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# METAMORPHIC ZONATION IN NORTHERN GREECE, AND ITS BEARING ON THE EOHELLENIC OBDUCTION ISSUE

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## ABSTRACT

The ophiolites of Northern Greece are generally ascribed to a late Vardar ocean, sutured during the Late Jurassic-Early Cretaceous Eohellenic phase. This interpretation is not supported by the broad metamorphic zonation of N-Greece. The most recent works result in a strong NE-SW polarity, going from the inner Rhodope to the External Hellenides. It is characterised by a decreasing age and grade of the HP-LT metamorphic events, from Eohellenic eclogites in the Rhodope nappes to Hellenic blueschist facies in the Pelagonian, thrust over the lower grade, Eocene flysch. In a typical subduction-obduction-collision belt such as the Alps, the suture zone runs within the innermost, Eoalpine eclogitic domain. In the obduction belt of the Oman mountains, which can represent a stage of the Eohellenic evolution, the oceanic homeland of the ophiolite is located on the inner side of the higher grade HP-LT rocks (eclogites), developed in the deformed continental margin. We suggest that, on the Hellenic transect, the Tethyan suture has to be found to the NE of the Rhodope massif, not in the Vardar zone.

## INTRODUCTION

The origin of the ophiolites of Northern Greece (Fig. 1), thrust over the Pelagonian units during the Late Jurassic-Early Cretaceous, Eohellenic phase, is a long debated issue (see Ricou et al., 1986, and Surmont et al., 1991, with references therein). Most authors accept an origin from the Vardar (Axios) zone, which would be a suture between two continental domains, the Pelagonian to the SW, and the Rhodopian to the NE. This view roots mainly in i) the major extension of the ophiolitic outcrops in the Vardar zone, with respect to the adjacent zones; and ii) the former conception of the Rhodopian - Serbo-Macedonian domain beeing an old continental block ("zwischengebirge") surrounded by the Hellenic and Balkanic branchs of the Alpine-Himalayan belt.

The theory of a passive, Rhodopian intermediate block was progressively abandoned in recent years, and replaced by the view of a reactivated, polymetamorpic crystalline mass associated with metasediments, and deeply involved in the Alpine orogeny. Nappe structures and high-grade metamorphism, included eclogitic relics, were described there, and reported to the Eohellenic-Hellenic evolution (see below). Thus, the regional setting of the Vardarian-Pelagonian ophiolites is dramatically changed, and we feel an urge to re-examine the problem of the location of the ophiolitic suture in this renewed geological frame.

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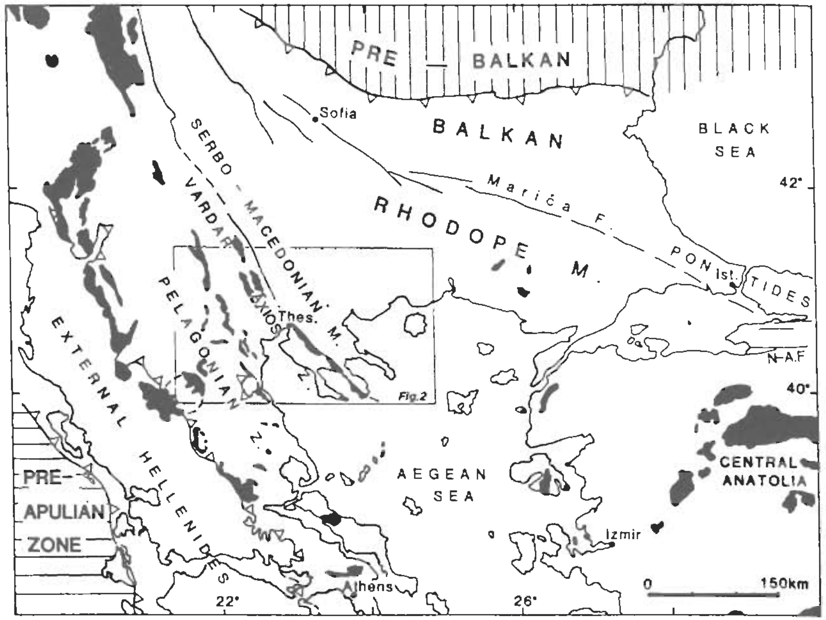


Fig. 1: Location of the studied area (framed) in the Balkano-Hellenic transect of the Alpine zone between Europe (vertically ruled) and Africa (horizontally ruled). Black: ophiolites. Simplified after Biju-Duval et al., 1974.

