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METAOPHIOLITE ASSOCIATION IN THE RHODOPE MASSIF AS A STRATIGRAPHICAL AND STRUCTURAL MARKER

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Abstract: The paper is a brief survey of the geological setting and metamorphism of the Metaophiolite Association within the metamorphic basement of the Rhodope Massif on Bulgarian territory. It emphasizes the stable stratigraphic level of metaophiolites in the lower layers of the Variegated Formation of the Rhodopian Supergroup. Usually, they crop out in deep tight synclinal folds between anticlinal structures. On the basis of new geological arguments and lithological analysis that take into consideration the syn-metamorphic deformation and metamorphic changes, an attempt is made to reconstruct the primary lithostratigraphy of the metamorphic complex. In addition, some corrections of the current stratigraphic column and geological map of the Rhodope Massif are also made. The view that fold structures dominate instead of thrusts is affirmed. Geological relationships assume that the most likely way for the integration of serpentinites into the Variegated Formation of the Rhodopian Supergroup was obduction of fragments of serpentinized oceanic crust onto an ancient continent consisting of gneisses of the Prarhodopian Supergroup. The ophiolites have undergone various metamorphic changes: hydrothermal ocean and regional metamorphism in the amphibolite facies, culminating in migmatization. It is suggested that eclogitization occurred in local shear zones within the crust, and not along thrust surfaces or within subduction zones to mantle depth. The Metaophiolite Association is an important marker for the stratigraphic correlation of the metamorphic terranes as well as for the structural and metamorphic evolution of the Rhodope massif basement.

Key words: Rhodope Massif, ophiolites, primary lithostratigraphy, eclogitization.

1. Introduction

The Metaophiolite Association in the Rhodope Massif on Bulgarian territory is an important stratigraphic and structural marker for the reconstruction of the internal structure of the metamorphic basement. It is also a suitable indicator for pre-metamorphic geological settings as well as for metamorphic conditions and tectono-metamorphic evolution.

The investigation of metamorphic terranes always faces three interrelated problems: the internal structure, stratigraphy and metamorphic evolution. For their solution, two approaches are applied. The first, preferred by some regional geologists, represents subdivision of metamorphic terranes into tectonic units, often taking into account only absolute age data. This approach, considered as up-to-date, allows more freedom in the interpretation of geological constructions. On the other hand, combining different metamorphic formations into tectonic units is often accompanied by subjective evaluation and sometimes it may lead to significant discrepancy between the concepts and the real geological picture. The second, a traditional lithostratigraphic approach, requires extensive investigations, an extended database for the composition, relationships between the lithostratigraphic units, micro- and meso-scale deformations, and metamorphic petrology. But at the same time it gives a more reliable basis for characterization of the metamorphic terranes.

The Metaophiolite Association with its specific rock composition marks distinct stratigraphic layers and allows the tectonic structure to be decoded. The aim of this paper is to focus attention on some questions concerning mainly the stratigraphic and structural level of the Metaophiolite Association, based on actual geological studies. Clarifying these questions will contribute to a better understanding of both the genesis and metamorphic development of the Metaophiolite Association and the whole Rhodope Massif.

2. Geological settings of the Rhodopian Metaophiolite Association (RMOA)

The primary ophiolite rocks represented by serpentinized harzburgites, gabbros, low potassium-high magnesium tholeiites and tuffs underwent polymetamorphic alteration in different facies and were altered under different metamorphic conditions. As a result, talc-chlorite-actinolite schists, amphibolites, eclogites, pyroxenites, garnet lherzolites and metasomatic gabbroids were produced. The sequence of their formation marks several phases in the metamorphic evolution of the high-grade basement. The ophiolites are not regularly distributed in the Rhodope Massif. They appear widely in the Western and Eastern Rhodopes, where the largest serpentinite bodies and abundant metavolcanics are located, while in the Central Rhodope their appearance is restricted.

3. Stratigraphic position of the RMOA

The well-stratified metamorphic basement of the Rhodope massif is divided into two supergroups: Prarhodopian (PRS) and Rhodopian (RS). The ophiolitic association always has a stable stratigraphic position in the lower levels of the Rhodopian Supergroup. Nowhere does it mark sutures, thrust surfaces or subduction zones as some authors consider (Burg et al., 1990; Sokoutis et al., 1993; Haydoutov et al., 2004). The actual stratigraphic scheme of the metamorphic basement in the Rhodope Massif (Kozhoukharov et al. 1988) represents the sequence of lithostratigraphic units established after metamorphic consolidation of the high-grade basement involving all fold and fault deformations. Nevertheless, the stratigraphic sequence is sufficiently well preserved to allow the original pre-metamorphic sequence to be restored.

