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Geometry and kinematics of the Tertiary post-metamorphic Circum Rhodope Belt Thrust System (CRBTS), Northern Greece

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ABSTRACT

The complicated NW-SE trending Circum Rhodope Belt Thrust System (CRBTS) at the western margin of the Serbomacedonian massif that overthrusts towards SW the old ophiolitic suture of Axios zone is the main structural feature related to the inner Hellenic orogen in Central Macedonia. The final configuration of the CRBTS concerning the post-metamorphic thrust sheets of Oligocene-Miocene age has been studied here in detail. These post-metamorphic thrust sheets resemble flat-ramp geometry associated with oblique-lateral ramps and strike-slip faults. The main transport direction is towards SW (N220°-250°). We have recognised in the CRBTS at least five thrust domains in which at least three sheets of the Serbomacedonian basement are involved. Within thrust domains, relatively older, SW-verging asymmetric folds associated with a dominant S2-foliation (axial plane foliation) reveal similar kinematic symmetry with the aforementioned post-metamorphic thrusts. The whole thrust system is bounded to the Serbomacedonian massif by a steep arcuate, NW-SE trending fault zone, which reveals right lateral oblique reverse to right-lateral strike-slip movements and is attributed to a regional transpressive deformational regime. NW-SE orogen parallel extension takes place locally. NE-directed back-thrusts rooted from this fault zone accompany this transpressive deformation and locally modify the boundary by emplacing rocks of the CRBTS onto the Serbomacedonian massif. Transpressive deformation here ascribed either to the Apulian-Eurasia convergence or to the post-thickening extension of the inner part of the Hellenic Orogen.

INTRODUCTION

Recently developed research methods (i.e. seismic tomography, cross-balanced sections, etc.) along different parts of orogenic belts, throughout the world, give rise to fresh ideas and knowledge about the mountain building (orogenic) processes (i.e. stacking, uplifting, extension and exhumation). These issues have allowed nowadays the better understanding of the orogenic anatomy and evolution.

Within this frame, thin-skinned deformation or else the geometry and kinematics of the thrust systems have been well established especially in the foreland portion of the orogens. On the other hand, the thrust systems in the hinterland part, which commonly incorporate basement slices have not been studied in detail.

In the inner Hellenic mountain belt (fig. 1) and more precisely at the western margin of the Serbomacedonian massif (Sm) located in Central Macedonia, there is a well defined NNW-SSE trending complicated thrust system that constitute the Circum Rhodope Belt (CRB) bounding to the west the ophiolitic rocks of Axios zone. This thrust system, hence called Circum Rhodope Thrust System (CRBTS) offers the possibility to study thrusts in the inner part of the orogen. Our knowledge of the innermost Hellenic Circum Rhodope Belt has refined and increased through the pioneer investigation and mapping by Monod (1965); Mercier

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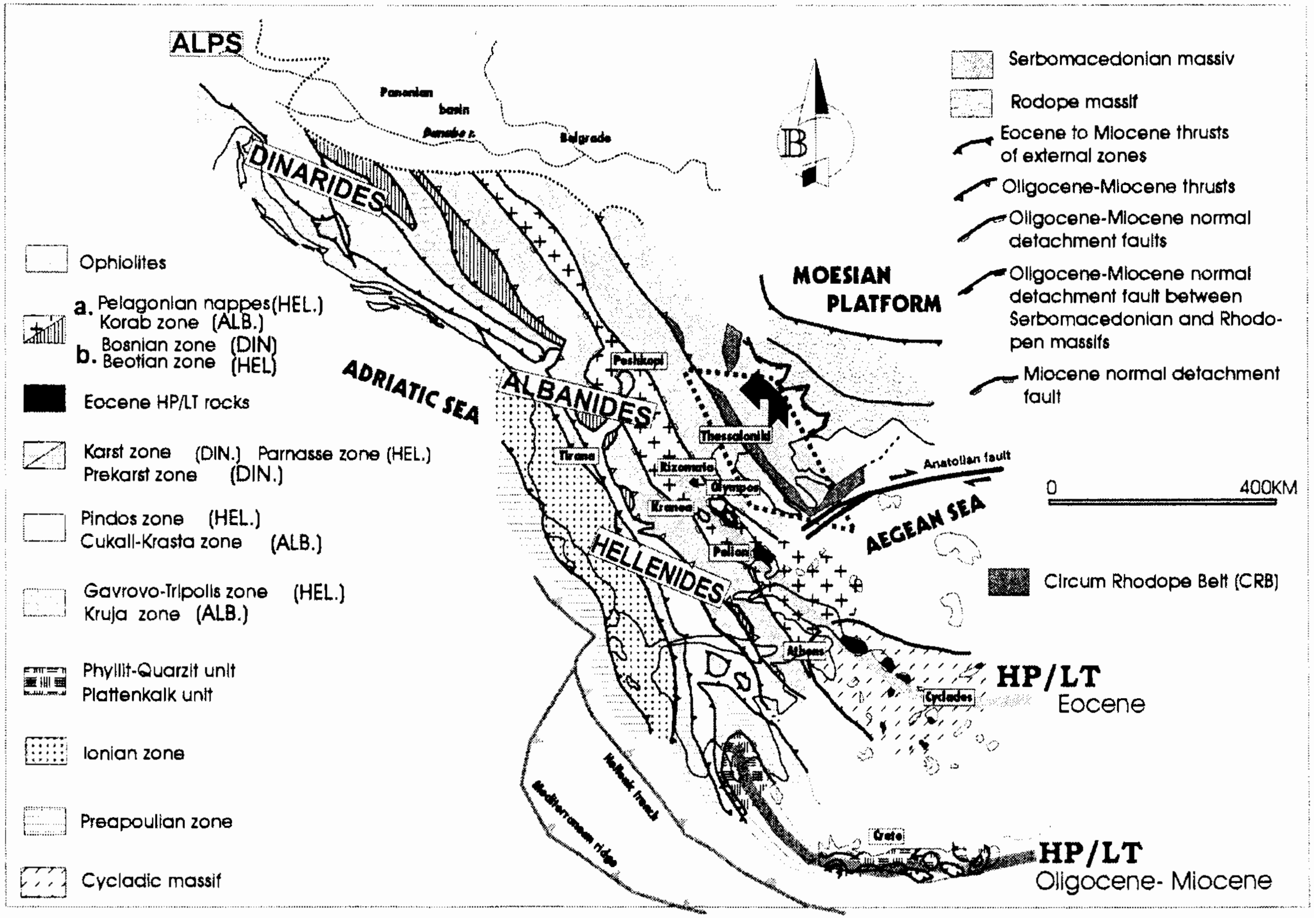

