinities to oceanic crust (LIATI, 1986, 1987 and this study). The same is true also for amphibolites of the Bulgarian part of the Rhodope Zone (KOLCHEVA and ESKENAZY, 1987).

Conclusively, the protoliths of the amphibolites of the Rhodope Zone were tholeiitic basalts with MORB affinities and partly mixed geochemical characteristics with IAT. The nature of the associated metasediments and the lack

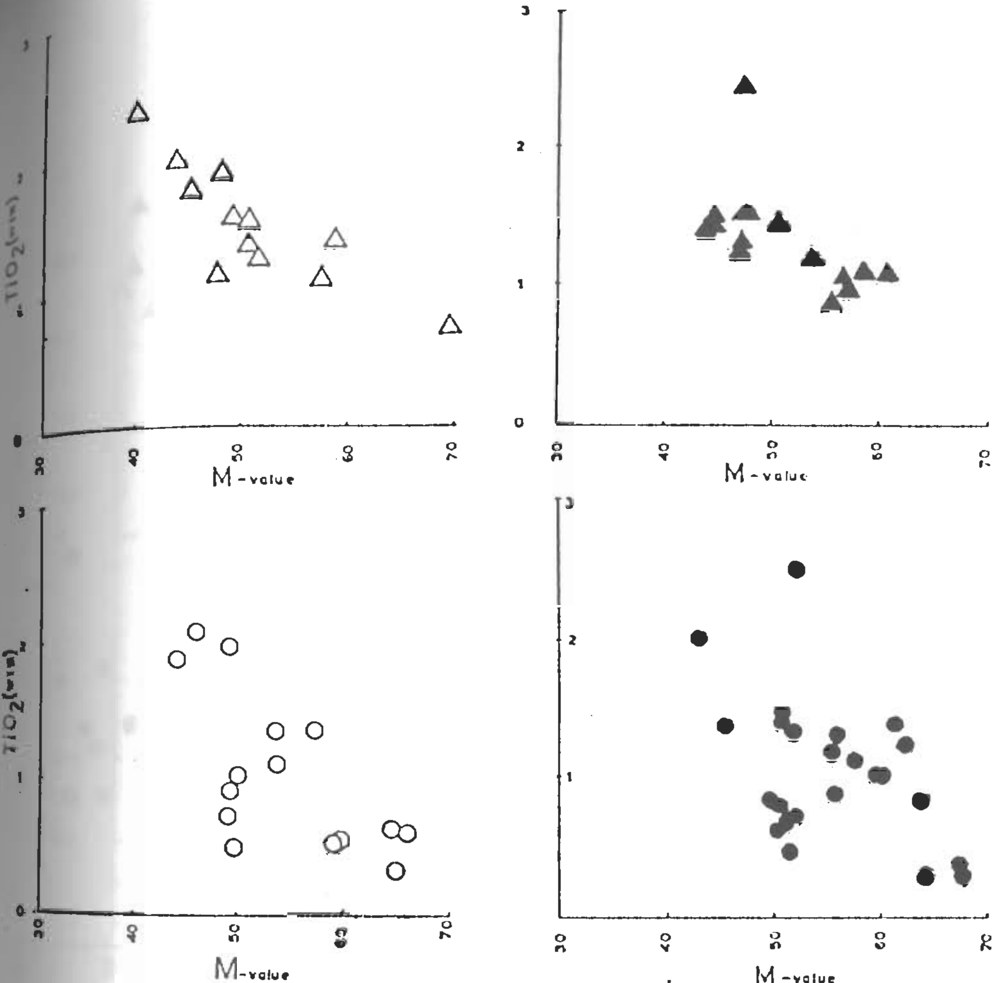


Fig.4 : TiO_2 against M-value. The continuous evolution trend (TiO_2 increase with advanced fractionation) indicates that differentiation processes took place and reconfirm the igneous nature of the protoliths.

Σχήμα 4 : TiO_2 προς την τιμή-Μ. Η συνεχής εξελικτική τάση (αύξηση TiO_2 με την πρόοδο της κλασματικής κρυστάλλωσης) υποδηλώνει διαδικασίες διαφοροποίησης και επιβεβαιώνει την μαγματική φύση των πρωτολίθων.

