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CRUSTAL-SCALE THRUST COMPLEX IN THE RHODOPE MASSIF. STRUCTURE AND KINEMATICS

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ABSTRACT

Mylonitic gneisses of the Bulgarian and Greek Rhodope were deformed under amphibolite facies conditions of medium pressure type metamorphism. The kinematic information contained on the strain regime and histories of these gneisses shows that ductile, shear-deformation occurred during development of a nappe complex. The nappe complex is characterised by south to southwestward (forelandward) piling-up and both coeval and subsequent extension. Different lithologies, deformation and metamorphic histories permit to distinguish a lower (footwall) and an upper (hangingwall) terranes that define a crustal-scale duplex. As eclogites and oceanic crust are involved, these events mark collision between two continental units followed by crustal thickening.
The two collided blocks would be the Moesian continent to the north, and the Lower-Rhodope promontory to the south. The Lower-Rhodope continental promontory appears between the metamorphic ophiolitic suture described herein, to the northeast, and the Vardar ocean to the southwest. We suggest that the Lower Terrane was a migrating block detached from Eastern Apulia in Anisian times, thus forming the Vardar ocean. It collided with the northern margin of Tethys in Bulgaria during the Cretaceous.

INTRODUCTION

The Rhodope massif was believed to be a stable Precambrian to Hercynian continental block surrounded by two branches of the Alpine-Himalayan collisional system: the Balkan belt to the north, and the Dinarides - Hellenides belt to the south (e.g. Kober 1928; Boncev 1971, 1988; Foose & Manheim 1975; Dewey *et al.* 1973; Hsü *et al.* 1977; Burchfiel 1980). Alternatively, recent interpretations assume that the main, synmetamorphic deformation event is Mesozoic in age and, therefore, link the Rhodope massif with the Alpine-Himalayan orogen (e.g. Burg *et al.* 1990). In effect, rocks underwent multiphase tight to isoclinal recumbent folding that has transposed lithologic contacts into the main-phase foliation plane. There was erosion, tectonic denudation and deposition of colluvial - proluvial sediments unconformable on the metamorphites as soon as Maastrichtian - Paleocene times (Boyanov *et al.* 1982; Goranov & Atanasov 1992). Emplacement of several crystalline sheets at shallow depths occurred during the early Cenozoic (Ivanov *et al.* 1980, 1984, 1985). This was followed by Oligocene extension and rhyolitic volcanism.

This paper deals with the mylonitic gneisses of the Rhodope Massif. They were deformed under amphibolite facies conditions of medium pressure type metamorphism (biotite-garnet-staurolite are common in metapelites) and are examined in the light of the last decade advances in the understanding of microstructure development. Our aims are :

1) To establish the deformation regime and histories indicated by field observations and microstructures of the mylonitic gneisses.

2) To show that significant ductile deformation occurred during formation and emplacement of a large-scale nappe complex.

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3) To integrate the kinematic results on the Rhodope thrust complex in a geodynamic context and to reappraise the collision model of this part of the Alpine-Himalayan collisional system.

DEFORMATION REGIME AND HISTORY

Deformation phases

Regional metamorphism is associated with polyphase deformations characterised by successive and often coaxial generations of folds (e.g. Meyer 1969; Papanikolaou & Panagopoulos 1981; Ivanov *et al.* 1985; Kilias & Mountrakis 1990), which we interpret as a suite of progressively formed sets of structures. Three major deformations are designated D1, D2 and D3.

- D1 corresponds to relics of an early foliation and/or metamorphic layering determined in isoclinal F2 fold hinges.
- D2 is the main fabric forming event coincident with peak metamorphism on the regional scale. It produced the most prominent, shallow-dipping foliation S and isoclinal, recumbent, occasionally sheath folds. A pronounced lineation L is formed by aligned micas and amphiboles, elongated quartz and feldspar grains, and occurs in all rock types parallel to fold hinges. L is also a stretching lineation since it is parallel to streaks of boudinaged grains and deformed xenoliths in orthogneisses.
- The D3 phase encompasses crenulation and several kilometre wavelength folds trending differently according to different areas. Roughly E-W, south-facing folds seem more frequent and N-S, west facing chevron folds are existing in other parts of the area. No time relationship between these sub-perpendicular trends as been identified. Small-scale folds are of similar type with local, axial-planar crenulation cleavage. In analytical terms D3 structures deform the S foliations and represent a distinct deformational event probably diachronous at the regional scale and often related geographically to the numerous intrusions of late tectonic granitoid plutons (Fig. 1).

In this article we are concerned with the D1-D2 event which we refer to as the main-phase deformation. The study is based upon field mapping and oriented rock collection along several traverses in both Bulgaria and Greece. In all the areas investigated the main phase foliation S dips shallow and lineations L are oriented nearly horizontally, striking nearly N-S to NE-SW on a regional scale.

