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ORIGINAL PAPER

Kinematics of the Southern Rhodope Core Complex (North Greece)

Jean-Pierre Brun · Dimitrios Sokoutis

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Abstract The Southern Rhodope Core Complex is a wide metamorphic dome exhumed in the northern Aegean as a result of large-scale extension from mid-Eocene to mid-Miocene times. Its roughly triangular shape is bordered on the SW by the Jurassic and Cretaceous metamorphic units of the Serbo-Macedonian in the Chalkidiki peninsula and on the N by the eclogite bearing gneisses of the Sideroneron massif. The main foliation of metamorphic rocks is flat lying up to 100 km core complex width. Most rocks display a stretching lineation trending NE–SW. The Kerdylion detachment zone located at the SW controlled the exhumation of the core complex from middle Eocene to mid-Oligocene. From late Oligocene to mid-Miocene exhumation is located inside the dome and is accompanied by the emplacement of the synkinematic plutons of Vrondou and Symvolon. Since late Miocene times, extensional basin sediments are deposited on top of the exhumed metamorphic and plutonic rocks and controlled by steep normal faults and flat-ramp-type structures. Evidence from Thassos Island is used to illustrate the sequence of deformation from stacking by thrusting of the metamorphic pile to ductile extension and finally to development of extensional Plio-Pleistocene sedimentary basin. Paleomagnetic data indicate that the core complex exhumation is controlled by a 30° dextral rotation of the Chalkidiki block. Extensional displacements are restored using a pole of rotation deduced from the curvature of stretching lineation trends at core complex scale. It is argued that the Rhodope Core Complex has recorded at least 120 km of extension in the North Aegean, since the last 40 My.

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Keywords Aegean extension · Metamorphic core complex · Ductile deformation · Normal faulting · Block rotation · Late Neogene sedimentary basins

Introduction

Core complexes originate from the exhumation of middle to lower crustal ductile rocks between separating blocks of the brittle upper crust during large-scale extension (e.g. Crittenden et al. 1980; Wernicke and Axen 1988). The fact that the Moho is rather flat below the core complexes, despite large amounts of extension, suggests that both ductile crust and uppermost mantle are weak enough to allow lateral flow for compensating heterogeneous stretching of the upper brittle crust (Block and Royden 1990; Buck 1991). This may take place if the Moho-temperature exceeds 800°C (Ranalli 2000). Core complexes therefore have a strong dynamical significance, as they are indicators of a hot and weak lithosphere (Sonder and England 1989). Thermal relaxation following thickening (England and Thompson 1986) may provide such conditions but requires a rather long relaxation time. Mantle delamination (Bird 1979), back arc environments (Hyndman et al. 2005), slab detachment (Gerya et al. 2004), triple junction interaction or hot spot migration (Wakabayashi 2004) are other settings where strong thermal softening of crust and mantle may occur.

Slab retreat that controlled the Aegean extension (Le Pichon and Angelier 1981) is characterized by two domains of core complex-type extension, in the Cyclades (Lister et al. 1984; Gautier et al. 1990, 1993; Lee and Lister 1992; Gautier and Brun 1994a, b) and in the southern Rhodope (Dinter and Royden 1993; Sokoutis et al. 1993). By reference to the Vardar suture zone, their general tectonic setting is strikingly different. The Cyclades Core Complex (CCC) is located in the under-thrusted plate while the Southern Rhodope Core Complex (SRCC) is in the overriding plate. In both cases, core complexes reflect extension of a previously thickened crust synchronous with ongoing thrusting, close to the retreating subduction trench. Therefore, thermal and mechanical conditions that favoured their development can be related to both continental collision and subduction.

Until recently, the two core complex domains were considered to have initiated synchronously in late Oligocene–early Eocene times (see syntheses by Gautier et al. 1999; Jolivet et al. 2004). However, growing evidence (Burchfiel et al. 2003; Brun and Sokoutis 2004; Kounov et al. 2004) suggest that the extension started during middle Eocene times in the Rhodope, 10–15-Ma earlier than in the Cyclades. In other words, the SRCC and the associated Neogene sedimentary basins offer the most complete record of the about 40 My of Aegean extension. With its maximum measurable width of at least 120 km, parallel to the stretching direction, the SRCC is the largest core complex in the Aegean region and likely one of the largest worldwide. This implies that the exhumation of the SRCC has accommodated a minimum of 120-km extension. Both the 40-My lifetime and the 120 km of displacement emphasize the interest of the SRCC for the understanding of extension in domains of plate convergence.

The purpose of the present work is (a) to re-examine the kinematics of the SRCC since Eocene times and (b) to explain the spatial and temporal relationships, between core complex exhumation and late Neogene sedimentary basins. The ductile deformation patterns due to extension is reviewed first at regional scale and then their relations to previous earlier events of crustal-thickening as well as later brittle normal faulting related to basin formation. The Thassos Island is used as a case study for details. Structural, geochronological and paleomagnetic data are used to set up a regional-scale kinematic model of the SRCC. Particular emphasis is given to the type of core complex that exhumes between rotating blocks of brittle upper crust and the process by which ductile fabrics are progressively incorporated into the brittle crust while preserving the record of successive rotation increments.

Deformation pattern at regional scale

Geological setting

The Southern Rhodope Core Complex (SRCC) displays a triangular shape bordered to the west by the Vertiskos thrust units of the Serbo-Macedonian in the Chalkidiki Peninsula and to the north by the Central Rhodope of south Bulgaria (Fig. 1a).