In the present paper, we address the question using metamorphic and related structural arguments. Admittedly, metamorphism must be regarded as a major tectonic marker in obduction-collision belts. We will compare the broad metamorphic zonation of Northern Greece to that of two well-documented belts, Western Alps and the Oman Mountains.

## METAMORPHIC ZONATION OF NORTHERN GREECE

It will be described in the frame of the classical tectonic divisions of Northern Greece, taking into account the wealth of more recent publications on the area, and some personal observations. We will distinguish in every case, as far as possible, the share of the Eohellenic = Eoalpine, Late Jurassic-Early Cretaceous events, and that of the Hellenic = Alpine s. str., Tertiary events, keeping in mind that obduction (in the sense of Coleman, 1971, and Michard et al., 1985) was achieved by the earliest.

Starting from the East (Fig. 2), we meet successively with four major domains.

1.- **The Rhodopian domain** *sensu lato*, including the Serbo-Macedonian massif. It is characterized by polymetamorphic, crystalline units associated with undated metasediments (marbles, calcschists). The general structure is that of an upwarped pile of nappes (Papanikolaou and Panagopoulos, 1981; Ivanov, 1988; Burg et al., 1990). Thrusting was mainly to the southwest, and at least during the latest phase, dated as Late Eocene (Papanikolaou, 1981; Burg et al., 1990; Kilias



and Mountrakis, 1991). An early, HP-LT metamorphic evolution has been documented by eclogitic relics from various areas (Liati, 1986; Kolceva et al., 1986; Mposkos, 1989; Liati and Mposkos, 1990; Dimitriadis and Godelitsas, 1991). It was followed by a Barrovian metamorphism, the grade of which changes according to the considered tectonic unit (Mposkos, 1987). In the lowermost unit of the Greek Rhodope, it occurred in the range of the garnet-chloritoid to staurolite-chloritoid zones, whereas it reached the conditions of migmatite formation in the overlying unit.

The chronology of this long metamorphic evolution is still poorly constrained. The eclogite formation likely corresponds to an Eohellenic event (Liati and Mposkos, 1990; Burg et al., 1990, with references therein). Whole rock, Rb/Sr dating of a Serbo-Macedonian gneiss gave ages close to 337 Ma and 113 Ma (Mantzos, 1991). K/Ar dating on horblende concentrates from various amphibolites indicated Eocene to Paleocene ages (Liati, 1986; Celet and Clément, 1991). Uplift and low P/T conditions culminated with the emplacement of numerous Oligocene granitoids, and unconformable, Oligo-Miocene calc-alcaline volcanics.