Fig. 1. Simplified map showing the main geological zones and tectonic elements of the Hellenic orogenic belt in the Balkan region. The studied area is located in the frame. HP/LT= High-pressure/Low Temperature metamorphic event.

(1968); Kauffman et al., (1976), Kockel et al., (1977) and Vergely (1984).

In this paper, based on our detailed field survey we reconnaissance the general geology of the area and investigate the geometry and kinematics of the post-metamorphic thrusts within the CRBTS and their eastern boundary with the Serbomacedonian massif. We also examine the general features and geotectonic position of the CRBTS during the final stage of the orogenic processes and propose the transpression mode of deformation for that part of the inner Hellenic orogen.

GEOLOCICAL SETTING

The CRB has been firstly defined by Kauffman et al., (1976). It build up by several NE-dipping asymmetric anticlinoria and synclinoria with wavelengths of 2-3 km and NE-dipping or overturned limbs in between repeated SW-directed thrust sheets. Some of these repeated thrust sheets, moreover, involve Paleozoic or older crystalline basement (Mercier, 1968; Kockel et al., 1977) making the final configuration of the CRBTS more complicate (fig. 2).

The Circum Rhodope Belt comprises Late Paleozoic and Mesozoic marginal sedimentary and volcanic rocks. They are placed from east to west in three lithostratigraphic units: (a) Deve Koran-Doubia unit, (b) Melissochori-Cholomontas unit and (c) Aspro Vrisi-Chortiatis unit (Kauffman et al., 1976; Kockel et al., 1977). The Deve Koran - Doubia unit consists of Late Paleozoic volcanoclastic sediments and neritic Triassic carbonate rocks. The Melissochori-Cholomontas unit, without volcanoclastic rocks, is composed of Triassic pelagic carbonate rocks and detrital flysch-type sediments (olistostromal in parts, Svoula Fm according to Kockel & Mollat, 1977) of Lower-?Middle Jurassic age. The Aspro Vrisi-Chortiatis unit is composed of carbonate rocks in the lower parts and deep-sea metasediments (schists, phyllites, radiolarian cherts) and dolerites. During Late Jurassic-Lower Cretaceous these rocks have been subjected to low-grade metamorphism associated with an S1-foliation, sub-parallel to bedding.

The Serbomacedonian massif bounding to the east the CRBTS consists of multiple deformed and metamorphosed Paleozoic or older rocks such as two-mica gneisses, amphibolites, mica schists that were intruded by syn-or post-acid plutonic rocks of Mesozoic and Tertiary emplacement age (Kockel et al., 1977; Vergely, 1984; De Wet et al., 1989; Tranos et al., 1993).

The dominant S1-foliation of the CRB rocks is folded by SW-verging asymmetric close F2-folds, associated with an axial plane S2-crenulation cleavage, and syn-metamorphic thrusts during the Late Cretaceous-Early Tertiary low-grade tectonometamorphic event (Mercier, 1968; Vergely, 1984; Tranos et al., 1993; Burg et al., 1996). The S2-foliation dips commonly towards NE, whereas S1/S2 crosscutting relationships form an intersection lineation Ls1/s2 parallel to F2-axes (Mercier, 1966; Vergely, 1984).