The SRCC is mostly constituted by dominantly flat-lying units of marbles and orthogneisses and to a lesser extent, micaschists, paragneisses and amphibolites. The protoliths of orthogneisses correspond to plutonic units of Hercynian age, clustering between 270 and 310 Ma throughout the Greek Rhodope (Wawrzenitz and Krohe 1998; Liati and Gebauer 1999; Turpaud and Reischmann 2003; Liati and Fanning 2005). The stratigraphic age of marbles and associated meta-sediments and amphibolites is unknown, but they most likely represent peri-Tethys sedimentary and volcanic series deposited on top of the Hercynian basement. These metamorphic rocks are intruded during Oligocene–Miocene times by the two syntectonic granitoid plutons of Vrondou (Kolocotroni and Dixon 1991) and Symvolon (Kyriakopoulos et al. 1989). The composite crystalline massif is partly covered by late Miocene to Quaternary dominantly lacustrine sediments with however, a marine transgression during the Messinian. The sediment deposition is tectonically controlled by steep normal faults trending in two main directions E–W to NE–SW and NW–SE (Fig. 1b). This late brittle deformation that initiated in the upper Miocene times cuts the whole SRCC into several sub-massives, namely Falakron, Menikion and Lekani to the north and Pangaion, Kerdylion and Thassos Island to the South (Fig. 1c). The apparent isolation of Thassos from the onshore part of the SRCC is likely responsible for the interpretation of the Thassos Island as a single core complex in itself (Wawrzenitz and Krohe 1998).

To the west of the SRCC, the Vertiskos Gneiss Complex (Fig. 1a) corresponds to the upper part of the Serbo-Macedonian Massif. It consists of a pile of thrust units affected by HP metamorphism (Dixon and Dimitriadis 1984; Michard et al. 1994) that were emplaced toward the WSW likely in Cretaceous times (Burg et al. 1990, 1996). To the north of the SRCC, the Sideroneron Gneiss Unit (Fig. 1a), thrust over the marble-gneiss units of the Falakron and Lekani, contains evidence of high pressure (HP) (Liati and Mposkos 1990; Liati and Seidel 1996) and ultra-high pressure (UHP) (Mposkos and Kostopoulos 2001) metamorphism, dated at 140 Ma (Liati and Gebauer 1999; Liati 2005) and 184 Ma (Reischmann and Kostopoulos 2002), respectively. Another UHP metamorphic event has been

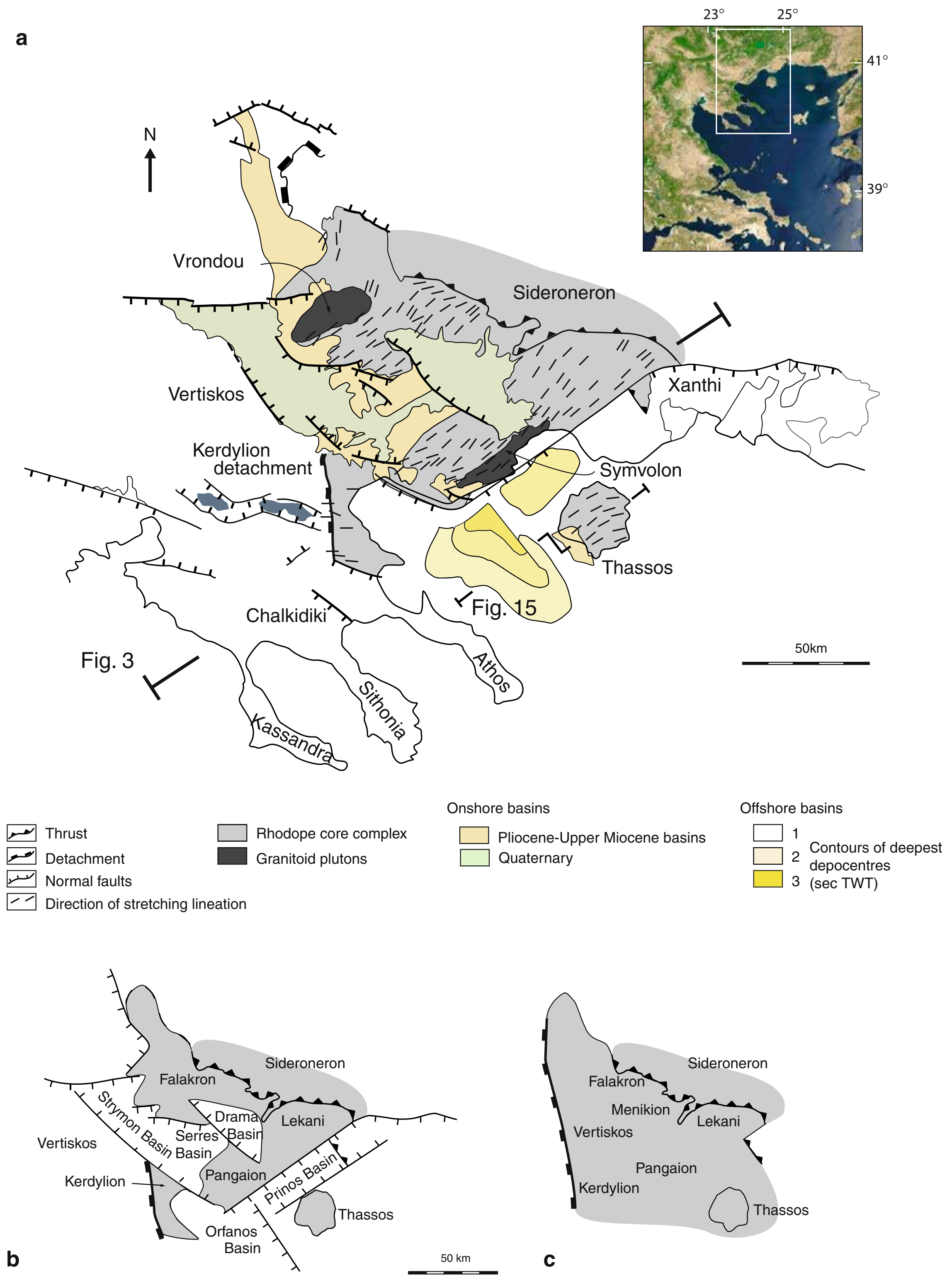


Fig. 1 **a** Simplified map of the Southern Rhodope Core Complex with location of cross sections shown in Figs. 3 and 15. The *insert* shows the location in Northern Greece. **b** Main crystalline massives and late Neogene sedimentary basins of the southern Rhodope. **c** Boundaries of the Southern Rhodope Core Complex after removal of Neogene sedimentary basins

dated at 72 Ma in the Kimi area of Eastern Rhodope by Liati et al. (2005). These Jurassic and Cretaceous age UHP metamorphic events are far older than the Tertiary history of the SRCC and are thus likely unrelated to the formation of the core complex. For this reason, the mechanism of exhumation of these UHP rocks is beyond the scope of the present paper. The latest HP metamorphic events recorded in this area are dated at 51 Ma and 42 Ma (Liati 2005). These geochronological evidences suggest that thrusting of the Sideroneron gneiss unit on top of the Pangaion marbles is most probably related to the Cretaceous–Eocene times convergence that affected both the Serbo-Macedonian Massif as well as the Rhodope Massif (Burg et al. 1990, 1996; Ricou et al. 1998).