Strain regime and intensity

Reduction in grain size and in porphyroclast content are diagnostic for strain gradients from protomylonites to ultramylonites. In order to assess the kinematic reliability of microstructures we have determined the bulk strain accumulated during the main-phase deformation (location of measurements is given figure 2). To avoid problems of ductility contrasts between matrix and strain marker, spatial distribution of K-feldspar porphyroclasts in the abundant augen-gneisses has been used (Hanna & Fry 1979). We assumed that the principal axes of finite strain are indicated by X the extension axis (lineation), Y the intermediate axis (XY the foliation plane) and Z the axis of shortening (pole to XY). At least two mutually perpendicular section, XZ and YZ, and eventually also XY planes were used to carry out a simple two-dimensional strain analysis. For each specimen the basic two-dimensional strain data were combined to estimate the bulk finite strain ellipsoid. Due to the accuracy of the techniques employed strain values were quoted to one decimal place only and must be considered as approximate. However they provide some valuable information on the shape of the finite strain ellipsoid (K value, Fig. 2) and the intensity (r) of deformation. Consistency of results confirms that the X axis and XY plane of the calculated finite strain ellipsoid were oriented parallel to the specimen lineation and foliation, respectively. They also indicate that deformation took place close to plane strain, that strain intensity is reasonably homogeneous on a regional scale but with marked changes in shear strain (Fig. 2) and that little volume variations were involved.