Additionally, Late Eocene bioclastic limestones and marls as well as Late Eocene-?Early Oligocene sandstones, conglomerates and volcanoclastic rocks overlie unconformably the Late Paleozoic-Mesozoic CRB rocks (Mercier, 1968; Kockel et al., 1977). Although, they expose in relatively small outcrops, their dating is crucial for the Tertiary tectonic evolution of the area. The LateEocene-?Early Oligocene rocks together with their underneath CRB rocks have been subjected to a younger post-metamorphic deformational event (Vergely, 1984; Tranos, 1998), which has been attain our interest.

Finally, during the Neogene a brittle extensional deformation related to high-angle normal faults gave rise to the extensive development of continental-type basins that cover the CRBTS and Serbomacedonian massif at many places (Tranos, 1998).

On the contrary westerly of the CRBTS the Axios zone represents the ocean developed in Mesozoic and closed during the Late Jurassic causing the obduction of the ophiolitic rocks onto the marginal rocks of the CRB (Vergely, 1984).

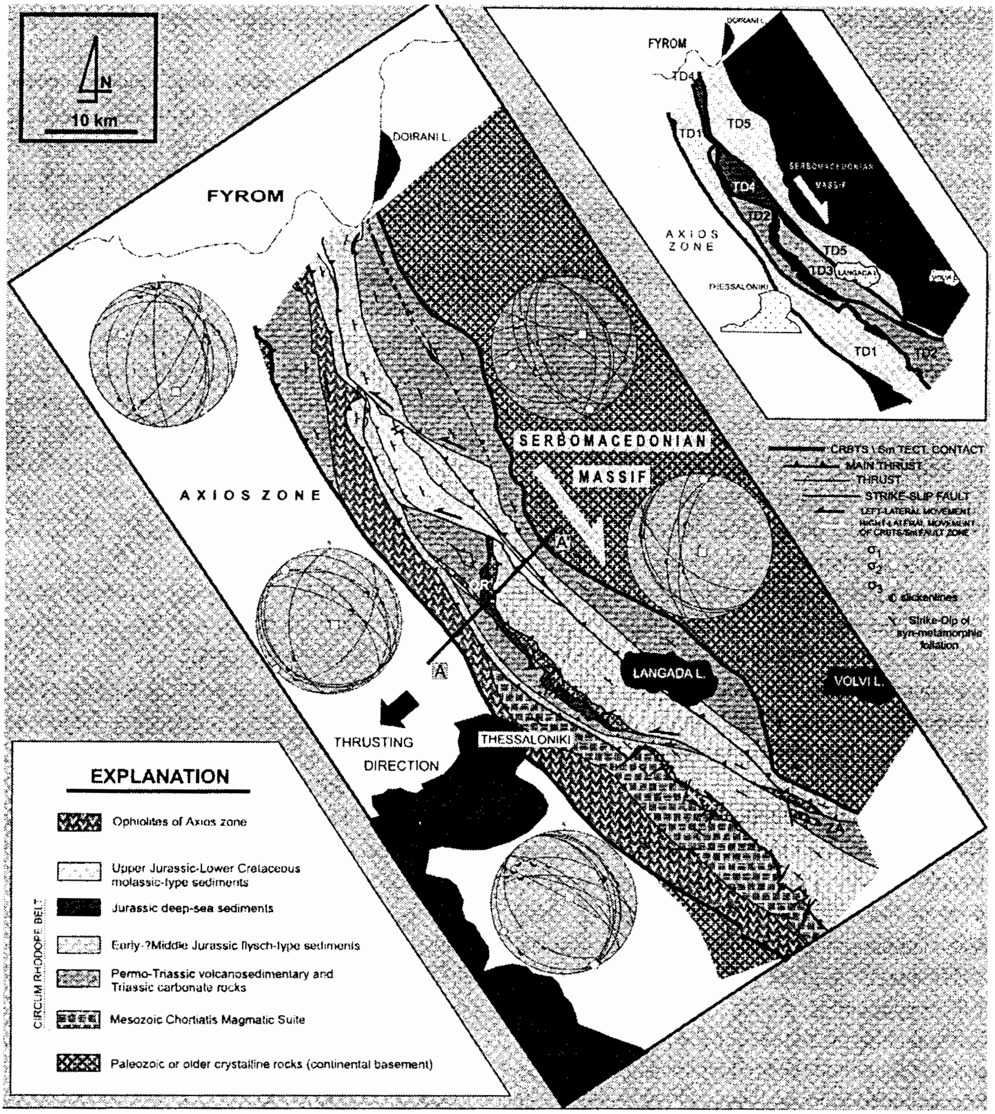

Fig. 2. Generalised geological and tectonic map of the CRBTS. It is based on compilation of field data and geological maps of Mercier, (1966) and Kockel et al., (1977) at scale 1:100.000. In the inset map at the right upper corner the thrust domains TD1, TD2, etc. of the CRBTS are shown. Fault-slip data and the principal stress axes are shown. OR=Oreokastro, ZA= Zangliveri.