A suite of reliable criteria have been used to reconstruct the primary rock composition and relationships of the lithological units, sequences and features of different metamorphic events, periods of hiatus in the evolution, marked by transgression, igneous intrusion or discordance (Kozhoukharova, 2008). The pre-metamorphic reconstruction model distinguishes two lithological complexes (Fig. 1). The lower one is an ancient infracrustal continental complex, the PRS, consisting of highly reworked para- and ortho-metamorphic gneisses, complemented by leptite or porphyroblastic gneisses. The absence of marbles is a specific feature of the PRS. All rocks had already been metamorphosed before the deposition of the upper RS rock complex. Cadomian, Hercynian and Alpine granitoid magmas and several generations of their aplite-pegmatite vein-like derivates penetrated the complex, causing migmatization, granitization, feldspathization and reheating, particularly more intensively in the deeper stratigraphic levels. As a result, the PRS was enriched in components like Si, Al, Na, K, Ba, Rb, Cs, Zr and obtained the geochemical signature of granite-granodiorite. Subsequently, superimposed metasomatic processes considerably altered the composition and structure of the protolith, to the extent that it can be identified only by geochemical methods. The Prarhodopian Supergroup forms the core of anticlines and dome structures (Fig. 1).

The Rhodopian Supergroup (RS) is a new transgressively deposited typical supracrustal variegated complex, consisting of metamorphosed volcanogenic-sedimentary rocks. Its primary rocks were flyschoid pelite-calcareous sediments (Variegated Formation - VF), overlain by limestones (Marble Formation - MF). The ophiolites occupy the lower levels of the VF, where they alternate with or are covered by sediments or are intercalated with them (Fig. 2). A clear lateral variation is observed in the primary composition of the VF.

Two types of VF are distinguished: a) the West Rhodopian (Satovcha) type, and b) the Central Rhodopian (Loukovitsa) type (Fig. 2).

a) The West Rhodopian (Satovcha) type of VF represents a rock assemblage formed in regions with abundant basic volcanism. The volume of basic-ultrabasic orthometamorphic rocks prevails over parametamorphic rocks (Fig. 2). The VF usually commences with ophiolites (serpentinites or amphibolites) lying directly on gneisses of the Prarhodopian Supergroup. Serpentinite lenses and megaboudins of variable size (from several meters to 10-12 km long) are associated with amphibolites. The VF continues upwards as a thick sequence of layered and massive medium- to coarse-grained amphibolites, actinolite-chlorite and biotite schists, interleaved with graphite-bearing garnet quartzites and magnetite-haematite jaspilites. The bulk sedimentation was contaminated by volcanic tuffs, while only very thin and rare calcareous or aluminium-rich metapelite layers appear in the upper levels of the VF. Fine-grained amphibolite dykes, often enriched in ore minerals, cross-cut the layered amphibolites and serpentinites. Rare small gneiss xenoliths with sharp contours, ripped from the sole, occur among the amphibolites. The chemical composition of the amphibolites corresponds to normal and high magnesium arc tholeiitic and picritic basalts. The Satovcha type of VF is widespread in the Western Rhodope – the valley of Mesta river, and in the Eastern Rhodope – Byala Reka dome, Avren syncline, Chakalarovo syncline and Drangovo horst.