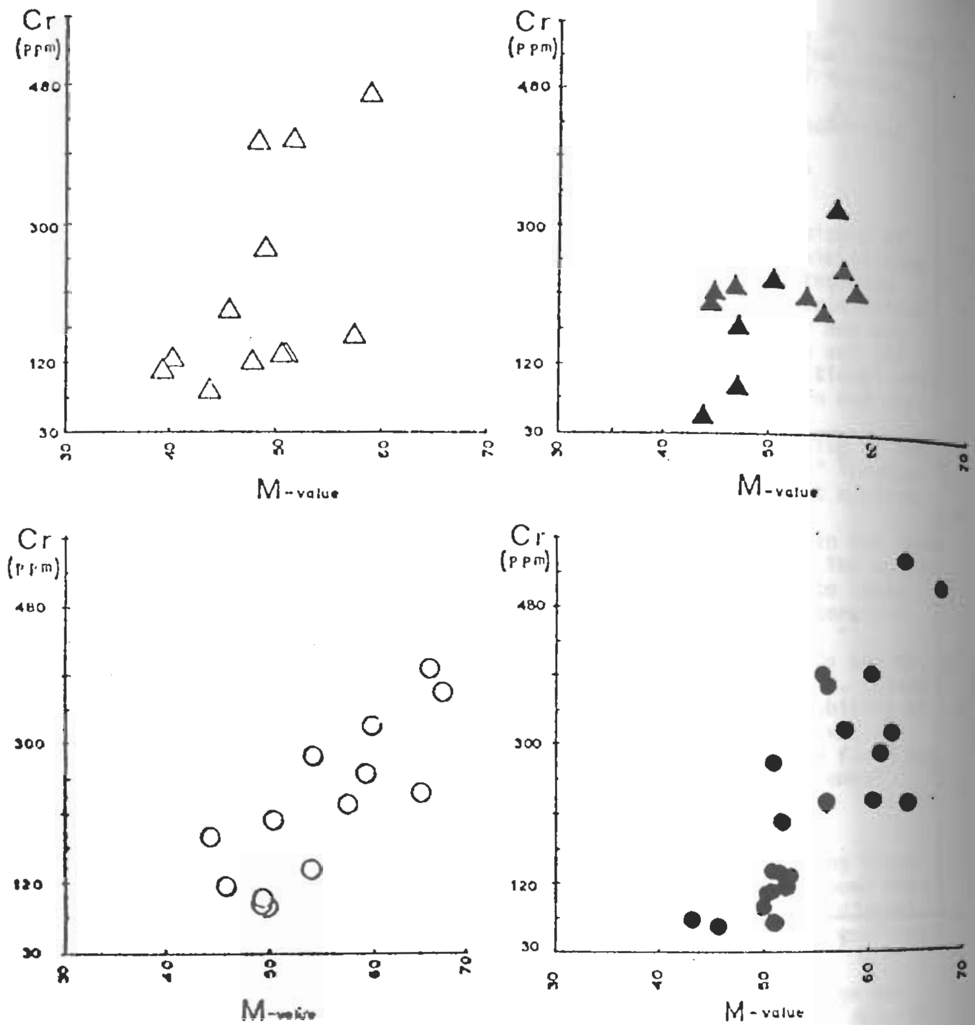