GEOMETRY AND KINEMATICS OF DEFORMATION

a. Post-metamorphic structures in mesoscale

From the post-metamorphic structures recognised within the CRBTS, the most characteristic ones are the NW-SE striking post-metamorphic thrusts. They mostly dip towards NE (fig. 3, 4a), i.e. the internal part of the Hellenic orogen forming the fore-thrusts of the CRBTS, whereas the SW-dipping ones form the back-thrusts. The

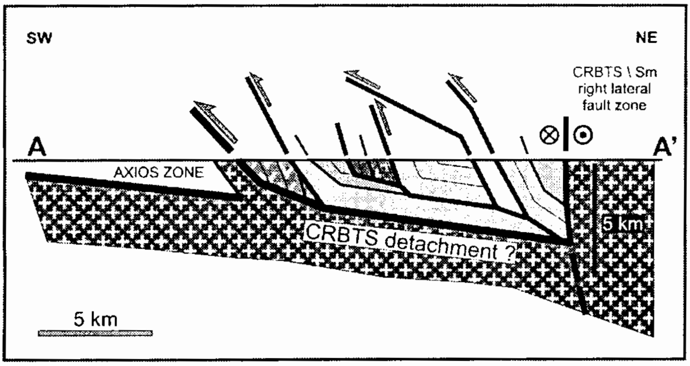

Fig. 3. A-A' cross-section of the CRBTS (see fig. 2). Explanation of the symbols in fig. 2.

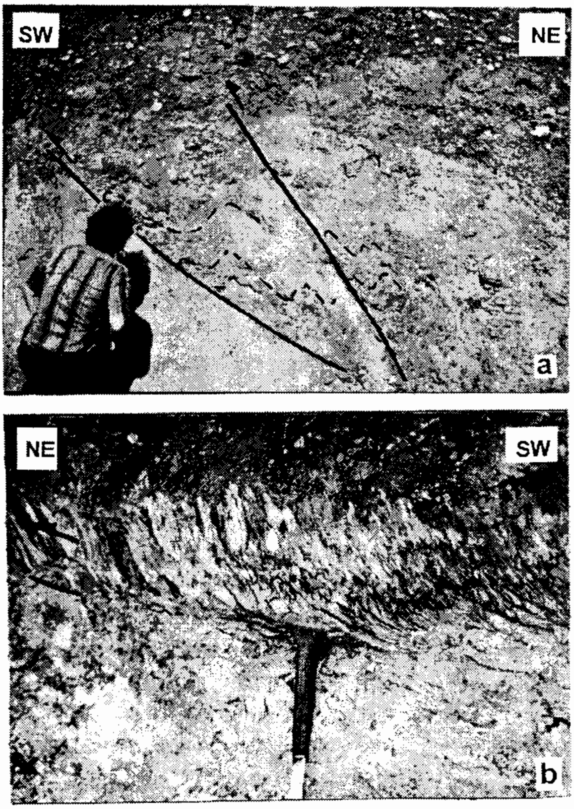

Fig. 4. Field photograph of (a) post-metamorphic fore-thrusts of the CRBTS exposed in the Lower-?Middle Jurassic flysch-type rocks area close to the Greek-FYROM borders. The thrusts clearly cut the syn-metamorphic fabric of the rocks and the SW-verging asymmetric folds, (b) SW-dipping back-thrust of the CRBTS at the central eastern part close to the boundary of the CRBTS with the Serbomacedonian massif (area of Zangliveri).

intensely formed array of NE-dipping fore-thrusts induces a general asymmetry of the CRBTS (fig. 2, 3).

The fore-thrusts affect all the lithologies up to the Late Eocene-?Early Oligocene molassic-type sediments as well as all the previous formed ductile structures. They expose as distinctive narrow shear zones to form leading imbricate fans, flat-ramp geometry and duplex structures. Their flat-ramp length is evaluated to be more than about 5:1, in mesoscale. Along the thrust surfaces there has take part no recrystallization, but only cataclastic flow processes, such as the pressure-solution and grain-boundary sliding leading to cataclastic fault rock and thrust zone weakening. Therefore, they are commonly characterised by S-C cataclastic fabric and slickenlines ranging from dip-slip to right lateral oblique-slip ones (i.e. their pitch varies from 80°SSE to 60°NNW).