All metamorphic rocks from the SRCC have undergone a high-temperature event of Tertiary age, with evidence of Barrovian type metamorphism up to partial melting in Thassos (Dimitriadis 1989). Most of the rocks have amphibolite facies parageneses with migmatites largely represented in the Kerdylion massif. Available geochronological data are used here to define at the scale SRCC the contours of cooling ages corresponding to 500°C or higher and 300°C, respectively (Fig. 2). Both maps show a young central domain going from Vrondou to Thassos Island. To the NE and SW, the rocks passed the 500°C isotherm in early to middle Eocene time and the 300°C in late Eocene–early Oligocene. In the central part, the rocks passed the 500°C isotherm in late Oligocene–early Miocene and the 300°C in middle Miocene-late Miocene. In both cases, this corresponds to mean cooling rates of at least 20°C/Ma.

The ductile deformation structures of the Southern Rhodope have been traditionally interpreted in terms of thrusting (Kockel and Walther 1965; Kronberg 1969) and renewed by Burg et al. (1990, 1996), Kilias and Mountrakis (1990) and Ricou et al. (1998). Consequently, the extensional interpretation, proposed independently but simultaneously by Dinter and Royden (1993) and Sokoutis et al. (1993), launched a debate about the significance of the intense ductile deformation observed in metamorphic rocks at the scale of the Southern Rhodope, from Sideroneron to Kerdylion. Even if the interpretation of the Southern Rhodope as a metamorphic core complex seems to be widely accepted (e.g. Dimitriadis et al. 1998; Kilias et al.1999), it is useful to recall the arguments in favour of an extensional origin of the SRCC, considering the complexities due to the superposition in time and space of extension effects over pre-existing thrust structures.

Kinematics of ductile deformation

The most striking structural character of the SRCC is the rather homogeneous attitude of planar and linear components of pervasive metamorphic rock fabrics and the consistent sense of shear indicated by associated kinematic indicators, at the scale of the whole core complex, i.e. over hundred kilometres from NE to SW as well as from SE to NW.

Despite local perturbation, mainly related to late deformation and especially to normal faulting, the metamorphic rocks display a flat-lying foliation (Fig. 3) and a stretching lineation rather uniformly oriented, from NE–SW to the North to ENE–WSW to the South (Fig. 1a). In the areas of Nestos, to the NE, and Kerdylion, to the SW, foliation is bent downward to steeper dips (Fig. 3).

Almost everywhere the orthogneisses have mylonite-type fabrics, with well-defined C′ type shear bands (Berthé et al. 1979), and contain bands of dark ultramylonites with rather common rolling structures (Van Den Driessche and Brun 1987). The presence of ultramylonite bands indicates local high-strain intensity and associated displacement. C′ type shear bands are also common in paragneisses and in layered marbles. The plutons of Symvolon (Sokoutis et al.

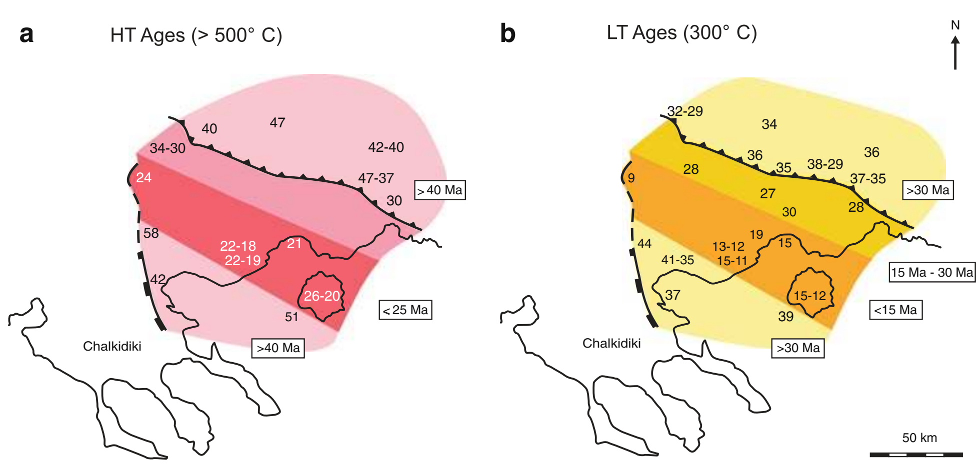


Fig. 2 Geochronological ages in the Southern Rhodope Core Complex for closing temperatures of 500°C or higher (**a**) and of 300°C (**b**). In both diagrams, the *darker band* corresponds to the youngest ages in the inner SRCC. Data from Del Moro et al. (1990), Dinter (1998), Dinter et al. (1995), Harkovska (1983), Harre et al. (1968), Hejl et al. (1998), Kokkinakis (1980), Kronberg (1969), Kyriakopoulos et al. (1989), Liati and Seidel (1996), Liati and Gebauer (1999), Lips (1998), Marakis (1969), Meyer (1968), Paishin et al. (1974), Sklavounos (1981), Soldatos quoted in Haubold et al. (1997), Wawrzenitz and Krohe (1998)