The Kimi Complex, assigned to an "Upper tectonic unit" (Mposkos and Kostopoulos, 2001) in the Eastern Rhodopes on Greek territory, is a direct prolongation of the Vucha Variegated Formation from the Avren syncline (Fig. 1).

volcanism in lower levels of the VF, there are variably thick layers (2-3 to 200-400 m) of porphyroblastic gneisses. The gneiss protoliths are believed to have been coarse-grained or fine clastic sands, rather than porphyroid granite. In the Sakar region the porphyroblastic gneisses are overlain by metaconglomerates. They presumably marked an abrupt change in the palaeoenvironmental setting before the formation of the ophiolite association. The obduction of ophiolite fragments from ocean crust is more likely at present. They ended up in a marginal sea where they were covered by sedi-

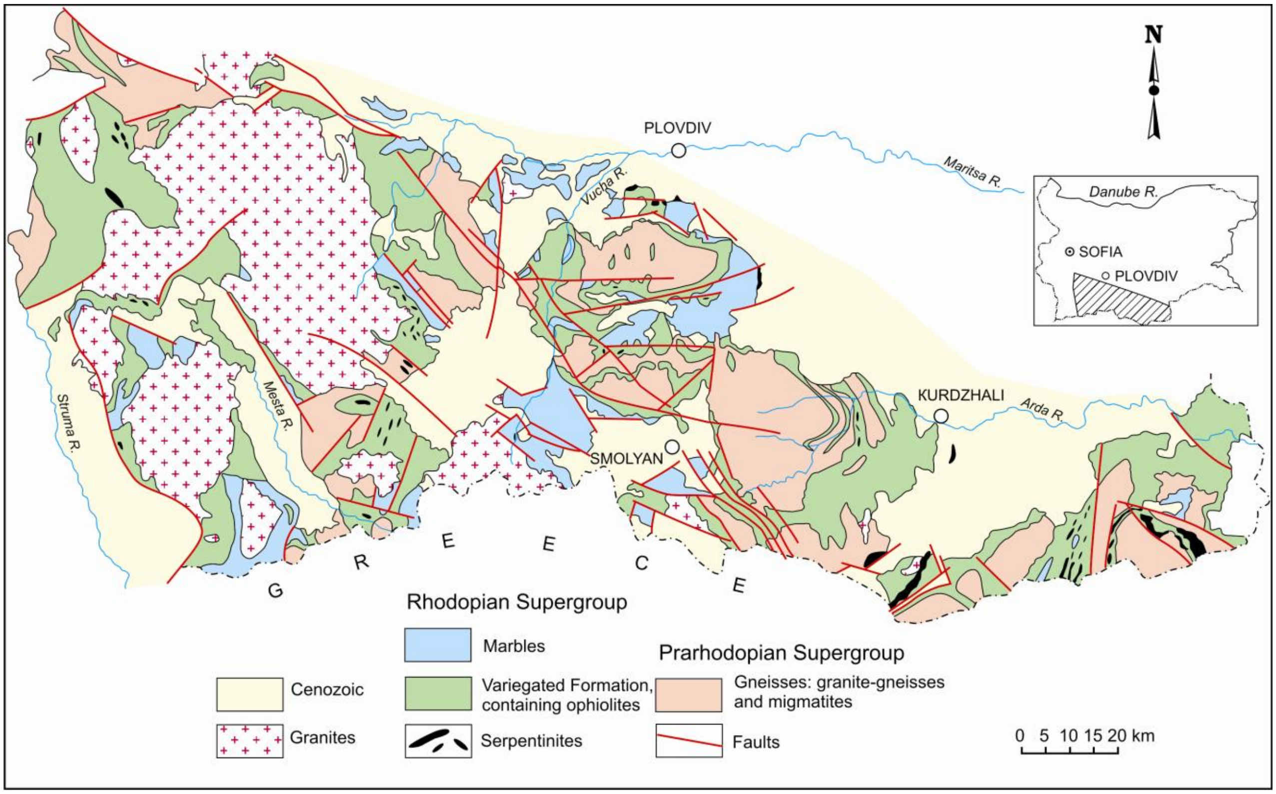

Fig 1. Geological map of the main lithostratigraphy metamorphic units in the Rhodope Massif.

b) The Central Rhodopian (Lukovitsa) type of VF consists mainly of alternating metapelites altered to biotite and two-mica schists (some of them kyanite-bearing), marbles, calc-schists and a few quartzites. Thin layers of amphibolite and lenses of serpentinite occur in the lower stratigraphic levels of the VF (Fig. 2). In some areas of the Central Rhodope (Northern Rhodope anticline), the amphibolites are connected to a sub-volcanic metadiabase body which cross-cuts the leptite gneisses from the base of the VF and includes xenoliths of them. In places beyond the volcanic zones, calcareous and alumina-rich pelites (future marbles and kyanite schists) are more widespread.