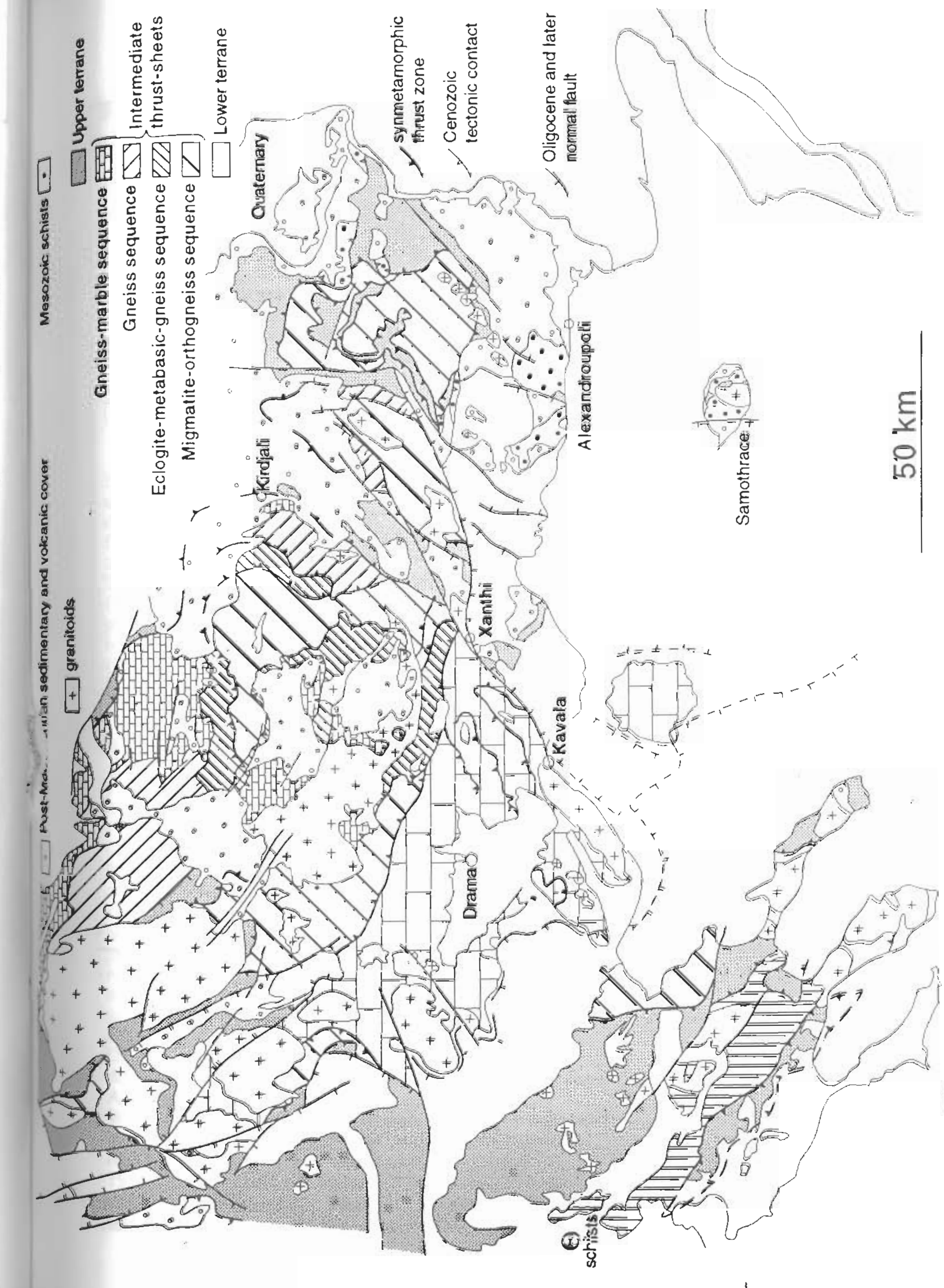

Figure 1 : Sketch map of the Rhodope massif. Θ-schists = Thessaloniki-schists and carbonates

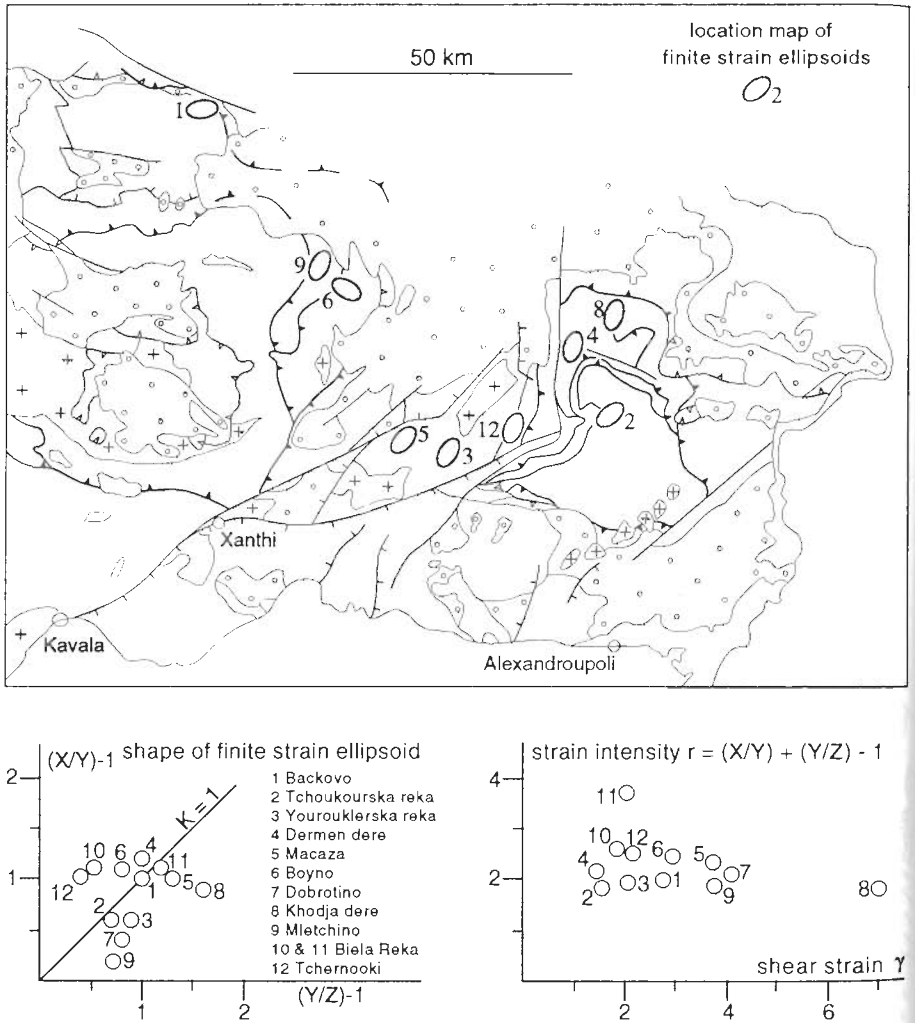

Figure 2 : Location of finite strain measurements presented to exemplify strain in every terranes defined in this article. r is calculated after the equation of Watterson (1968).

Sense-of-shear criteria

Recording of asymmetric microstructures to deduce the sense of shear within the gneissic pile (see review and discussions in Burg *et al.* 1981; Simpson & Schmid 1983; Hanmer & Passchier 1991) has been systematic. Asymmetric microstructures such as displaced broken grains, orientation of spindle-shaped porphyroclasts of mica, feldspar and hornblende, pressure shadows of sigma and delta type, shear-band foliations oblique to S and intrafolial drag folds are common. Where sense of shear could not be determined in the field, observations of saw-cuts and thin sections gave additional information on the asymmetry of shapes and crystallographic fabrics. Since the lineation developed in plane strain, it can be equated with a kinematic direction in dominantly shear regime. A similar approach and conclusion has been reached by other workers (Kilias & Mountrakis 1990; Stavropoulou *et al.* 1991). Each microstructure independently gives variable to opposed, yet regionally consistent answers for the sense and direction of shear of the flow, hence defining different tectonic units that we will discuss in the next section.