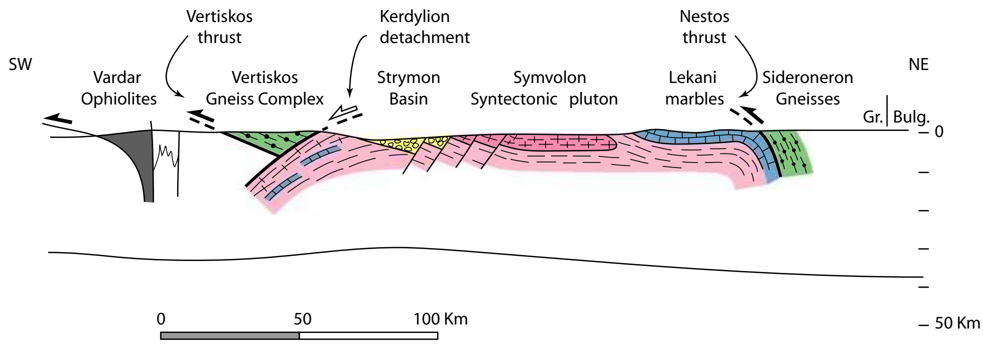


Fig. 3 Synthetic cross section of the Southern Rhodope Core Complex and neighbouring units. For location see location in Fig. 1a

1993; Dinter and Royden 1993) and Vrondou (Kolocotroni and Dixon 1991) display pervasive C/S type fabrics that indicate syntectonic emplacement (Gapais 1989). The sense of shear deduced from these shear criteria, i.e. the direction of movement, is consistent top to the SW or WSW (Dinter and Royden 1993; Sokoutis et al. 1993; Burg et al. 1996; Moriceau 2000).

In layered marbles, where calcite layers alternate with impure marble and dolomitic layers, boudinage and isoclinal folding with fold axes nearly parallel to stretching lineation with occasional sheath folds is rather common. Boudinage indicates a component of vertical shortening in the bulk finite strain. Stretching parallel fold axes and sheath folds, which mostly result from reorientation of linear elements during progressive deformation, attest for high values of principal stretching axis λ_1, i.e. high-strain intensities with a value of λ_1 commonly higher than 4.0.

The ductile fabrics described above, so specific to the core complex, and in particular the stretching lineation, have been interpreted in terms of either thrusting toward the SW (Burg et al. 1990, 1996; Ricou et al. 1998) or due to extension related to a SW-dipping detachment located in the Strymon Valley (Dinter and Royden 1993; Sokoutis et al. 1993; Moriceau 2000). Whether the stretching lineations shown in Fig. 1a represent thrusting or extension is therefore a relevant question. On one hand, stretching lineations observed in the syntectonic plutons of Kavala or Vrondou are undoubtedly related to Oligocene–early Miocene extension; on the other hand, those observed in the marbles and orthogneisses may be mostly related to Cretaceous thrusting, despite the fact that they have the same orientation than those of the plutons (Fig. 1a). This means that both, thrusting and extension occurred along similar principal directions of stretching. In fact, the metamorphic fabric is composite. This is demonstrated by the structures observed in the vicinity of the Symvolon Pluton (Fig. 4), which emplaced within interlayered marble and gneiss during the early Miocene (Kyriakopoulos et al. 1989; Dinter et al. 1995). The granite is strongly deformed and exhibits pervasive C/S fabrics, whose intensity increases toward the contact with the country rocks, with a NE–SW-oriented stretching lineation. The sense of shear is everywhere top to the SW. During pluton emplacement, the country rock was already deformed as demonstrated by the dykes of the Symvolon Pluton that cut at high angle the shallow-dipping gneiss foliation (Fig. 4a).

The intensity of shearing deformation in the pluton is such that the country rocks must have been sheared and stretched at the same time. Consequently, any previous linear element within the country rock was likely rotated toward the principal stretching direction. For this reason, even if the gneisses and marbles had a previous lineation oblique to the stretching direction developing in the granite, it has been rotated close to the new stretching lineation. This interpretation is strongly supported by dyke deformation in the vicinity of the Symvolon Pluton. Figure 4a shows a gneiss outcrop with two sets of dykes cross cutting the foliation of the country gneisses. The youngest dykes cut the foliation at high angle, whereas the oldest ones have been sheared (top to the SW), rotated to low obliquity to gneiss foliation and stretched giving pinch and swell structures. Figure 4b displays boudinage and pinch and swell structures of dykes with different thicknesses and different obliquity to the foliation. If we assume that dykes emplaced almost vertical, i.e. perpendicular to a nearly horizontal shear direction, the commonly observed dyke rotation to obliquities of less than 20° with the shear plane (gneiss foliation) indicates minimum γ values (in terms of simple shear) of around 3. Corresponding amounts of stretching (magnitudes of the principal finite strain axis λ_1 of the order of 3.3) are able to reorient most of previous planar and linear fabrics at low angle to the principal plane $\lambda_1\lambda_2$ and principal axis λ_1 of the finite strain ellipsoid (where: $\lambda_1 \geq \lambda_2 \geq \lambda_3$). Consequently, even if foliation and lineation of the metamorphic rocks have an older deformation history, including possible deformation related to Cretaceous age thrusting, they are strongly reworked by the latest horizontal stretching and can be accepted as markers of the extensional history.