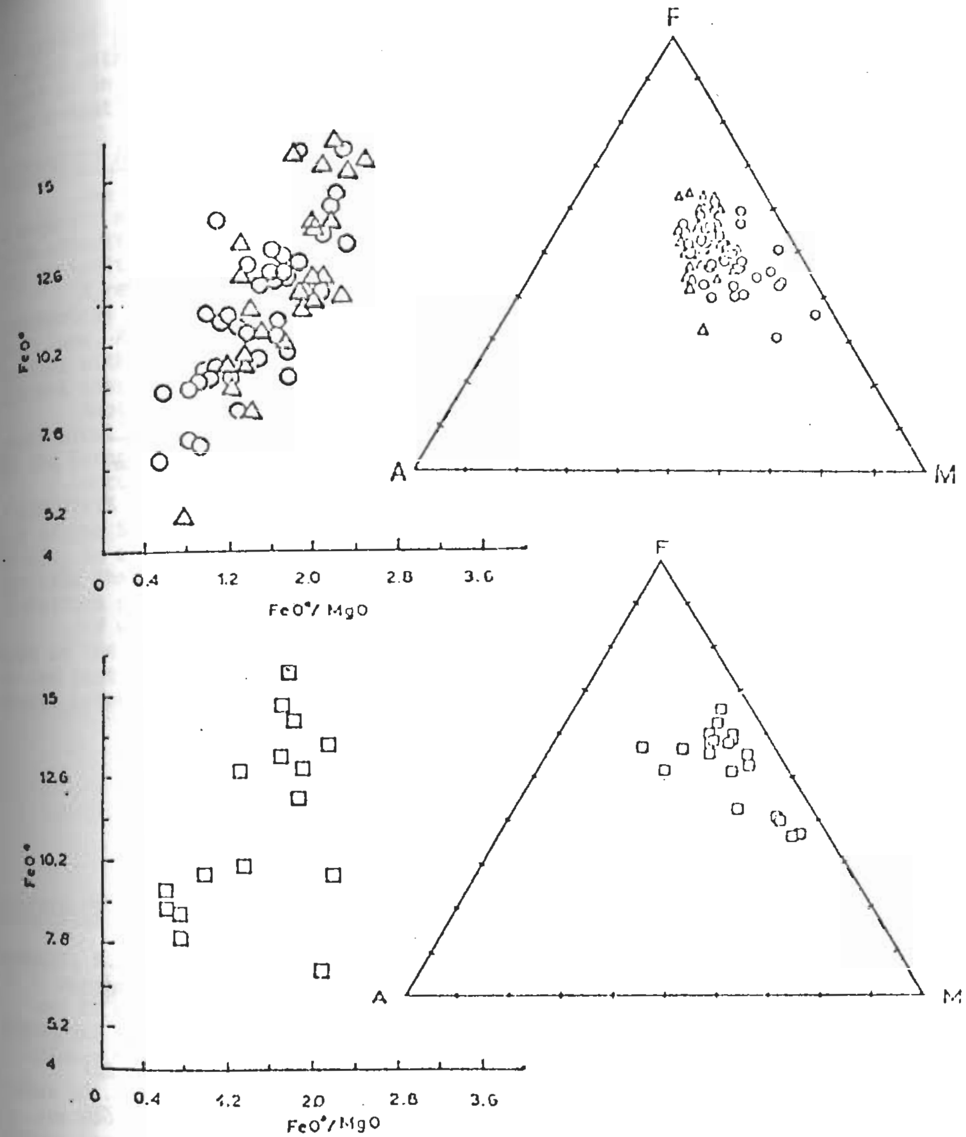