SYNMETAMORPHIC THRUST SYSTEM.

Strain gradients from protomylonites to ultramylonites and ubiquitous sense-of-shear criteria indicate that the mylonitic gneisses mentioned above suffered intense, non-coaxial ductile deformation. In addition, the area studied displays a sequence of gently dipping (commonly less than 30°) lithologies and foliations that bear microtectonic evidence for superposition of distinct terranes with contrasting tectonic-metamorphic histories. Therefore, the Rhodope Massif is considered as a region of large-scale nappe tectonics (Fig. 1 and 3). The main-phase foliation contains a dominantly north-northeast lineation pattern defined by isoclinal and exceptionally sheath-fold axes, mineral lineations, and boudinage. Abundant sense-of-shear criteria indicate bulk top-to-south-southwest shear (Fig. 4) also consistant with magmatic fabrics of late, often calc-alkaline granitoids (e.g. Kolocotroni & Dixon 1991) that deform the nappe system into large dome and basin structures (Fig. 1)

Burg *et al.* (1990) have discussed some lines of evidence supporting a Mesozoic age of the major tectonic-metamorphic event. These were (i) Whole-rock samples of a late tectonic yet schistosed pluton with a magmatic fabric consistent with that of surrounding gneiss define an isochron of ca. 90 Ma (Zagorcev & Moorbath 1983; Soldatos & Christofides 1986). (ii) A Mesozoic age proposed for the amphibolite facies regional metamorphism on the basis of stratigraphic and structural correlations in Greece (Kronberg *et al.* 1970; Koukouvelas & Doutsos 1990). (iii) The Moho surface below the Bulgarian Rhodope is as deep as 50 km (Geiss 1987), and it is therefore likely that the crust has undergone substantial thickening not long before Oligocene extension.
Supportive evidence for the Mesozoic age of the tectonic and metamorphic event has been granted in the recent years. Lead-isotopes and U/Pb ages (Arnaudov *et al.* 1990b) support a long, Cretaceous to Oligocene metamorphic activity. In particular, ca. 50 Ma. old zircons in pegmatites intruding earlier amphibolite facies fabrics (Arnaudov *et al.* 1990a) provide a youngest age boundary for the main tectonic and metamorphic, thrust related event. These dates are consistent with ages ranging from 95 to 37 Ma in the Rhodope massif of Greece (K-Ar data on hornblende concentrates, Liati & Kreuzer 1990). Also, the oldest sediments deposited on the metamorphic rocks are dated Maastrichtian-Paleocene (Goranov & Atanasov 1992).
We distinguish two major thrust units termed, for sake of simplicity, the lower and upper terranes. In our definition they are separated by major, ductile mylonitic zone that were not recognized in earlier identifications of two main units (e.g. Papanikolaou & Papagopoulos 1981). In our view, the upper and lower terranes represent the crystalline footwall and hangingwall of a crustal scale duplex, respectively, involving intermediate crystalline thrust sheets between the ophiolitic "hanging-wall" and continental "floor" units (Fig. 3).