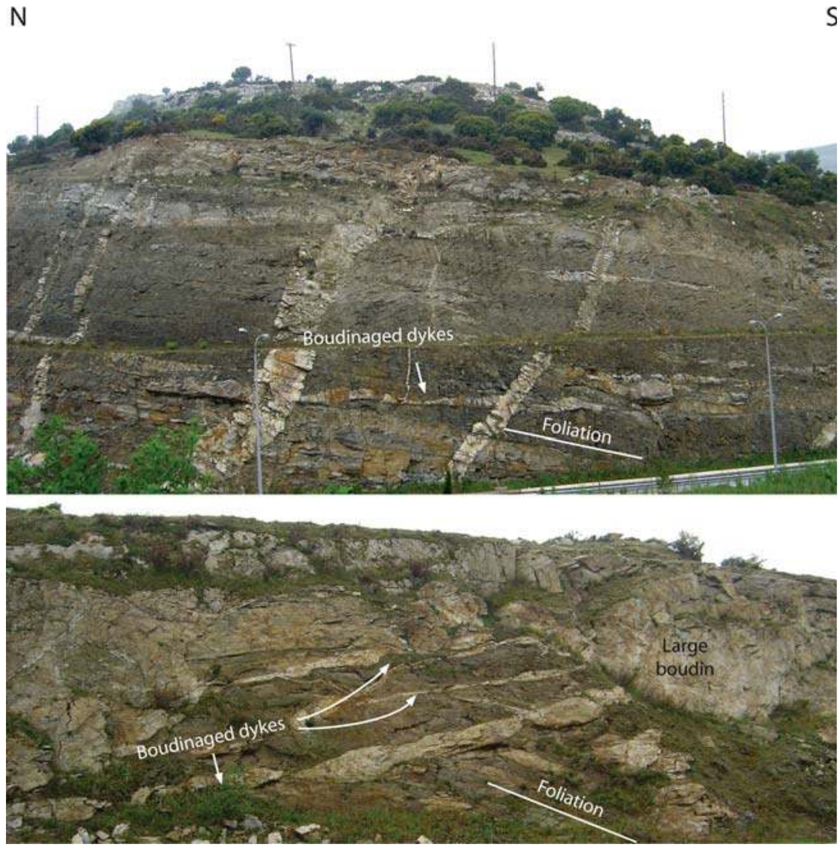


Fig. 4 Deformed dykes in the country rocks of the Kavala pluton road cut along the motorway NE of Kavala. The earlier dykes trend at small angle to the orthogneiss foliation and are strongly stretched and boudinaged. The younger ones crosscut the orthogneiss foliation at high angles

The Kerdylion detachment zone

The exhumation of the core complex has been initially related to a southwest-dipping detachment zone located to the north of the Strymon valley (Dinter and Royden 1993; Sokoutis et al. 1993). However, field evidences strongly question the validity of such an interpretation. The oldest sediments in the Serres basin, above the detachment, (Fig. 1b) are Tortonian, whereas the end of the exhumation history of the metamorphic rocks, as indicated by fission track data (Hejl et al. 1998), is early Miocene. This directly leads to an impossible scenario according to which the sedimentary infilling of the basin, supposed to have been taking place directly on the detachment's hanging wall during its activity, is younger than the end of the exhumation of the metamorphic rocks close to the detachment. The contact between sediments and metamorphic rocks at few places is a low angle fault zone that more frequently corresponds to either steeply dipping normal faults or to depositional basal contacts. In the Thassos Island, the low-angle basal contact shows evidence of displacement but does not correspond to a detachment. As discussed in detail in a following section, this low-angle fault zone represents a previous lithological contact reactivated during flat-ramp-type décollement in Pliocene–Pleistocene times. This of course is significantly younger than the exhumation of the metamorphic rocks. For the above reasons, the so-called ''Strymon valley detachment system'' (Dinter and Royden 1993; Wawrzenitz and Krohe 1998; Krohe and Mposkos 2002) cannot be considered as a detachment in the sense of either Wernicke (1985) or Wernicke and Axen (1988). The following section, entirely dedicated to Thassos, gives a new interpretation of this structure in terms of décollement within the upper brittle crust during Pliocene–Pleistocene times.

A better detachment candidate at the SRCC scale is the Kerdylion detachment that separates the Kerdylion massif from the Serbo-Macedonian Massif of the Chalkidiki Peninsula (Fig. 1). This major structure was either considered as a thrust by Burg et al. (1996) or as a detachment by Dinter (1998) and Krohe and Mposkos (2002) but in the latter case as not directly related to the Southern Rhodope Core Complex. It corresponds to WSW-dipping thick zone of mylonites and ultramylonites derived from the migmatitic gneisses and granites of the Kerdylion massif. All kinematic criteria indicate a-top-to the WSW sense of shear. This detachment is the major tectonic boundary controlling the ductile extension of Northern Aegean. Toward the north it disappears below the sediments of the Strymon Basin but probably correlates at the Eastern part of the Strymon–Serres Basin, with the low dipping C/S mylonites and cataclasites of the Elaion pluton, a small tabular-shape granitic body close to the Vrondou Pluton.

The available geochronological ages in Kerdylion and Vrondou areas (Fig. 2) suggest a middle Eocene age for the onset of the ductile extension and the associated Kerdylion Detachment. This strongly suggests that extension in the Aegean started earlier than previously proposed (e.g. Gautier et al. 1999; Jolivet et al. 2004), coeval with the ongoing thrusting of the South Aegean, as argued by Krohe and Mposkos (2002). From this point of view, it is worth noting the occurrence of a late Eocene–early Oligocene basin in the Rhodope Massif of SW Bulgaria (Burchfiel et al. 2003; Kounov et al. 2004).

The late Neogene sedimentary basins

In the southern Rhodope, the oldest Neogene sediments are Serravalian in the Nestos delta (Kousparis 1979), to the NE of the Prinos basin, (Fig. 1b) and Tortonian in almost all the other basins (Lalechos 1986). In other words, sedimentation is, on average, more than 30-My younger than the onset of extension. To the south, sediments partially cover the Kerdylion detachment and, to the north, those of the Drama Basin nearly reach the Nestos thrust (Fig. 1a). Instead of being located close to the detachment, like in classical models of core complexes, the basins are largely dispersed over of the whole core complex. Therefore, both in terms of timing and location, the late Neogene basins of southern Rhodope do not display simple relationship with the SRCC. It is, however remarkable that they formed on each side of the young thermal axis of early Miocene age, (compare Figs. 1, 2). The small time gap between the timing of the ductile crust exhumation, in this particular domain of the core complex, and the age of oldest sedimentation in the surrounding basins, strongly suggests that the two phenomena are related.

Thassos

Lithology

The main lithological units of the Thassos Island are from base to top (Fig. 5): (1) a lower unit of marbles with intercalations of paragneisses and micaschists, (2) a slab of gneisses dominantly derived from granitoids and rhyolites but also including paragneisses and micaschists, (3) an upper unit of marbles with some intercalations of paragneisses and micaschists and numerous amphibolite bodies, (4) some small lenticular units of migmatites and gneisses and (5) non-metamorphic Neogene conglomerates.