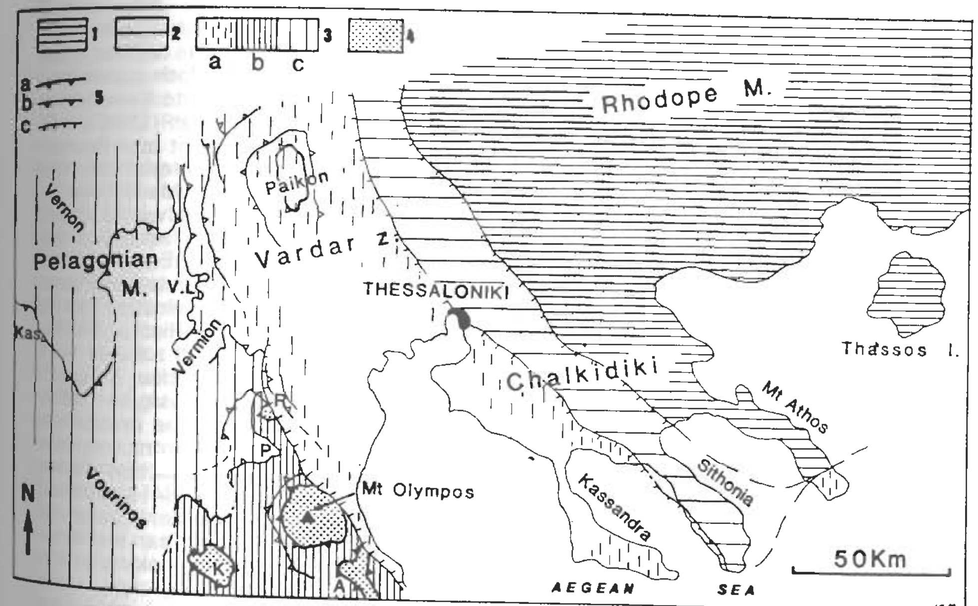


Fig. 2: Sketch map of the metamorphic zonation of Northern Greece. Location: Fig. 1. Structural limits from the Geological map of Greece, 1/500 000, modified after Godfriaux and Ricou, 1991 (Paikon area), and Sfeikos et al., 1991 (M. Olympos area).-1: Rhodopian zone; Eohellenic, eclogite-facies metamorphism, overprinted by Hellenic, Barrovian metamorphism. 2: Circum-Rhodope zone; low-grade HP-greenschist facies, mainly Eohellenic (?). 3: Vardarian-Pelagonian domain; a: very-low grade to low-grade HP-greenschist facies, mainly Hellenic; b: Eohellenic greenschist to blueschist-greenschist metamorphism, overprinted by Hellenic blueschist facies; c: very-low grade to low-grade Eohellenic metamorphism, overprinted by low-grade, Hellenic metamorphism. 4: External Hellenides; late Hellenic, low-grade HP-greenschist facies. 5: Main tectonic contacts; a: Pelagonian basal thrust; b: other thrusts; c: normal faults.- A: Ambelakia; K: Kranea; Kas: Kastoria; P: Pieria Mountain; VL: Vegoritis Lake.

2.- **The Circum-Rhodope zone**. It involves metasedimentary and metavolcanic units of Permo-Triassic to Jurassic age, together with subordinate crystalline and serpentinite slices. It overlies the Rhodopian dome on its eastern and southern (Athos peninsula) boundaries (Maratos and Andronopoulos, 1965; Papanikolaou, 1981). In the Thessaloniki-Chalkidiki area, the faulted contact between both zones is steeply dipping, as are most of the stratigraphic and tectonic planar markers inside the Circum-Rhodope zone itself. The western boundary of the zone, toward the Vardar zone, is a matter of convention. On Fig. 2, we choosed the faulted contact which runs along the eastern border of the Chalkidiki ophiolites, since their continuity with the Vardar ophiolites is established on petrological (Gauthier, 1986) and geophysical grounds (Kiriakidis, 1989; Edel et al., 1991).

The metamorphic grade of the Circum-Rhodope metasediments and metavolcanics is strikingly lower than that of the adjoining (or underlying) Rhodopian zone. It usually ranges in the lower greenschist facies, with local occurrence of chloritoid (Kougoulis et al., 1990), but the phengite substitution of white micas suggest an early, low grade HP-LT event. The age of the metamorphic events is poorly constrained: it is bracketed between the Jurassic age of the Svoula flysch and the 52 Ma radiometric age of the intrusive Sithonia granite (Musallam and Jung, 1986).

3.- **The Vardarian-Pelagonian domain**. On Fig. 2, we joined together the classical Vardar (Axios) and Pelagonian (sensu lato) zones, as defined, for example, in Mountrakis (1984, 1986) or Vergely (1984)'s works. Both zones can be considered as an Eocene pile of nappes involving the composite Eohellenic-Mesohellenic material in the sense of Jacobshagen and Wallbrecher (1985), i.e. the Pelagonian continental rocks (Pelagonian sensu stricto, basement and Permo-Triassic to Jurassic cover), plus the marginal and oceanic material of the Eohellenic nappes (ophiolites and associated sediments), and the Mesohellenic, unconformable cover rocks (Aptian to Paleocene). The Vardar zone would differ from the Pelagonian merely because of its lesser uplift and shallower erosion, the Eohellenic nappe and Mesohellenic sequence (the uppermost units at Eocene time) being better preserved there, and less affected by the Hellenic metamorphism. This view is supported by the recent description of a Pelagonian window in the Paikon Mountain, in the middle of the Vardar zone (Godfriaux and Ricou, 1991). The lowest unit in the core of the window, referred to the Pelagonian zone as well as the overlying unit, has a strong parity with the Circum-Rhodope rocks.