Furthermore, in the region of previously active

ments (Kozhoukharova, 2008). The composition of the basic metavolcanic rocks suggests arc tholeiites. Evidence for an autochthonous volcanic origin of the amphibolites includes: relict igneous texture, xenoliths of leptite gneisses derived from the basement, and basic dykes cross-cutting the gneisses of the PRS. These facts suggest possible initial rifting of the ancient continental fragment.

4. Structural position of the RMOA

The Prarhodopian and Rhodopian supergroups were subjected to synmetamorphic folding at least twice. In the general synmetamorphic structural plan, domes and linear positive structures are observed, whose cores consist of gneisses of the PRS.

The spaces between them contain pinched subvertical, inclined or recumbent synclines, filled by rocks of the Variegated Formation containing ophiolites. The largest of the typical inclined and recumbent synclines are: West Rhodopes-Debren syncline, Central Rhodopes-Ardino syncline and East Rhodopes-Zhalti Chal syncline. The last is a complicated doubly folded inclined syncline, such that the serpentinite bodies have been deformed into megaboudins (Fig. 1). The main direction of linear structures in the Central Rhodopes is E-W with a southern vergence, while in the East Rhodopes the direction changes to NNE-SSW (Avren syncline) but later also to NW-SE (Zhalti Chal syncline). The folds observed in the northern part of the West Rhodopes have mainly a NW-SE orientation and are inclined to the SE. They are obliquely cut by the Rila-Rhodopian granite batholith (Fig. 1). In the southern part of the West Rhodopes a later NE-SW direction was imposed (Fig. 1). Usually, the morphology of the folds is variable, and in addition they are complicated by minor isoclines along their limbs. The boudinage structure of the whole Variegated Formation and enclosed ophiolites is clearly expressed. Rod-like structures appear in the axial parts of folds. In places, small fragments of their keels were downfolded into migmatite gneisses, and are now observed as rootless amphibolite or eclogite bodies. In some places the tight synclines become narrow and in their lower parts they pass into shear zones where eclogites and garnet lherzolites occur. An example is the Avren syncline in the Eastern Rhodope, where the ophiolites continue into Northern Greece in the Kimi Complex. A new structural plan was superposed on the earlier synmetamorphic plan during Alpine tectonic reactivation. The folds have a NNE-SSW (10-15^{o}) direction, often associated with retrogression of the metamorphic rocks. Some of the old fold structures were reactivated. Local detachment thrusts formed along the periphery of the Rhodope massif and on the slopes of Palaeogene depressions.