A Stephanian intrusion age of the orthogneisses has been obtained with the Pb–Pb evaporation method on single zircons (Turpaud and Reischmann 2003). This confirms, as in many other places in the Greek Rhodope, that the gneiss units likely represent a Hercynian-type basement on top of which the Tethyan sediments were deposited. The paragneisses associated with the orthogneisses could represent either Palaeozoic sediments involved in the Hercynian orogenic cycle or the earlier sediments of the Tethys sedimentary sequence, to which the upper marble unit more likely belongs. Pollen dating in the upper part of the conglomerates, close to Limenaria village, has given a late Pliocene–early Pleistocene age (Lyberis and Sauvage 1985).

The general structure of the Thassos Island (Figs. 5, 6) results like most of the SRCC from the superposition in time of three tectonic events: (1) thrusting that brings the slab of gneisses and migmatites and the overlying upper marble unit on top of the lower marble unit, (2) ductile deformation that gives to all metamorphic rocks a strong planar and linear fabric, generally parallel to lithological layering, and (3) normal faulting responsible for the development of kilometre-scale tilted blocks in the south-western part of the island (Figs. 5, 6).

Kyanite-sillimanite bearing micaschists close to the main thrust near Theologos yield PT conditions of 5.5 ± 1.5 Kb and 600 ± 50°C. These micaschists also show evidence of incipient partial melting, coeval with the ductile fabric related to extension. In the Stavros Peninsula, also close to the base of the main thrust sheet, garnet amphibolites yield temperatures ranging from 545 to 660°C—i.e. in the range of the previous estimate—but significantly higher pressures from 6.5 to 9.5 Kb (D. Kostopoulos 2004, personal communication). This suggests that at the onset of extension the gneiss unit was at a temperature close to 600°C and at a depth of 25 ± 5 km.

Sokoutis et al. (1993) interpreted the ductile deformation of Thassos as the result of early Miocene extension due to the similar deformation and age of the syn-kinematic Symvolon Pluton (Kyriakopoulos et al. 1989). This was later confirmed by Wawrzenitz and Krohe (1998) through extensive Rb–Sr and U–Pb dating that demonstrates a rather continuous-cooling history of Thassos metamorphic rocks from ca 700 to ca 300°C between 26 and 12 Ma (Fig. 7) in the rocks affected by pervasive ductile deformation. However, these authors also obtained ages of around 50 Ma for the small units of gneisses and migmatites located along the Limenaria basin (''Upper metamorphic unit'' in Fig. 5) showing that these rocks were already incorporated in the upper brittle crust during ductile extension. This led them to consider the basin boundary as the trace of a first low-angle detachment fault.

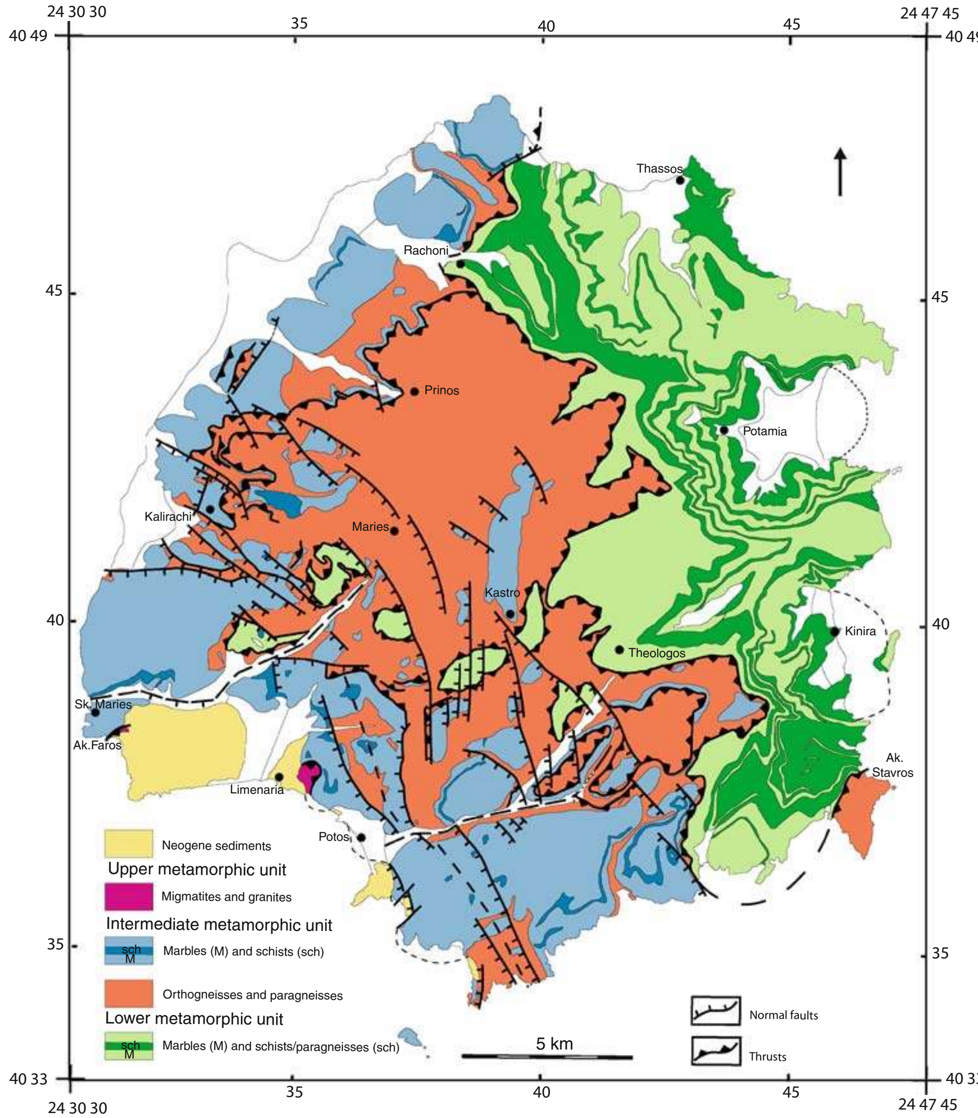


Fig. 5 Geological map of the Thassos Island. Lithological boundaries are mostly from Zachos (1982). Mapping of major thrust and normal faults is from the present work