In the Vardarian-Pelagonian nappe domain, the metamorphism is mostly Eocene in age, and therefore its grade changes conspicuously with the position in the tectonic pile. In the Vardar zone, the metamorphic grade ranges from very-low grade (Almopias sub-zone, Vermion nappe) to low-grade HP-greenschist facies (Paikon window). In the latter area, Mercier (1968), and Vergely (1984) described stilpnomelane and lawsonite, for which they suggest an Eohellenic age of crystallisation, based on microstructural arguments. However, we can estimate the grade of the Eohellenic metamorphism in this northeastern area looking at the sub-ophiolitic, Triassic-Jurassic layers of the easternmost Pelagonian units (Vegoritis Lake and Vermion area), since these units and the overlying ophiolites are uncomformably covered by an anchimetamorphic Cretaceous-Paleocene sequence. The Vegoritis Triassic-Jurassic layers include greenish-purple slate intercalations with a low- to very-low grade, muscovite-chlorite assemblage. From these preliminary observations, we conclude that the Eohellenic, obduction-related metamorphism was a low- to very-low grade metamorphism in this part of the Vardarian-Pelagonian domain. If correct, the stilpnomelane-lawsonite assemblages of the Paikon area would be better ascribed to the Eocene HP-LT metamorphism, clearly evidenced to the S and SW of the same domain.

About 50 km south of the Paikon transect, on the western side of the normal fault zone that separates the collapsed Vardar zone from the uplifted Pelagonian (e.g. Kilias et al., 1991), the base (relative autochthon) of the Pelagonian pile of nappe crops out in several antiformal windows (Olympian zone, see below). The lowest Pelagonian nappes (Pierian and Infrapierian units), as well



as the associated Ambelakia nappe underneath, show a strong, blueschist facies recrystallisation, mostly Eocene in age (Godfriaux, 1968; Godfriaux and Ricou, 1991). However, the occurrence of an early, Eohellenic blueschist event was documented on radiometric grounds in equivalent units more to the south (Maluski et al., 1981). In the Mt. Olympos region itself, Shermer et al. (1990) pointed to a greenschist to blueschist-greenschist event at about 100 Ma, followed by a 53-61 Ma blueschist facies metamorphism (40 Ar/39 Ar method). These Authors date the thrusting of the blueschists over the Olympos unit at 36-40 Ma, which is consistent with the stratigraphic data, and the cooling down to 100-150°C, associated to normal faulting of the eastern side of the window, at about 16-23 Ma. The Eocene metamorphic evolution is associated with pervasive, SW-verging kinematic indicators, that can be observed in the nappes and in their relative autochthon, in the Olympos and Kranea windows (Vergely and Mercier, 1990; Kilias et al., 1991; Godfriaux and Ricou, 1991; Sfeikos et al., 1991).

In the northwestern part of the Pelagonian zone, from the Vourinos area to the Vernon massif north of Kastoria, the metamorphic grade seems roughly intermediate between that of the Vardar-Vermion and Pieria-Ambelakia areas. Permo-Triassic formations close to Kastoria were affected by a low-grade greenschist event, possibly superposed to an earlier (but undated) HP-LT event (N. Spyropoulos, pers. comm.). In the mylonitic zones that crosscut the Vernon Hercynian granite (Mountrakis, 1984), the phengitic substitution of the intrafolial white micas associated with Na-amphibole, epidote, albite, biotite relics and K-felspar phenoclasts reaches Si 3.44 (B. Goffé, unpub. data). This indicate P-T conditions in the range of 8-9 kbar at 400°C (Massonne and Schreyer, 1987). Whole rock Rb/Sr dating of these rocks would give ages close to 300 and 60 Ma (Mountrakis, pers. comm.), related to the granite emplacement, and to the synmetamorphic thrust tectonics, respectively. Top-to-the-SW kinematic indicators formed pervasivly during the latter event (Spyropoulos et al., 1986; Kilias and Mountrakis, 1989). As for the obduction-related metamorphism, judging from the Upper Jurassic-Lower Cretaceous mélange beneath the Vourinos ophiolite, two main stages must be distinguished: i) a HT-LP, amphibolite facies metamorphism, dated at about 170-180 Ma, and related to the intra-oceanic detachement of the future ophiolite (Spray and Roddick, 1980); ii) a low- to very-low grade metamorphism coeval with the ophiolite emplacement onto the mélange.