The fore thrusts form, in mesoscale, two common HW/FW geometrical cases. In the first case, both the footwall and hanging wall rocks dip towards NE with almost similar, but higher (commonly with 50°-70° towards NE) angles than the thrust, which

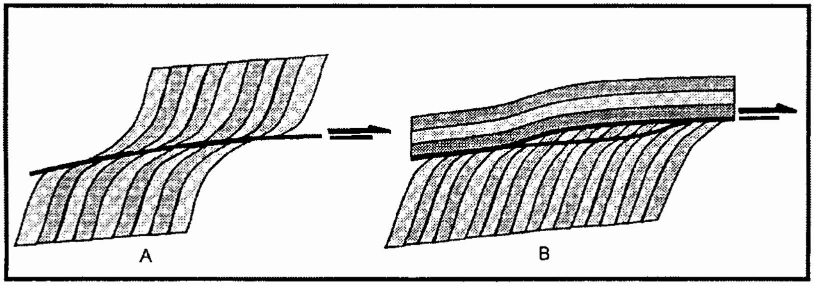

Fig. 5. Sketch scheme of the two common geometrical HW/FW cases that recognised along the post-metamorphic thrusts of the CRBTS. (a) FW and HW rocks dip towards the same direction, but with higher angles than the thrust, (b) the thrust dips at low-angle forming FW ramp and HW flat geometry.

dips 10°-30° towards NE (fig. 5a). The other case refers to a low-angle NE-dipping thrust forming footwall ramp and hanging wall flat geometry (fig. 5b).

On the other hand, the back-thrusts have been found to dominate close to the CRBTS boundary with the Serbomacedonian massif affecting also all previous structures. They dip with various angles towards SW and show similar kinematics with the fore-thrusts, but the gently dipping back-thrusts affect the more steep ones forming repeated NE-directed thrust zones.

Within the CRBTS, apart the prevalent post-metamorphic thrusts, we have mapped several WNW-ESE trending left-lateral strike-slip faults dipping at moderate angles to the NNE as well as NNE-SSW trending right-lateral strike-slip faults (fig. 2). They present very constant orientation and kinematics and some of them have originated as oblique ramps to the frontal ramps of the fore-thrusts. More precisely, the WNW-ESE faults are characterised mainly by slickenlines dipping gently towards WNW (pitch 10°-30° WNW), whereas the NNE-SSW faults by almost horizontal slickenlines. These faults are characterised as conjugate faults defining by their function a NW-SE orientation of extension.

Finally, there are many steep-inclined to vertical NE-SW to ENE-WSW strike-slip faults with left- or right-lateral sense-of-shear forming a small enclosing dihedral angle (fig. 2). They have been defined as transfer or tear faults, because they differentially advance the forward displacement of the different parts of the post-metamorphic thrusts. Many of these faults have been observed later to reactivate as left-lateral oblique normal to normal faults (see also Tranos, 1998).

The kinematics of the aforementioned structures has been deduced using microstructures widely accepted as slip and sense-of-shear indicators such as slickenlines, accretion steps, Riedel structures, S-C cataclastic fabric (Hancock, 1985; Pettit, 1987).

The above-described thrusts and strike-slip faults affect all CRBTS ductile structures and they reveal strain compatibility yielding a similar ENE-WSW shortening as this indicated by their geometrical and kinematic elements. In addition, both the thrusts and strike-slip faults have been clearly affected by the high-angle normal faults that caused the extensive formation of the Neogene basins (see also Tranos, 1998). So that overprinting criteria, geometry and kinematics and strain compatibility indicate that the overall post-metamorphic structures have simultaneously functioned during a unique deformation event.

Moreover, from the fault-slip data collected at several localities we have computed the paleostress tensors using the algorithm of Carey & Brunier (1974) (fig. 2). The average angle between computed shear stress and observed slickenlines is smaller than 15° for each fault-stress diagram, which is fairly acceptable in comparison to the 20° and 45° misfit angle suggested by

Carey (1979) and Angelier (1979), Gephart (1990) respectively. As a result a general ENE-WSW oriented maximum stress axis (σ_1) seems to drive the aforementioned post-metamorphic deformation including the main SW-directed fore-thrusts of the CRBTS and the other described structures.

In addition, following the experimental results of Ramberg (1970) we can mention that similar ENE-WSW to E-W trending maximum principal stress axis (σ_1) is determined by the NNW-SSE to N-S trending open upright buckle folds that have been observed to affect the Late Eocene-?Early Oligocene molassic-type sediments.

Another important element concerning the post-metamorphic deformation of the area is the NW-SE extension associated with the 'bookshelf kinematics' of the WNW-ESE strike-slip faults and the overall strike-slip geometry and kinematics (fig. 6). NW-SE extension could be considered as an orogen-parallel extension.

b. Geometry of the CRBTS

Based on the major out-of-sequence thrusts of the studied post-metamorphic thrust system that have on their HW flysch-type sediments of Early-?Middle Jurassic age, the lithological composition as well as the structural features and structural evolution of the area we divide from the bottom to top the CRBTS into four main thrust domains that their internal structure is dominated by syn-metamorphic SW-verging asymmetric folds and syn-and post-metamorphic SW-directed imbrications (fig. 2, 3).