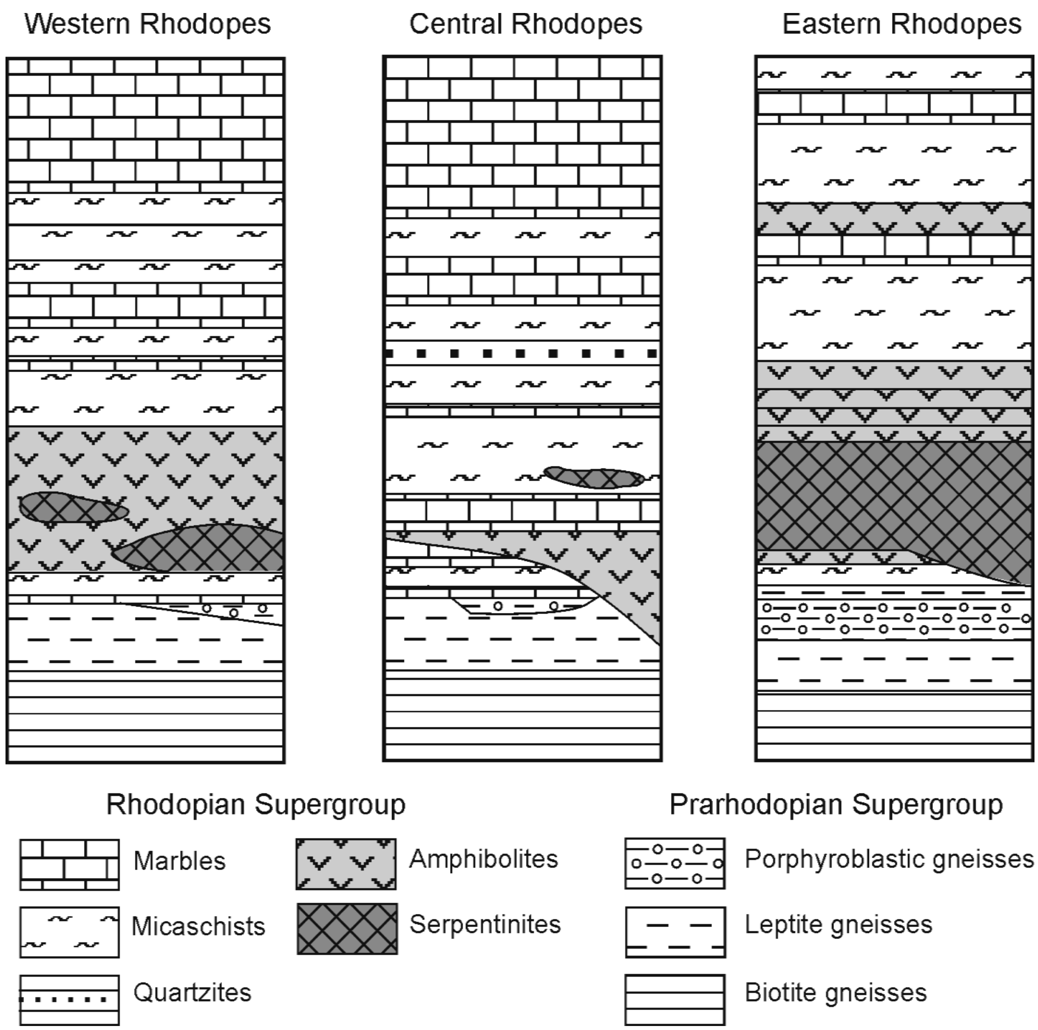

Fig. 2. Generalized lithostratigraphic columns of the Variegated Formation.

5. Brief remarks about the evolution and metamorphism of the Metaophiolitic Association

The primary ophiolite rocks such as serpentinites, gabbros, gabbro-norites, low potassium-high magnesium tholeiites and tuffs underwent polymetamorphic alteration in different facies. Several stages of metamorphism have been identified.

1. Hydrothermal ocean metamorphism – lizardite-chrysotile serpentinitization of peridotites took place in a hydrous environment.

2. Proterozoic tectonic episode – obduction of oceanic crustal fragments (serpentinites) over the marginal parts of an ancient Precambrian continent consisting of Prarhodopian gneisses (metamorphosed during the first Precambrian cycle); igneous activity expressed as basic volcanic and intrusive rocks; sedimentation of politic-calcareous flyschoid sediments that cover the serpentinites. The marbles contain Mesoproterozoic to Neoproterozoic microfossils (Kozhoukharov and Timofeev, 1989; Tchoumatchenko and Sapunov, 1989), indicating a Precambrian age for the ophiolites.

3. Second Precambrian cycle. Regional metamorphism took place generally in the amphibolite facies and synchronous folding of the Rhodopian Supergroup. Two or in some places three metamorphic episodes, marked by two or three consequent mineral assemblages, separated by deformation, were distinguished in the mica schists. Serpentinite bodies have been replaced at their margins by talc-chlorite-actinolite schists. Basic volcanic rocks were transformed into various amphibolites at T = 480-540 ^{o}C and P = 4-6 kbar. Eclogitization took place in local narrow ductile shear zones in the amphibolites, producing omphacite-garnet-rutile assemblages at T = 450-550 ^{o}C and P = 9-12 kbar, while the dominant metamorphism of the country rocks is medium-pressure amphibolite facies (Kozhoukharova, 1980; 1996).

An instructive example for eclogitization “in situ” represents Gr-lherzolite bands within a serpentinite body in the Avren syncline in the Eastern Rhodope (Kozhoukharova, 1996;1999). Thin 1-2 cm stripes, consisting of garnet, enstatite, diopside, olivine and spinel alternate with serpentine bands. The stripes gradually disappear towards the central parts of the body. The P-T conditions of crystallization in the zones is in the range 560-811 ^{o}C/8-15 kbar, while in the country rocks they are 480-540 ^{o}C/4-6 kbar (Fig. 3). The arguments for a metamorphic origin are: lherzolite banded segregations are displayed only at the lithological contact of serpentinite bodies, entirely concordant with the general stratification and metamorphic schistosity of the rock complex; eclogite minerals everywhere replace serpentine, but they themselves are not deformed and altered; Gr-lherzolites are found only in the strongly folded synclines.