4.- **The External Hellenides**, cropping out below the preceding pile in the Olympian windows (Mt Olympos, Kranea and Rizomata windows: Godfriaux, 1968; Vergely and Mercier, 1990; Sfeikos et al., 1991). This domain remained unaffected by the Eohellenic events, and the sedimentary record is almost continuous from Triassic up to Eocene time (Middle Triassic to Middle Eocene carbonates, Late (?) Eocene flysch). Metamorphism developed at about 36-40 Ma (Shermer et al., 1990). It is of low- to very-low grade. Its P conditions are not clearly constrained up to now. T was about 300°C, except in the upper part of the series (i.e., in the shear zone below the sole thrust of the Pelagonian pile) where it reached 400°C, according to Barton et al. (1979).

## DISCUSSION AND COMPARISONS

1.- **Tectono-metamorphic polarity of N.-Greece.**-From the preceding description, it results that the Alpine belt of Northern Greece has a strong, NE-SW tectono-metamorphic polarity:

- the Eohellenic metamorphism reached the conditions of the eclogite facies in the Rhodopian domain. In the Circum-Rhodope and the Vardarian-Pelagonian domain, it reached that of the greenschist-blueschist transition in some of the lowest units (if the available radiometric datations from the Pierian-Ambelakia units are correct), but did not exceed a very-low grade metamorphism of unknown P/T ratio in the uppermost. Finally, it entirely lacks in the Olympian windows.
- the Hellenic metamorphism occurred in HT-LP conditions in the Rhodopian domain, at least during its latest stages, when it reached the amphibolite facies. Approximately at the same time (Early to Middle Eocene), it occurred in HP-LT

conditions in the Pelagonian zone s.l. (included the Eohellenic nappes and the Ambelakia unit), reaching the blueschist facies in the deepest units. Metamorphism developed some time later (Late Eocene) in the inner part of the External Hellenides (Olympian windows), when the Pelagonian nappes emplaced on it.

- an overwhelming majority of kinematic indicators related to the Tertiary metamorphic evolution show a top-to the SW direction of mouvement, should it be in the Rhodopian domain or in the Pelagonian.

It is therefore logical to consider the Rhodopian domain, which is no longer an "hinterland" for the Alpine belt of Northern Greece, as one of the Internal zones of the belt, if not the innermost. If we compare this pattern with that of well-documented Tethyan belts, such as the Western Alps and the Oman Mountains, we are induced to reconsider the location of the Eohellenic suture itself.

2.- **A comparison with the Western Alps.**- The Western Alps belt can be regarded broadly as a mirror image of the Hellenides, verging toward Europe instead of Africa. As for the Hellenides, the Alps were built through a long, polyphased development, involving an Early to Late Cretaceous "Eoalpine" pre-collisional phase (subduction and obduction events), followed by a Mesoalpine-Late Alpine collisional period (e.g. Coward and Dietrich, 1989, with references therein). On a metamorphic map of the belt (Fig. 3), a zonation appears, resulting in a strong transverse polarity. The Eoalpine metamorphism is only known from the most internal zones of the belt, where it is recorded by eclogite relics and associated high-grade metapelites (Goffé and Chopin, 1986). In the same areas, the Mesoalpine metamorphism probably began in HP-LT conditions, but quickly