TD1: The deepest thrust domain covers the westernmost parts of the CRBTS and thrusts over a narrow strip of Paleozoic or older crystalline rocks of the ?Serbomacedonian massif (Kockel et al., 1977) or Stip-Axios unit (Ricou, 1965). It includes Late Paleozoic volcanoclastic and Triassic carbonate rocks of the CRB, a slice of ophiolitic rocks of the Axios zone and the greenschist rocks of the Magmatic Chortiatis Suite succeeded tectonically by another thrust sheet of the Paleozoic crystalline slice of ?Serbomacedonian massif. The sole thrust of the TD1 is considered here to represents the CRBTS detachment, i.e. the detachment that separates the complicate CRBTS from the Axios zone and the Tertiary continental crust (fig. 3, 7).

TD2: The next thrust domain consists of flysch-type sediments of Jurassic age that clearly thrusts over different lithologies such as the ophiolites, greenschists and their tectonically overlaid Paleozoic crystalline rocks. Apart the basal flysch-type sediments, the TD2 domain includes also rocks similar to the rocks of the TD1, which the later expose at the Oreokastro and the Zangliveri area, but their exposure is obscured at the central part due to the next TD3 thrust domain.

TD3: This thrust domain consists only of Early-?Middle Jurassic flysch-type sediments that thrusts over either the previous TD2 or the Paleozoic or older crystalline rock slice that is sandwiched in between rather forming a breaching thrust.

TD4: Above the TD3, there exists another thrust domain, which is composed of Early-?Middle Jurassic flysch-type sediments and molassic-type sediments of Late Jurassic-Early Cretaceous age. The TD4 thrust domain overthrusts with an out-of-sequence basal thrust the TD3, TD2 and TD1 domains.

TD5: It is the easternmost and the uppermost thrust domain of the CRBTS that consists exclusively of CRB rocks and more particular of Early-?Middle Jurassic flysch-type sediments tectonically imbricated with the Late Paleozoic volcanoclastic and Triassic carbonate rocks. This thrust domain overthrusts the TD4, TD3 and TD2 thrust domains as well as the Paleozoic or older crystalline rocks, which have mentioned before to be sandwiched between the TD2 and TD3 domains.

c. The CRBTS boundary with the Serbomacedonian massif

The most intricate feature concerning the CRBTS is its eastern boundary with the

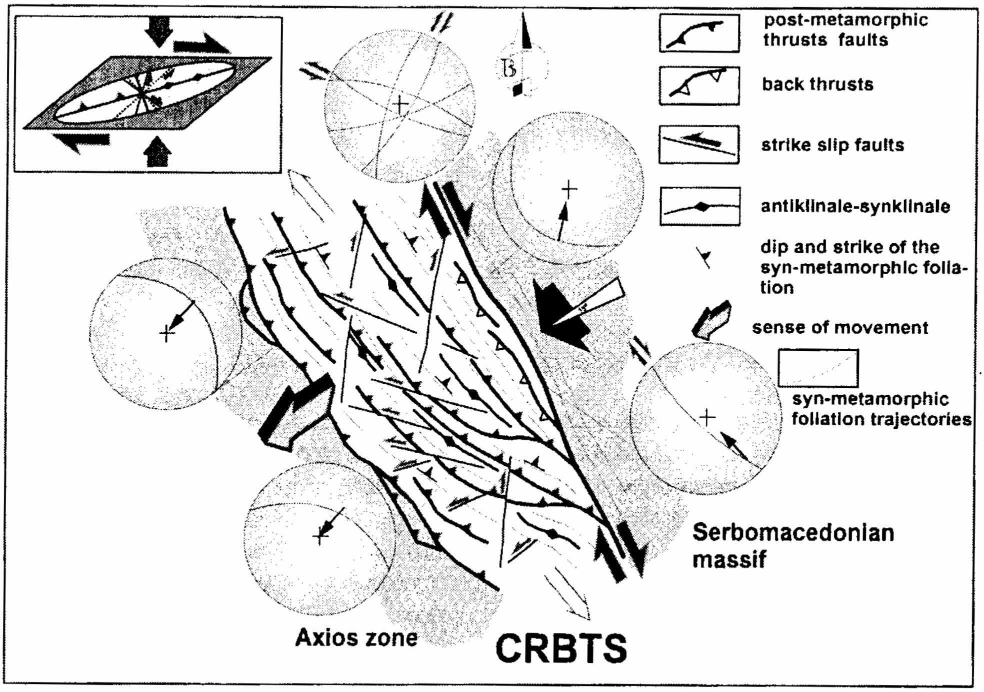

Fig. 6. Simplified schematic pattern indicating the geometrical and kinematic elements of the main post-metamorphic structures of the CRBTS. They explained by the transpression deformational model as shown in the frame at the left upper corner.