The same serpentinite body continues into Northern Greece in the Kimi Complex. Mposkos and Kostopoulos (2001) reported the discovery of microdiamond and coesite inclusions in garnet from eclogites and metapelites. The authors considered that these facts alone are enough to conclude that the rocks had once been transported by subduction to depths exceeding 220 km. However, the ensemble of all the geological and petrographic features of metamorphic complexes in the Rhodope massif does not favour such a traditional decision.

Eclogitization develops locally only in the confined space of shear zones, where a new HP heterofacial mineral assemblage crystallizes synchronously with the dominant amphibolite facies metamorphism of the country rocks (Fig. 3). Preservation of serpentine proves that the temperature of the dominant regional metamorphism does not exceed 580 ^{o}C. Isotopic data indicate a Neoproterozoic age of 610 Ma for the eclogites from the Central Rhodope (Arcadaskiy et al., 2003) and 572±5 Ma for the amphibolites from the Eastern Rhodope (Haydoutov et al., 2004).

The ophiolites located within zones of migmatization and granitization (Cadomian or Hercynian age) are intensively affected by feldspathization and metasomatic processes. Locally, swarms of pegmatite veins cut the serpentinites and form “dykes” of metasomatic gabbroids with xenoliths of partially assimilated serpentinites. Chemical interaction between the serpentinites or amphibolites and aplite-pegmatite veins resulted in various metasomatic gabbroids, outwardly resembling igneous rocks. They are of variable appearance and structure: massive, agglomeratic, streaky, lenticular or schistose. Often lens-shaped segregations of plagioclase with variable anorthite content (from oligoclase to bytownite-anorthite) form a specific spotted (“leopard”) structure. Other grey-greenish segregations (which represent reworked ultrabasic inclusions in pegmatite veins), consisting of olivine, pyroxene, amphibole, garnet, talc and chlorite, show reaction textures: coronas, corrosion relationships, different types of pseudomorphs, symplectites and diablastic intergrowths. The formation of metasomatic gabbroids at the expense of basic and ultrabasic ophiolites can be observed at many locations in the Rhodope massif. In the early stages of regional metamorphism, the alteration of ophiolites has a nearly isochemical recrystallization in a compressive regime. During later stages, during decompression, increased mobility of the components occurred and the metamorphism passes into clear metasomatic alteration and assimilation of ophiolites.

6. Discussion

The stable stratigraphic position of the Metaophiolitic Association within the sequence of the Variegated Formation (Rhodope Supergroup) refutes the hypothesis of late post-metamorphic incorporation of the ophiolites into the basement. Nowhere do ophiolites or serpentinites mark sutures, thrust surfaces or deep faults. The ophiolites as an integral part of the volcano-sedimentary Variegated Formation are synchronous with the transgressive Neoproterozoic sedimentation of the Rhodopian Supergroup. It is proposed that only the serpentinites were tectonically obducted onto the margin of an ancient continental fragment (the Prarhodopian Supergroup), where they were covered by pelitic-carbonate sediments.

The problem of the origin of eclogites in the Rhodope Massif is similar. The eclogites are not exotic bodies uplifted from mantle depths, and they are always located amongst the ophiolitic amphibolites. Mposkos and Krohe (2006) supposed that the Kimi complex in Northern Greece was subducted to mantle depths (150-200 km), and then rapidly exhumed. But the Kimi complex is not an isolated block, rather it is a direct continuation of the Variegated Formation of the Rhodopian Supergroup cropping out in the Avren syncline and in the whole Rhodope Massif. It is impossible to believe that the whole Rhodope Massif passed through a subduction zone of high deformation, reached mantle depths and was then exhumed, retaining untouched its stratigraphy and fold structures. It is also inexplicable how the serpentine (for which temperature stability reaches only to 580–600°C) was not affected by the extreme P/T conditions. It must be mentioned that reserpentinization in any metamorphic complex in the Earth`s crust is impossible.

On the other hand, the presence of microdiamonds and coesite in the metamorphic rocks is not a sufficient argument for crystallization at mantle depths. A number of experimental data in tribochemistry and tribology provide a new point of view about the realization of high temperatures and pressures in zones of friction, sufficient for the crystallization of diamond and coesite (Kozhoukharova, 2008a).