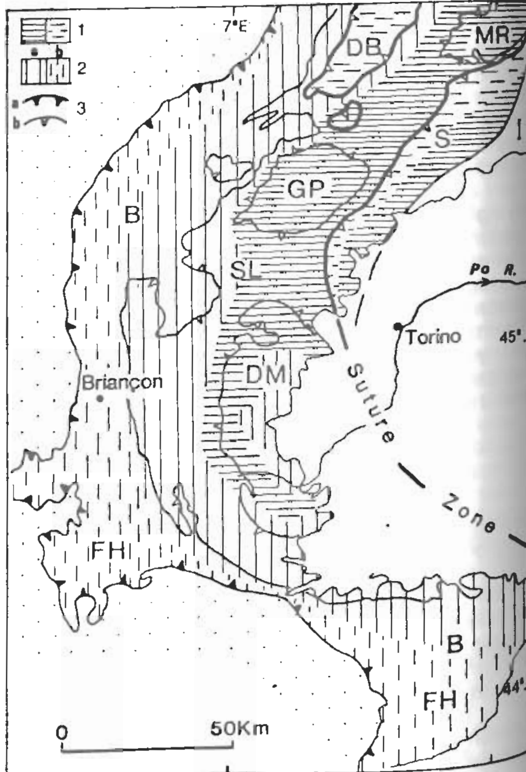


Fig. 3: Sketch map of the Western Alps, showing the location of the suture zone with respect to the broad metamorphic zonation, after Goffé and Chopin, 1986. 1a: Eoalpine eclogite facies, overprinted by Mesoalpine Barrovian metamorphism. 1b: HP-greenschist metamorphism, Eo- and/or Mesoalpine. 2a: Mesoalpine blueschist facies metamorphism, partly overprinted by greenschist facies. 2b: low-grade to very-low grade, Mesoalpine metamorphism. 3a: basal thrust of the Internal (Pennic) zones above the External Alps (dotted). 3b: basal thrust of the ophiolitiferous Schistes Lustrés nappes (SL), above the European units: B, Briançonnais and Sub-Briançonnais, with the overlying Helminthoid Flysch units (FH); MR, Monte Rosa; GP, Gran Paradiso; DM, Dora-Maira. African units: DB: Dent-Blanche; S: Sesia; I: Ivrea zone.



evolved toward Barrovian conditions (Late Eocene-Oligocene Lepontine phase). In contrast, in the frontal part of the Internal zones, the Mesoalpine metamorphism is characterised by blueschists facies assemblages in the deepest units, and by lower-grade assemblages in the uppermost, or more external ones.

The most important observation for our point is that the ophiolitic suture is located within the zones affected by the earlier, and higher-grade metamorphism, and runs along the inner boundary of the Mont-Rose, Grand-Paradis, and Dora-Maira massifs. These upwarped crystalline nappes, where the Lepontine Barrovian metamorphisme left a strong structural imprint, with pervasive, top-to-the-West kinematic indicators (Chopin et al., 1991; Wheeler, 1991), can be compared with the Rhodopian massif. We suggest that the Eohellenic suture zone should also be located somewhere on the eastern side of the Rhodopian massif.

3.- **A comparison with Oman.**- In contrast with both the Hellenides and the Alps, the Oman Mountains did not suffered collision during Tertiary time. Their structure and metamorphism only depend on the Eoalpine, obduction-related thrust tectonics, the age of which is bracketed between 110 and 80 Ma (Michard et al., 1991, with references therein). Although the age of the Oman obduction is somewhat younger than that of Northern Greece, we can suspect that the Oman model fairly represents the state of Northern Greece before the onset of the Tertiary collision. Then, in the southern Oman Mountains near Muscat (Fig. 4), continental rock- units crop out from beneath the ophiolitic nappe, and show a transverse and vertical metamorphic zonation. The higher-grade, eclogite-facies rocks are limited to the deepest and innermost (north-easternmost) units, the blueschists-facies and lower-grade units extend above, and mostly on the external side of the eclogitic zone.

Again, the important point is that the ophiolite homeland is located on the inner side of the eclogitic zone, and, more generally, on the inner (oceanic) side of the metamorphic area that developed in the continental margin at the time of obduction (or roughly at that time). In contrast, the larger part of the Oman ophiolite extends outside of this metamorphic margin, and overlies low- to very-low grade continental rocks and mélanges. In this external part of the Oman Mountains, the only high-grade rocks left are the amphibolites of the infra-ophiolitic sole, formed during the intra-oceanic detachement of the future ophiolite, at about 100 Ma. The latter situation closely compare with that of the supra-Pelagonian ophiolitic inliers such as the Vourinos massif, whereas the HP-LT metamorphic margin of the Muscat area would compare with the Rhodopian area, before the Tertiary collision.