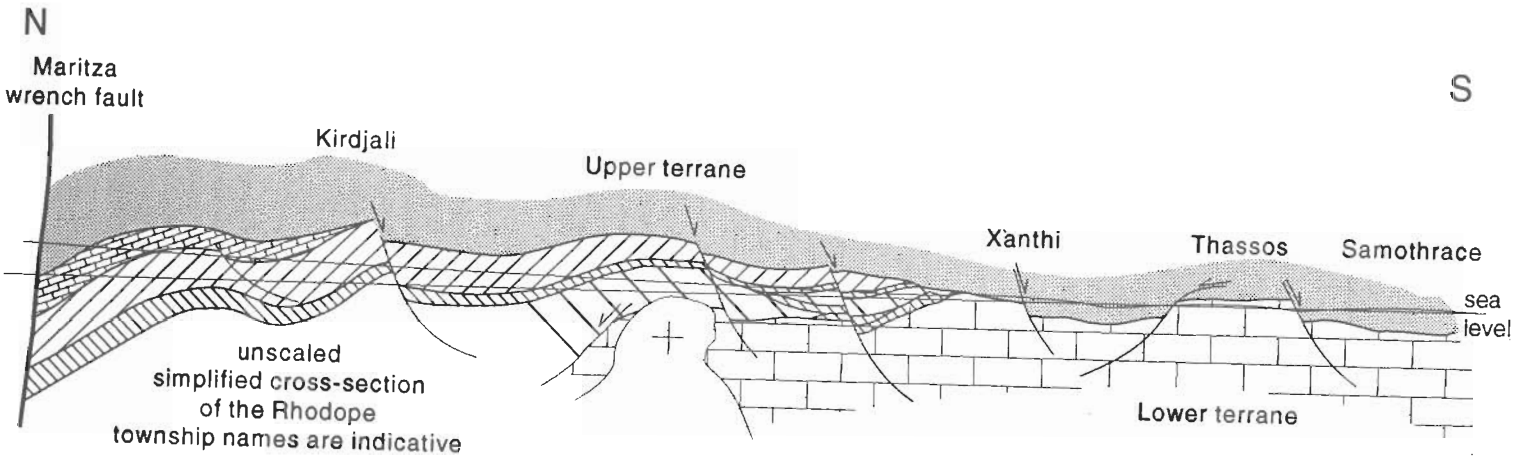

Figure 3 : Simplified cross-section of the Rhodope massif to illustrate the crustal duplex defined by the upper and lower terranes. Ornaments as in figure 1.

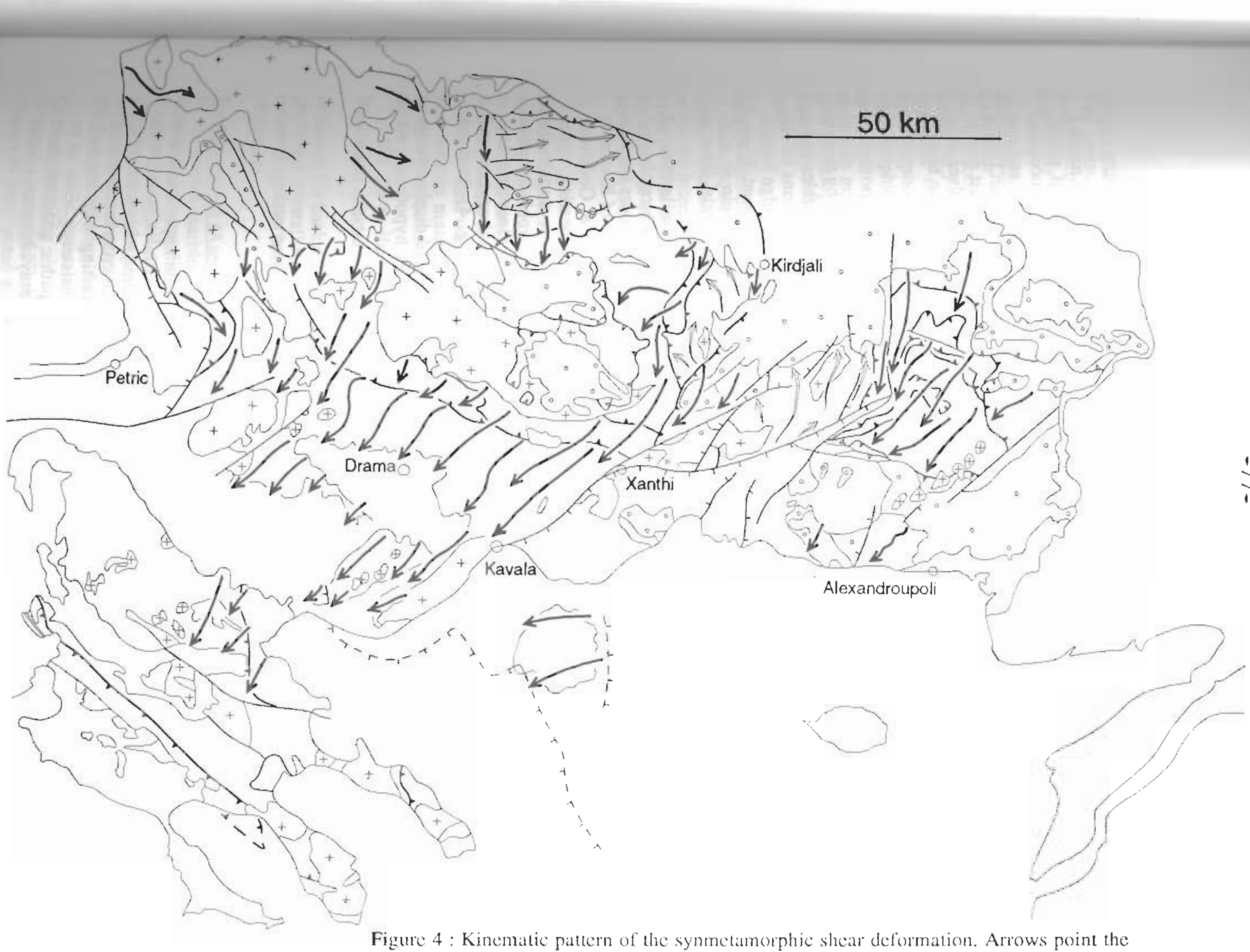

Figure 4 : Kinematic pattern of the synmetamorphic shear deformation. Arrows point the displacement of the upper part of rock units relative to the lower one. Black arrows are related to thrust movements; white arrows are associated with extension features.