Fig. 5: Cr against M-value. The continuous evolution trend (Cr decrease with advanced fractionation) indicates that differentiation processes took place and reconfirm the igneous nature of the protoliths.

Σχήμα 5: Cr προς την τιμή-Μ. Η συνεχής εξελικτική τάση (ελάττωση του Cr με την πρόοδο της κλασματικής κρυστάλλωσης) υποδηλώνει διαδικασίες διαφοροποίησης και επιβεβαιώνει τη μαγματική φύση των πρωτολίθων.



Squares: metagabbros

Fig. 6: FeO^* against FeO^*/MgO (after MIYASHIRO, 1975) and AFM triangle (after IRVINE & BARAGAR, 1971). The amphibolites show clearly a tholeiitic trend.

Σχήμα 6. FeO^* προς FeO^*/MgO (κατά MIYASHIRO, 1975) και τρίγωνο AFM (κατά IRVINE & BARAGAR, 1971). Οι αμφιβολίτες δείχνουν σαφή θολεϊιτική τάση.

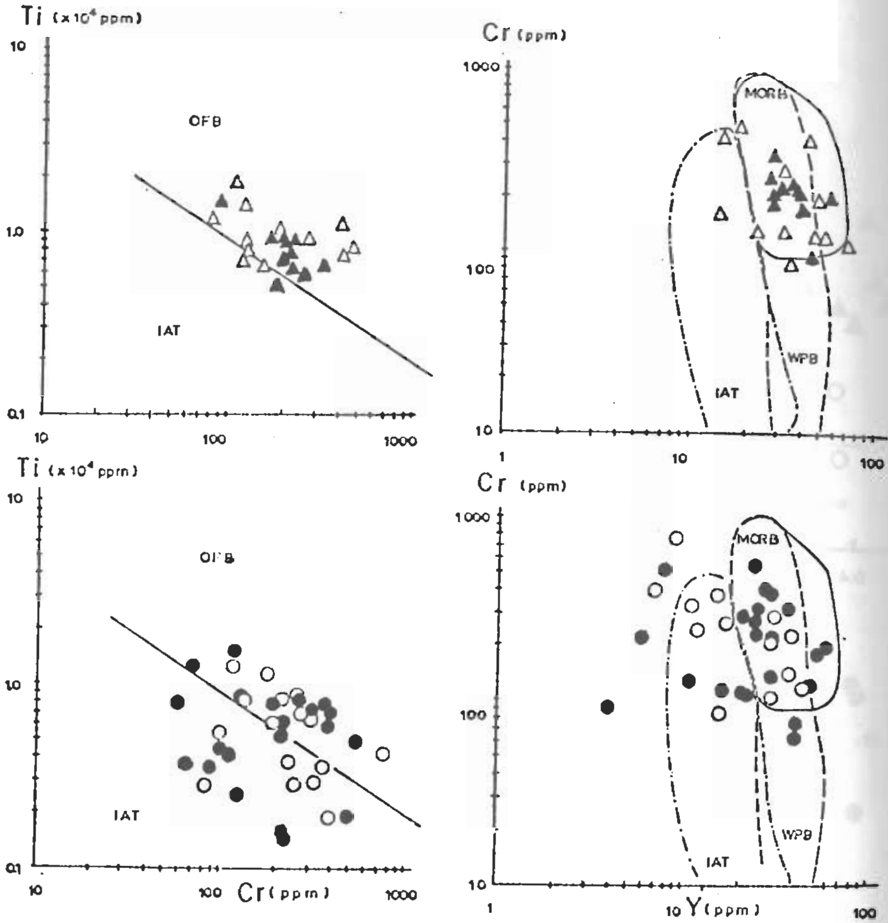


Fig. 7: Ti-Cr (after PEARCE, 1975) and Cr-Y (after PEARCE, 1979) discriminant diagrams. The amphibolites of Eastern Rhodope are projected both in the IAT and OFB field whereas those of Central Rhodope plot entirely in the OFB field (see text). IAT: island arc tholeiites, OFB: ocean floor basalts.

Σχήμα 7. Διάγραμμα Ti-Cr (κατά PEARCE, 1975) και Cr-Y (κατά PEARCE, 1979). Οι αμφιβολίτες της Ανατολικής Ροδόπης προβάλλονται τόσο στο πεδίο IAT όσο και στο OFB ενώ αυτοί της Κεντρικής Ροδόπης στο πεδίο OFB (βλ. κείμενο).

of typical pelagic sediments indicate that the protoliths of the amphibolites were erupted either in a minor ocean during the initial stages of spreading (Red-Sea type) or in a marginal basin. A marginal basin environment could explain, to some extent, the mixture of arc and spreading-ridge geochemical characteristics.

DISCUSSION AND GEOLOGICAL IMPLICATIONS

The geochemical data, in conjunction with the field observations, reveal a magmatic nature for the amphibolites of the Rhodope Zone. These were tholeiites with affinities to MORB and partly mixed geochemical characteristics with island arc tholeiites.

A remarkable characteristic of the amphibolites is that the island arc geochemical signatures are encountered mainly in the eastern part of the Rhodope Zone. Advancing to the west, towards Central Rhodope, the number of amphibolites with island arc characteristics diminishes while in the area of Xanthi-Echinos these are completely lacking.

Another important point that can be made is the similarity of the geochemical characteristics of the amphibolites of the Rhodope Zone with those of the Serbomacedonian Zone.

According to geochemical data from the Vertiskos and Kerdyllia Series (SAPOUNTZIS et. al. cited in KASSOLI-FOURNARAKI et. al., 1985), the amphibolites of the Serbomacedonian Zone were tholeiites with affinities to ocean floor basalt. In addition, geochemical data from the Olympias area (MANTZOS, 1988) indicate that the amphibolites of this part of the Serbomacedonian Zone were tholeiites possibly erupted in a marginal basin.

If we take into consideration other similarities between the two zones, such as the kind of the last metamorphism (KOCKEL & MOLLAT, 1977) and the age of the last metamorphism (Eocene) (HARRE et al., 1968) it seems that the differences between the Rhodope Zone and Serbomacedonian Zone become fewer and fewer.

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