4.- **A proposal, and some questions.**- Comparing the metamorphic zonation of Northern Greece with that of Oman and the Alps, and the broad polarity of the belt, we can suggest that the Eohellenic suture zone was located to the northeast of the Rhodopian domain. This domain, or some part of it, rather than the Pelagonian, would represent the continental margin first affected by the contractional and metamorphic events related to the Eohellenic obduction, some time after the intra-oceanic detachement of the ophiolite. If correct, the Vardar zone would no longer represent the Tethyan suture, but only a Tertiary structural zone.

This proposal first raises the question of the precise location of the alleged eastern suture. It seems that the Bulgarian Marica zone could be a good candidate for this suture (I. Godfriaux, pers. comm.). Without entering the problem (see Burg et al., this volume), we can observe that meta-ophiolites (included ultramafics) are represented in the northern and eastern parts of the Rhodope Mountains.

Our hypothesis also raises the question of the chronological consistency of obduction and metamorphism. In fact, the Northern Greece ophiolites were detached by intra-oceanic shearing as soon as 180-170 Ma (Spray and Roddick, 1980), which is equivalent to the 172±5 Ma age of a gabbro dyke from the Thessaloniki ophiolite (Kreuzer, citated by Musallam and Jung, 1986). But the future ophiolites likely remained immersed or partly immersed as an island arc area