The lower terrane: Schist-carbonate-gneiss sequence.

The tectonostratigraphy of the lower terrane (the Pangeon or Boz Dag unit, e.g. Kronberg *et al.* 1970; Kronberg & Raith 1977) comprises from bottom to top i) a unit of schists underlying ii) Palaeozoic marbles (Meyer *et al.* 1963, Ancirev *et al.* 1980), iii) leucocratic orthogneiss and paragneisses, and iv) an upper unit of micaschists, amphibolites and thin intercalations of marbles. The lower-terrane is particularly well identified between Drama and Kavala where marbles are involved in an imbricated, hinterland dipping thrust system (Kilias & Mountrakis 1991). Inverted, intermediate-pressure metamorphism evolves from greenschist facies conditions to the south (Zachos & Dimadis 1983) to sillimanite bearing migmatites to the north (Mposkos *et al.* 1989).

Upper terrane: Mafic-ultramafic-gneiss sequence

The upper terranes (Parvenec and Krumovitza of Ivanov 1988) are characterised by several km^2 outcrops of meta-ophiolites (Kozhoukharova 1984 a & b) enclosed in marbles and a sequence of mylonitic amphibolites schists and gneisses. Protolith compositions of the basic rocks (Kozhoukharova 1984 a & b) correspond to those of mid-ocean ridge basalts with a tholeiitic trend of differentiation and a close relationship to ocean-type crust. Trace-element and REE ratios of eclogites and related basic rocks support the origin as mid-ocean-ridge basalts (Kolceva & Eskenazy 1988; Liati *et al.* 1990). Consequently, there is lithological evidence for a hidden suture within the Rhodope.
Regional investigations and correlations based on map continuity, similarities of lithologies, in particular that of basic and ultrabasic rocks, structures, geochronological ages and strain regime reveal the wide extension of the upper terrane. It includes the Rila basic units, most of the Serbo-Macedonian (in particular the Vertiskos series of Kockel *et al.* 1977) and the crystalline klippen known to the west of Paikon (Ricou & Godfriaux 1991). On a regional scale, the metamorphic grade of the meta-ophiolite bearing, upper terrane varies from deep amphibolite facies in the north-eastern regions to low-amphibolite and greenschist facies conditions to the south and south-west. The metamorphic zonation is consistent with the foreland inferred to be to the south-southwest from kinematic data. The associated and synmetamorphic thrust-zone have involved oceanic lithosphere and caused the regionally subhorizontal north-northeast lineation pattern (Fig. 4). Inverted metamorphic zonation in the lower terrane can be attributed to this event.
Taking into account the mapped throw of the upper terrane, southwestward displacements of tens to hundreds of kilometres may be inferred. Following on this hypothesis, we provocatively suggest that the ophiolites of Samothrace (e.g. Kotopouli *et al.* 1989) represent a far-distant klippe.

Intermediate terranes.

Several intermediate thrust units are stacked between the Upper and Lower terrane. From the top to the bottom, they are :

Gneiss-marble sequence (Asenica unit)

The Gneiss -marble sequence occurs to the north squeezed between the upper and lower thrust terranes (Fig. 1). It comprises felsic orthogneiss and micaschists interlayered with paragneiss, marbles and minor amphibolites overlain by several hundred metres of thick, massive, and coarse-grained marble (Ivanov *et al.* 1984). Shear-sense criteria provide an internally consistent top to east-northeast shear deformation, contrasting with the bulk southward shear of the adjacent units (Fig. 4). This kinematic inconsistency leads us to separate the Asenica unit, dominated by marbles and quartzo-feldspathic gneisses, from the lower terrrane proper. In lithological terms, this intermediate unit may represent a more distal part of the carbonate platform that constitutes the lower terrane.

Gneiss sequence
The gneiss sequence is formed of quartzo-feldspathic, strongly deformed gneiss of dioritic composition intruded by metagranitoids, some of which presumably syntectonic. Gneiss commonly exhibit signs of partial melting. Very minor marble and amphibolites occur.

Eclogite-metabasic-gneiss sequence
Lenticular bodies of eclogites (Kolceva *et al.* 1986; Liati 1988; Liati & Mposkos 1990) and peridotites (Kozhoukharova 1984a & b) are present at the basal level (the 1-2 km thick Liaskovo Formation of Ivanov *et al.* 1980) of a distinct formation of paragneiss, minor graphitic marbles, and subordinate micaschists found as screens within bodies of metamorphosed gabbros, diorites and granitoids. Eclogites have an early high-pressure metamorphic history not known in the underlying lower terrane. There is a crustal-scale, synmetamorphic, shallow-dipping shear zone marked by the pervasive development of mylonitic microstructures along the base of the eclogite-bearing formation. Geochemical data on eclogites and associated ultrabasic rocks (Kozhoukharova 1984a & b; Kolceva & Eskenazy 1988; Liati *et al.* 1990) suggest they derive from the oceanic floor of a marginal basin.