Serbomacedonian massif (figs. 2, 3). This boundary has a NNW-SSE sigmoidal strike and it is recognised as a high-angle fault zone along which the low-grade metamorphic rocks of the CRB are juxtaposed against the high-grade metamorphic rocks of the Serbomacedonian massif (fig. 2). Moreover, the main foliation of both CRB and the Serbomacedonian massif close to this fault zone tend to be sub-parallel with it. It is important to mention that its mean trend slightly deviates about 10°-15° clockwise from the trend of the CRBTS thrusts. (fig. 2) and forms more than 30° dihedral angle with the NNE-SSW right-lateral strike-slip and 120°-140° dihedral angle with the WNW-ESE left-lateral strike-slip faults respectively. Whereas, the CRBTS/Sm fault zone is oriented rather perpendicular to the NE-SW steep strike-slip faults.

In the part located south of the lakes Langada and Volvi (close to Polygiros-Arnea area) the CRBTS/Sm fault zone dips with high-angles towards NE. Here, on the CRBTS/Sm fault zone we have recorded slickenlines and sense-of-shear kinematic indicators (Hancock, 1985; Petit, 1987) that indicate a right-lateral strike-slip movement. Northwards of Lake Langada to the CRBTS/Sm dips with high-angle toward SW due to the described back-thrusting of the CRBTS, which caused locally the re-treatment of the fault zone and the thrusting of the CRB rocks over the Sm.

A crucial structural element to our interpretation of the area is the relative dating of the CRBTS/Sm fault zone in relation to the CRBTS post-metamorphic structures. The CRBTS/Sm fault zone is considered here to be penecontemporaneous with the post-metamorphic structures of the CRBTS, because: (a) the main SW-directed fore thrusts of the CRBTS do not affect the CRBTS/Sm boundary, but they trun-

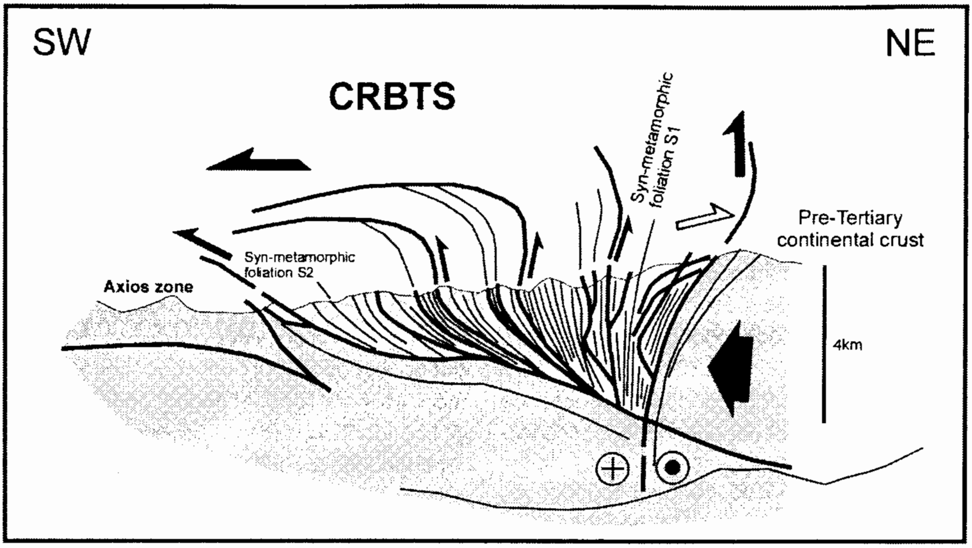

Fig. 7. Schematic cross-section showing the main geometry of the post-metamorphic structures of the CRBTS and their relationship with the previous syn-metamorphic structures.

cate or abut it, (b) the fault zone is also a post-metamorphic structure clearly affecting the syn-metamorphic fabric of both the CRB and the Sm massif, (c) the kinematics of the fault zone defines similar NE to ENE shortening and NW-SE extension as the described post-metamorphic structures of the CRBTS do, (d) both the fault zone and the structures of the CRBTS have been affected by the intensely developed high-angle normal faults that caused the formation of the extensive Neogene basins of the area.

TIMING OF DEFORMATION

The timing of the studied post-metamorphic deformation is addressed as Oligocene to Miocene from the following perspectives:

(a) It affects the Late Eocene-?Early Oligocene molassic-type sediments (Vergely, 1984; Tranos, 1998), which they exposed to be overthrust by the thrusts of the CRBTS. Similar post-metamorphic thrusts are referred in the South Bulgaria area to affect Oligocene molassic-type rocks (Burg et al., 1990).