Thrusting

At the scale of the island, thrusting is responsible for the superposition of the gneiss on top of the lower metamorphic unit (Fig. 6a). The main thrust sole, defined by the basal contact of the gneiss slab, is consideredan extensional detachment by Wawrzenitz and Krohe (1998). Imbricate slices of gneisses and marbles define several flat-ramp-type thrust structures of a km-scale (e.g. see the Rachoni Kalirachi area in Fig. 5). Similar structures can be also observed at outcrop scale in this area.

There are only two sites, Stavros Peninsula to the SE and the cape east of Thassos city to the north (see locations in Fig. 5), where rock fabrics can be attributed to the thrusting event. In these two sites, N–S-trending stretching lineations are overprinted by E–W-trending lineations associated with the ductile extension. This suggests that the direction of thrusting was roughly NS. Shear criteria associated to these N–S-trending lineations are too unclear to allow a sense of shear and thrusting to be proposed. With reference to the above discussion on reorientation of lineations, in the country rocks of the Symvolon Pluton during syn-kinematic emplacement, it is interesting to note that the two sites where two superposed lineations have been identified correspond to localities where the second lineation, associated to extension, is trending E–W, almost perpendicular to the previous N–S lineation. A right angle between a linear element and a direction of stretching is effectively the best configuration for a pre-existing lineation to be preserved from reorientation. This suggests that where the second lineation is trending NE–SW any previous NS lineation has been reoriented in the direction of the new extensional lineation.

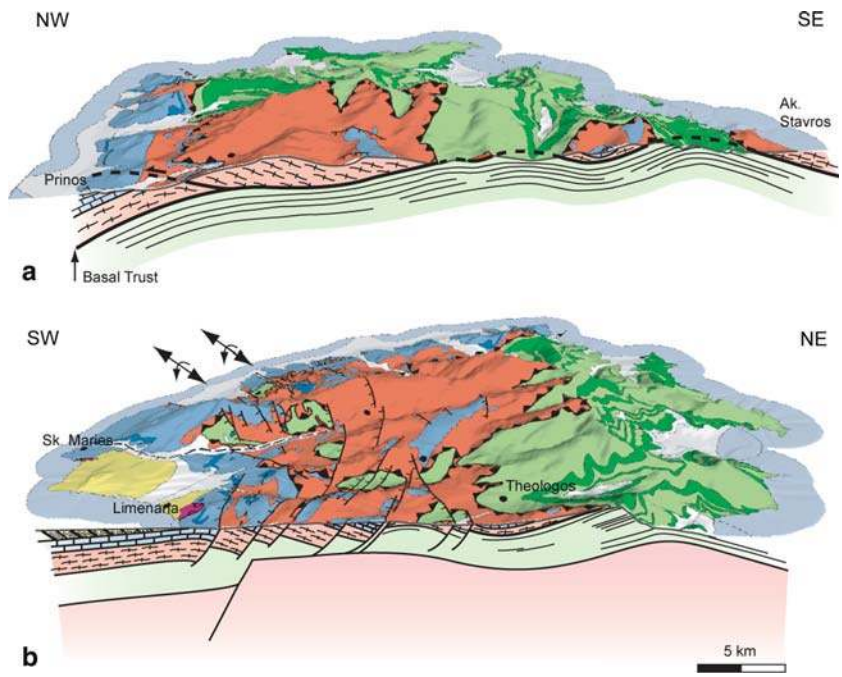


Fig. 6 3D diagrams showing the main structures resulting from thrusting (**a**) and from brittle extension (**b**)

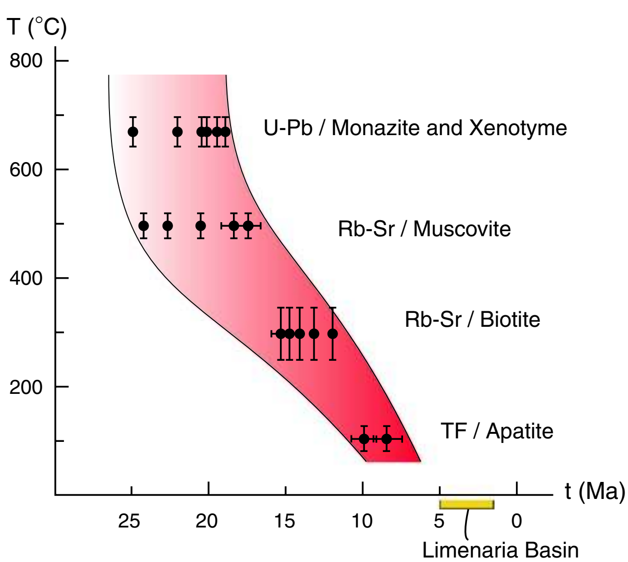


Fig. 7 Cooling of the Thassos metamorphic rocks in and relation with deposition of sediments. Geochronological data from Wawrzenitz and Krohe (1998) and Weingartner and Hejl (1994). Ages of sediments are from pollen analyses by Lyberis and Sauvage (1985)

In absence of stretching lineations, the geometry of thrust fault branching at map scale between Rachoni and Kalirachi (Figs. 5, 6a) would suggest NW-directed thrusting. It is therefore possible that the observed geometry could correspond to a lateral ramp or to ramp perpendicular to the thrusting direction but reoriented toward the direction of extension.

Ductile extension

Ductile extension in Thassos presents the same characters as those described for the whole SRCC. All rocks have a strong planar fabric, in general parallel to lithological layering, and most often display a stretching lineation and non-ambiguous shear criteria.