Migmatite-orthogneiss sequence
A thick sequence of quartzo-feldspahic migmatites (Verbovo formation of Ivanov *et al.* 1980) contains many leucogranite veins produced from melting of the country rock. As the rocks are intensely recrystallised, they rarely carry a lineation and associated shear-sense criteria. This very monotonous sequence may be equivalent to some of the Biela Reka formation of eastern Rhodope (Ivanov *et al.* 1980). Epidote-rich amphibolites and marble layers form the top of this sequence.

CRUSTAL EXTENSION FEATURES

Ductile deformations implying crustal extension seem coeval with those implying crustal stacking and related structures interact at all scales. They are often markedly separated from normal faults that were active in Oligocene and later extensions around the Aegean Sea (e.g. Lister *et al.* 1984; Sokoutis *et al.* 1993; Dinter & Royden 1993). We consider that extension first occurred as a consequence of accretion and underthrusting of continental and oceanic material and represents gravitational adjustment of an unstable orogenic wedge. It is accommodated by lateral extrusion of crustal blocks subparallel to the strike of the orogen.

Backward crustal stretching

Evidence for backward crustal stretching is found both from kinematic indicators and from preferred crystallographic orientations overprinting those formed during the thrusting event (Fig. 4). Such evidence is particularly conspicuous within some intermediate sequences.

Gneiss -marble (Asenica) sequence
In the gneiss-marble sequence the foliation surface outlines an open, several kilometres wide antiform trending N 080 and contains a lineation defined by the elongation (and/or boudinage) of all minerals and mineral aggregates. Top to east-northeast shear-sense criteria are widespread (Burg *et al.* 1990). A ca. 100 Ma Rb-Sr errorchron on a metamorphosed granitoid that shares the fabric described above reflects resetting of the Rb-Sr system during the regional metamorphic event (Zagorcev & Moorbath 1986).

Gneiss sequence
Similarly, west of Kirdjali (Fig. 1), a few-metre thick, tectonic contact is marked by a change in shear sense and direction from southward in the underlying eclogite-metabasite-

gneiss sequence to north-westward . Here like in the Asenica sequence, the backward shear with respect to the bulk regional shear is attributed to syn-orogenic extension, although it could be associated to more complex processes inherent to synmetamorphic thrusting at deep levels.

In both cases, there has been little or no retrogression of metamorphic mineral assemblages, and Late Eocene marine sediments unconformably overlie upon the metamorphic sequence, suggesting that regional, north-eastward shear deformation and metamorphism were followed by rapid exhumation. Exhumation may have also involved tectonic denudation along less penetrative, retrograde mylonitic zones with down-dip lineations and shear directions. It is more difficult to recognise equivalent shear zones with bulk southward shear close to that associated with thrusting. Such normal zones do exist (in particular on the southern sides of granitoid plutons) and are additional in throw to thrust zones. Their actual identification requires more work.

Gneiss domes

A strongly oriented granitoid with pervasive north-eastward sense of shear occurs in the core of the northeast trending Kecibir antiform. Gneiss, marbles and amphibolites resembling the lower terrane, yet bearing evidence for north-eastward shear, occur on both limbs of this Northwest facing antiform. They constitute a tectonic window below rocks of the upper unit that have consistent southwestward sense of shear criteria (Fig. 4). The core granitoid has intruded rocks that were foliated before intrusion. We interpret this area as the result of doming from deep crustal levels, which is supported by low pressure anatexites constituting the foot-wall of the lacolithic granitoid. Ductile normal faults with commonly retrogressed mineral associations occur on both limbs of the dome.
The Kecibir dome is easily recognised due to backward (hinterlandward) normal sense of shear. The tectonic setting, low pressure type metamorphism and huge importance of granites in the Pirin-Vrondou anticlinal axis suggests that it is also related to crustal extension. It is then exhumed after activation of shallow angle, ductile normal zones as suggested by