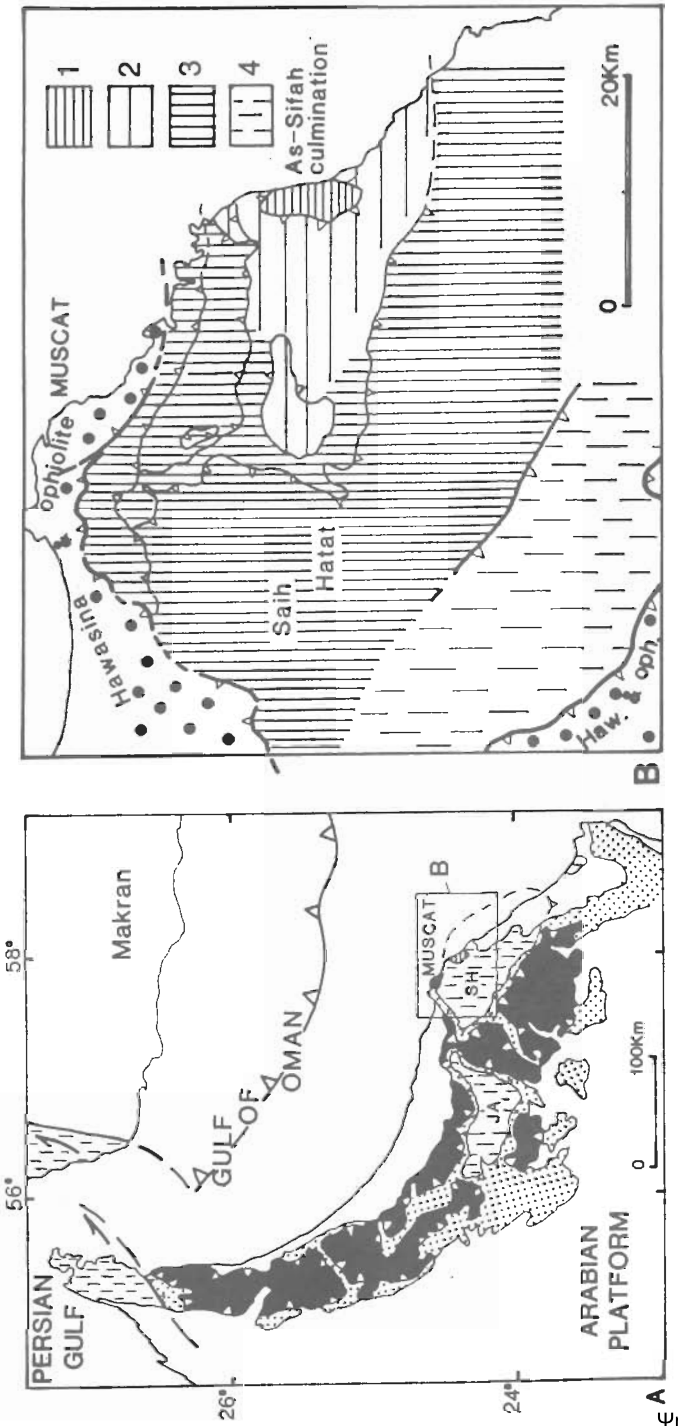


Fig. 4: Metamorphic zonation of the Arabian deformed continental margin under the Oman obduction, after Michard et al., 1985, 1991. A: Extension of the ophiolitic slab (black) and underlying, pre-oceanic Hawasina formations (dotted), thrust over the continental units (vertical dashes); location of the metamorphic area in the innermost part of deformed margin, Saih Hatat window (SH). Major contact in the Gulf of Oman: Makran subduction (teeth toward the upper plate), i.e. approximate location of the future suture.- B: detailed metamorphic zonation in the Saih Hatat window. 1: eclogite facies, mostly overprinted by blueschist-greenschist assemblages. 2: blueschist-greenschist facies metamorphism, mostly retromorphic. 3: low-grade, HP-LT assemblages (glaucophane-lawsonite, carpholite-pyrophyllite or carpholite kaolinite, aragonite). 4: very-low grade assemblages (illite-chlorite).



until Late Jurassic time, as shown by the ages of 156 to 147 Ma of the granitoid intrusions linked to some of these ophiolites, and by the occurrence of late Kimmeridgian reefal sediments on top of them (Bébien, 1982, 1991; Musallam and Jung, 1991). This is consistent with the Tithonian-Aptian age of thrusting of the ophiolites onto the Pelagonian zone, and with the 113 Ma dating of the Rhodopian early metamorphism, reported above.

Another issue is that of the thickness of the Eohellenic overload upon the Rhodopian-Pelagonian continent. The eclogite-bearing, Rhodopian units must have been overloaded by an almost 50 km-thick lithospheric wedge, while the Pelagonian domain to the southwest only received thin (10 km or so) ophiolitic slabs. How to explain the exhumation of the Rhodopian rocks from such great depth before Eocene? Moreover, how to account for the superposition of the low-grade, Circum-Rhodope rocks to the high-grade Rhodope? In fact, the same problem is faced in the Alps and Oman, and generally answered by invoking some sort of extensional process, combined with contraction and erosion (e.g. Wheeler, with references therein). It is also familiar to the Aegean geologists (Gautier et al., 1990; Avigad et al., 1991). Taking into account the few P-T-t and kinematic data available in our case, we can suggest, as a mere working hypothesis, the following evolution. Extensional unloading of the Rhodopian area would have operated first by NE-directed movements, which would have replaced the thick lithospheric wedge by the thinner Vardar-Pelagonian composite slab, involving the Circum-Rhodope slices at its base. Then, during Eocene-Oligocene time, i.e. during and after the contractional evolution leading to the HP-LT metamorphism in the deepest Pelagonian units, the exhumation of the Rhodopian units would have occurred by SW-directed, low-angle normal faults (cf pervasive, SW-verging kinematic indicators in the Rhodopian, Circum-Rhodopian and Pelagonian nappes, as well as the importance of Oligocene granitoid intrusions in the Rhodope domain).

## CONCLUSION

We used metamorphic arguments to discuss the location of the ophiolitic suture of Northern Greece. This approach possibly will seem surprising to some people more familiar with stratigraphic and structural arguments. However, it must be admitted that metamorphic imprints are highly significant with respect to major tectonic processes such as subduction, obduction, collision, and correlative thrusting events.

Our knowledge of the metamorphism in Northern Greece greatly changed in recent years, mainly due to the renewal of the Rhodopian geology. New insights on the structure and metamorphism of the Vardar and Pelagonian zones were also gained recently. It is now possible to recognize a metamorphic zonation going from the inner Rhodope to the external Flysch zones, and essentially characterized by a decreasing age of the metamorphic events, and by their decreasing grade. Comparing this zonation with that which appears, for example, in the Alps and the Oman Mountains, we are induced to suggest that the pre-orogenic continent-ocean boundary was located somewhere on the eastern border of the Rhodope massif. In the northeastern Hellenides, which are a southwest-verging belt, it is not likely to maintain the Eohellenic suture in its classical Vardarian position, as soon as high-grade Eohellenic and Hellenic metamorphic rocks are known more to the northeast.

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