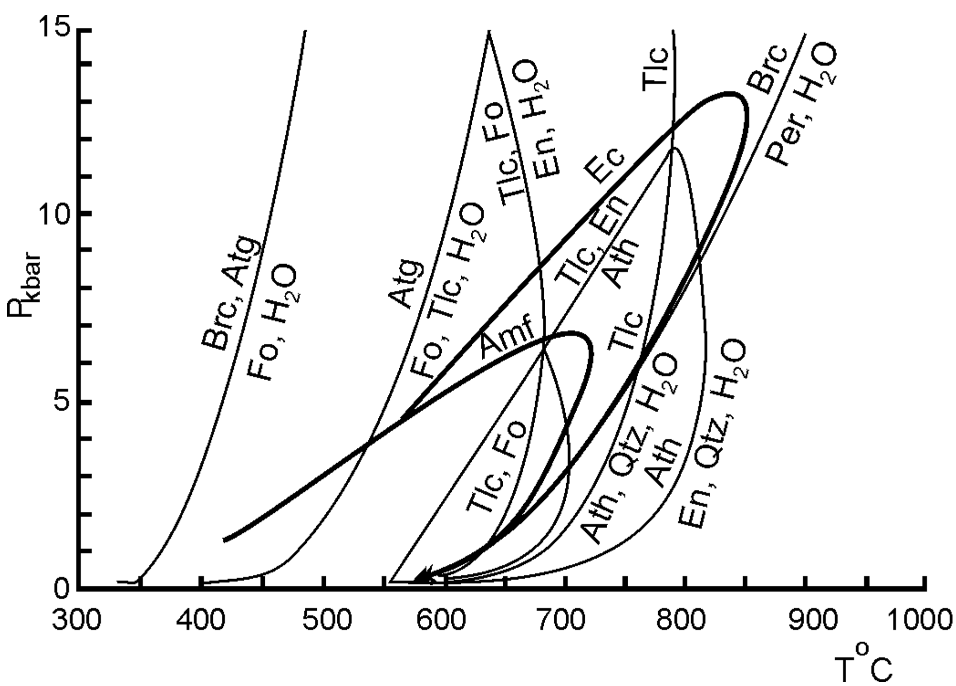

Fig 3. Schematic petrogenetical grid after Spear (1993) with two branches of regional metamorphism: Ec-eclogite facies; Amf-amphibolite facies.

The configuration of the Variegated Formations that contain ophiolites clearly outlines the fold structures in the metamorphic basement (Fig. 1). The idea that the Rhodope Massif represents an Alpine building – a "pile" of several discordant tectonic plates separated by Cretaceous sediments allegedly containing Mesozoic microfossils (Burg et al., 1996), remains unproven. No detailed geological maps, cross sections, descriptions of real tangible overthrusts and their contacts, have been published, except for a few simplified sketches. The alleged Cretaceous sediments have also not been proven, and were later demonstrated to be cataclastic mylonitized marble and calc-schists. The deformation microstructures, shown by the authors cited as evidence for thrusting, are usually observed in all metamorphic rocks that suffered folding. However, it seems that the above-mentioned authors (Burg et al., 1996) probably abandoned the thrust concept, admitting the existence of the Kessebir–Kardamos anticline (Bonev et al., 2006).

7. Conclusions

1) The pre-metamorphic stratigraphy of the Rhodopian Supergroup is represented by two main groups: a lower Variegated Formation and an upper Limestone Formation.

2) The ophiolites occupy a fixed stratigraphic level in the lower part of the Variegated Formation. Nowhere do they mark subduction zones, sutures or thrust surfaces.

3) Eclogites and Gr-lherzolite are crustal metamorphic products after ophiolites; they crystallized locally in narrow ductile shear zones, where HP-metamorphism took place, evidently during syn-metamorphic folding of the complexes. The dominant regional metamorphism is medium-pressure amphibolite facies. Heterofacies mineral assemblages were produced.

4) Feldspathization and granitization caused partial gabbroidization, dioritization and assimilation of the ophiolites at zones of active migmatization.

5) The age of the ophiolite protolith is Mesoproterozoic to Neoproterozoic.

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