GEODYNAMIC DISCUSSION

Recent work on the Vardar persuade to dispute the formerly accepted division into two oceanic basins separated by the Paikon Jurassic Arc because i) the Paikon is actually a tectonic window of Apulian facies underneath the ophiolitic nappes that represent the Vardar ocean (Godfriaux & Ricou 1991) and ii) the Jurassic age for the volcanics may be questioned (Ricou & Godfriaux 1991). Accordingly, a single Jurassic plate boundary should be alleged in the Vardar with the ridge that converted into subduction until the Late-Jurassic obduction on to Apulia (ref) between two Late-Triassic passive margins. Triassic sediments disrupted as tectonic lenses (and/or olistoliths) near Thessaloniki have recorded the setting of a passive margin through Anisian break-up (Kaufmann *et al.* 1976; Stais & Ferrière 1991). They likely stood between the Lower terrane (Drama) promontory and the Vardar ocean, symmetrically to the Maliac passive margin developed from the Anisian break-up on the western side of the Vardar ocean (Ferrière 1982). It comes out that the lower terrane was a migrating block detached from Eastern Apulia, thus forming the Vardar ocean (Fig. 5). It collided with the northern margin of Tethys in Bulgaria during the Cretaceous.
On the European (Moesian) side of the Rhodope, we are inclined to restore a Jurassic (Strandza) basin in a back-arc setting, rocks of the arc remaining in some of the Upper terrane metaophiolites (Kotopouli *et al.* 1989; Liati *et al.* 1990).

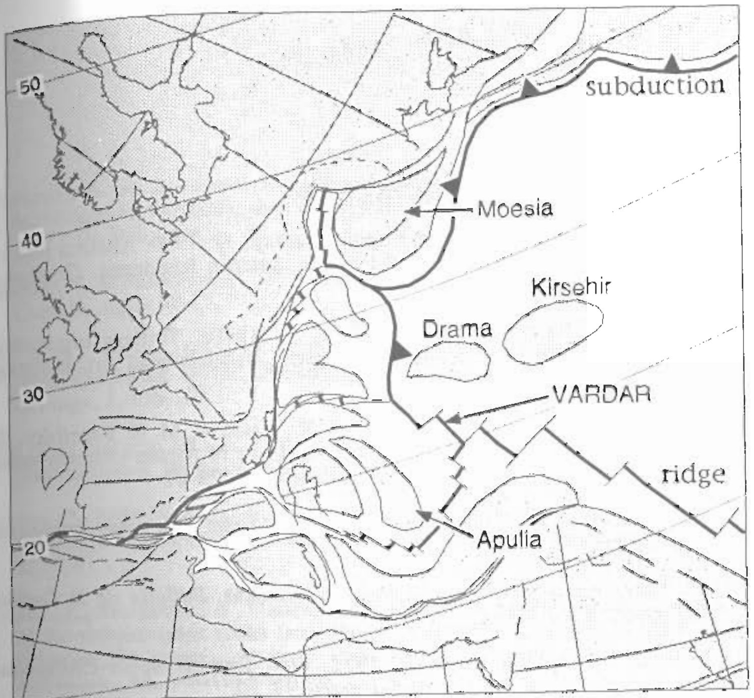

Figure 5 : Palaeogeographic reconstruction of this part of Tethys in Mid Jurassic times (180-170 Ma). Shaddowed = continental lithosphere; white = oceanic lithosphere. The Drama and Kirsehir blocks may belong to one bigger block.

CONCLUSION

- 1) - Finite strain analysis indicates that gneisses of the Rhodope Massif essentially deformed ductilely, in nearly plane strain conditions, in a dominantly non-coaxial deformation regime. The principal extension X direction can be taken as a kinematic direction.
- 2) - Variations in both subhorizontal X direction and sense of shear suggest that the Rhodope Massif is a region of large-scale nappe tectonics with consecutive extension.
- 3) - Fundamentally different deformation and metamorphic histories lead to distinguish several terranes. The lower (footwall) and upper (hangingwall) terranes define a crustal scale duplex with south to southwestward (forelandward) piling-up of large nappes. As eclogites and oceanic crust are involved, this event marks collision between two continental units followed by crustal thickening.
- 4) - East-northeast-vergent, flat-lying and synmetamorphic shearing associated with low-angle normal faults in metamorphic to granitic domes is attributed to extension, which occurred coeval with, and as a consequence of terminal continental collision. Gravitational collapse contributed to lateral spreading of the upward rising high-grade terranes.
- 5) - The Rhodope facies (pre-metamorphic ophiolites, calc-alkaline plutonic suite and eclogites) and first order structures (large tangential thrust movements and gravitational collapse accompanied by diapirism from deep crustal levels) are the result of plate tectonics. The two blocks that have collided are the Moesian continent to the north and the Rhodope continental promontory to the south.
- 6) - On a geodynamic point of view, the Drama continental promontory appears between the synmetamorphic ophiolitic suture described herein, to the northeast, and the Vardar ocean to the southwest. The lower terrane was a migrating block detached from Eastern Apulia while the Vardar ocean opened. The Rhodope collided with the northern margin of Tethys, in Bulgaria, during the Cretaceous.

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