(b) Volcanoclastic rocks dated as Late Eocene-Early Oligocene (Mercier, 1968) have been observed to incorporate into the post-metamorphic thrusts.

(c) The related to post-metamorphic deformation NE-SW shortening does not affect the Miocene basins sediments.

DISCUSSION AND CONCLUSIONS

Considering that transpression describes a complex movement involving both shortening normal to the fault zone and transcurrent shear parallel to the fault zone (Harland, 1971, Sanderson & Marchini, 1984; Krantz, 1995), the Oligocene-Miocene deformation of the CRBTS can be explained as the result of a transpressional deformation model. This explanation is supported both from the kinematics of the boundary itself and the geometry and kinematics of the post-metamorphic structures of the CRBTS in respect to the CRBTS/Sm fault zone. More precisely the following facts argue for the transpression tectonics (figs. 2, 6, 7):

(1) The apparent simultaneous dip-slip and strike-slip movement that observed along the CRBTS/Sm fault zone could be attributed to the slip-partitioning model resulted by the

transpressive deformation. This model has been already applied to other orogenic belts such as the North American Cordillera (Beck 1983, Ave Lallemant & Oldow 1988), the Alps (Mattauer 1986, Lacassin 1989) and seems to be more applicable to late stage deformation in orogenic process.

(2) Although, all horizontal strain parameters of the area remain unknown, we can obtain the maximum horizontal stretch of the strain ellipse to be oriented parallel to the main thrusts of the CRBTS and the CRBTS/Sm boundary as the shear direction of the strike-slip system. The fact that the trend of the main post-metamorphic thrusts of the CRBTS forms about 15° angle with the mean trend of the CRBTS/Sm fault zone (fig. 6) allow us to estimate the geometrical parameter ff = 15°, (ff = the orientation of the maximum horizontal stretch of the horizontal strain ellipse relative to the shear direction). This very small angle of the geometrical parameter ff in the transpressional strain model of Krantz (1995) is better explained by a strongly convergent strike-slip system.

(3) The NNE-SSW trending right lateral strike-slip faults that accomplish the main post-metamorphic thrusting of the CRBTS act as synthetic Riedel shear structures in relation to the major CRBTS/Sm fault zone forming relatively high angle (>30°) to the later. This high angle advocates the convergent transpression zone.

(4) The WNW-ESE trending left-lateral strike-slip faults that show 'bookshelf kinematics' and determine ENE-WSW shortening, form 120°-140° dihedral angle with the right-lateral CRBTS/Sm fault zone, so that they might characterised as X-shear structures (terminology according to Logan et al., 1979). The fact that the dihedral angle is higher than the ˜110° angle formed in the pure strike-slip system advocates the convergent strike-slip system.

(5) The NE-SW trending steep-inclined conjugate right- and left-lateral strike-slip faults of enclosing low-angle dihedral angle that oriented almost vertical to the fore thrusts of the CRBTS support the transpression tectonics.

(6) Finally, the NW-SE orogen-parallel extension is oriented at low-angle to the major CRBTS/SSM fault zone.

In more broad sense, during the Oligocene-Miocene times the Hellenic orogenic belt was driven by the convergence in between the Apulian and Eurasia plate (Dercout et al., 1988), well established in the foreland part of the Hellenic orogenic belt. On the contrary, a well-developed NE-SW extension is referred to dominate the inner Hellenic orogen from the Oligocene onwards. This extension has been well studied in the Serbomacedonian and Rhodope massifs dominates (Kilias & Mountrakis, 1990; Kolokotroni & Dixon, 1991; Koukouvelas & Pe-Piper, 1991; Socoutis et al., 1993; Dinter & Royden, 1993, Dinter, 1994, Kilias & Mountrakis, 1998), where the Strymon extensional detachment fault is privileged. This extensional deformation has been interpreted as post-orogen collapse related to subduction processes and gave rise to a widespread Oligocene-early Miocene igneous activity including both acid plutonic and acid volcanic rocks (Kilias & Mountrakis, 1998).

Therefore, the described here transpression tectonics of the CRBTS during the Oligocene-Miocene could be related to the convergence in between the Apulian plate and Tertiary Eurasia plate. This convergence has been well expressed at the external parts of the Hellenic orogen with the thin-skinned deformation, or else it represents a locally developed deformation caused by the possible frontal curvature of the detached mass due to the major Strymon extensional detachment fault in between the Serbomacedonian and Rhodope massif. The validity of the last case has been shown experimentally by (McKlay, 1987).

Concerning the transport direction in different parts of the orogen, we can acknowledge that the orogen-normal transport dominates the thin-skinned deformation of the foreland portion (fold and thrust belts) of the orogen as mentioned by Elliot, (1976). Instead, this study has shown that in the inner Hellenic orogen the transport direction is oblique to the orogenic grain, thus giving rise to transpressive deformation with both orogen-normal and orogen-parallel transport displacements.

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