The orthogneisses have everywhere a mylonitic fabric giving to the rock a strong layering, marked by thin dark bands of ultramylonites from sample to outcrop scales, visible in the landscape (Fig. 8a). In the orthogneisses, C′-type shear bands (Berthé et al. 1979) are pervasively developed (Fig. 8b). The fact that shear fabrics that develop are of C′-type instead of C/S-type indicates a prograde deformation (Gapais 1989) and therefore is in good agreement with a basement granitoid origin for the orthogneisses. At all studied sites, the sense of shear is consistently top to the W or SW. Analysis of grain textures in thin sections shows that deformation started with high-temperature plastic flow at temperatures higher than 500°C, in agreement with temperature estimates from metamorphic parageneses and progressively evolved toward lower temperatures, locally down to cataclastic flow (see photographs in Wawrzenitz and Krohe 1998). Locally, a first mylonitic foliation defines recumbent folds with a second foliation, parallel to the axial surface. This indicates that the overall gneiss fabric more probably is a composite fabric that results from the superimposition of ductile extension over a pre-existing fabric likely related to thrusting.

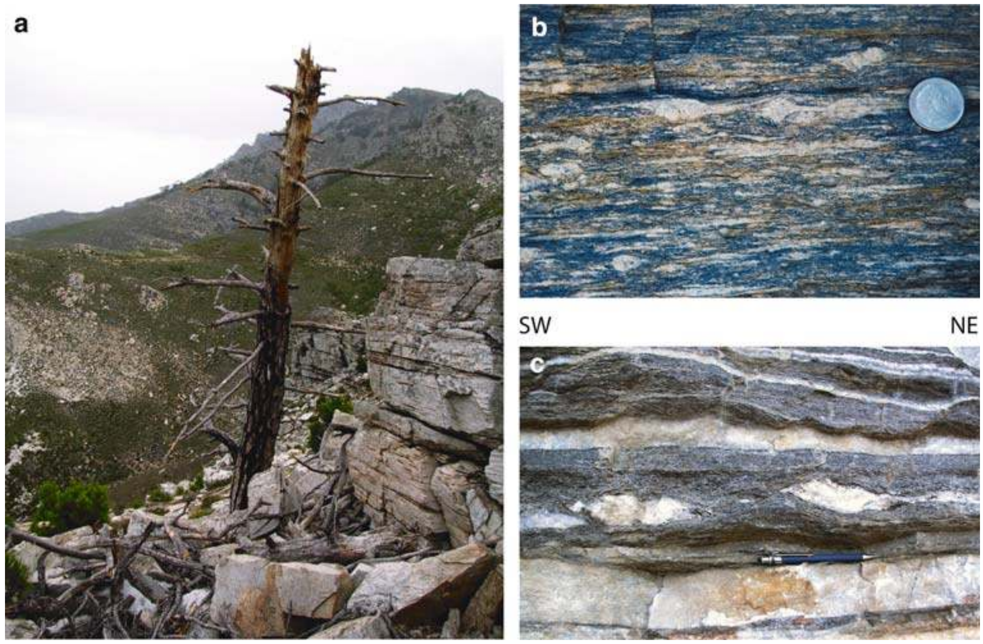


Fig. 8 Flat-lying foliation of the orthogneisses (**a**). C′-type shear bands in orthogneiss (**b**) and in marbles and micaschists (**c**)

In layered schists and marbles, C′-type shear bands are also rather common (Fig. 8c) giving like the orthogneisses senses of shear consistently top to the W or SW. Boudinage that occurs at various scales in layered marbles (Fig. 9a) and associated amphibolites is a rather common structure of the Thassos Island. It indicates that a component of layer perpendicular to shortening is combined with the top to W or SW shearing. Isoclinal folds always characterize small-scale folding with axes parallel to the stretching lineation (Fig. 9b) and sheath folds are rather common. As already argued for the reorientation of linear elements, such a systematic orientation of fold axes is a good indicator of high strain intensity. Moreover, the presence of sheath folds demonstrates that stretching is higher than 400% at least where they are observed.

Maps of foliation and stretching lineation (Fig. 10a, b) show that even if the foliation attitude varies at island scale, due to post-foliation deformation, stretching lineations display a regular curved pattern from ENE trends to the NE to SW trends to the S and SW. Shear criteria yield a very consistent top to the SW sense of shear, i.e. the direction of movement (Fig. 10b).

Rb–Sr and U–Pb ages (Wawrzenitz and Krohe 1998) together with apatite fission track ages (Weingartner and Hejl 1994) show that the Thassos rocks have undergone continuous cooling between 26 and 9 Ma, prior to sediment deposition in the Limenaria basin (Fig. 7). However, Wawrzenitz and Krohe (1998) argue for a complex extensional history with two major stages of ductile extension from 26 to 23 Ma for a pervasive mylonitisation and from 21 to

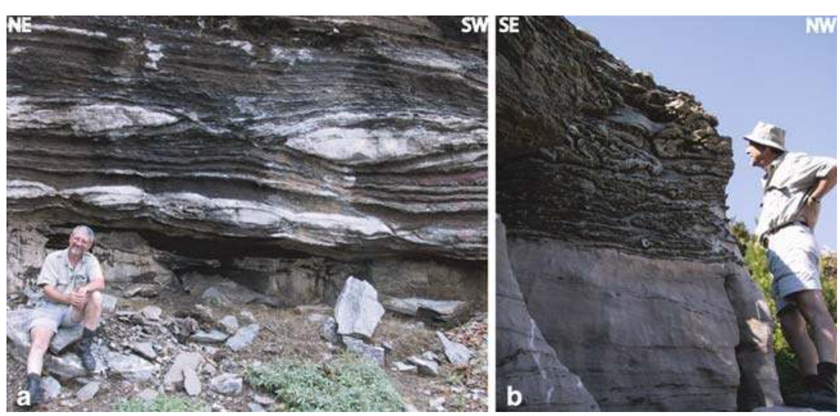


Fig. 9 Structures in marbles: boudinage (**a**) and folds with axes parallel to the stretching lineation (**b**)

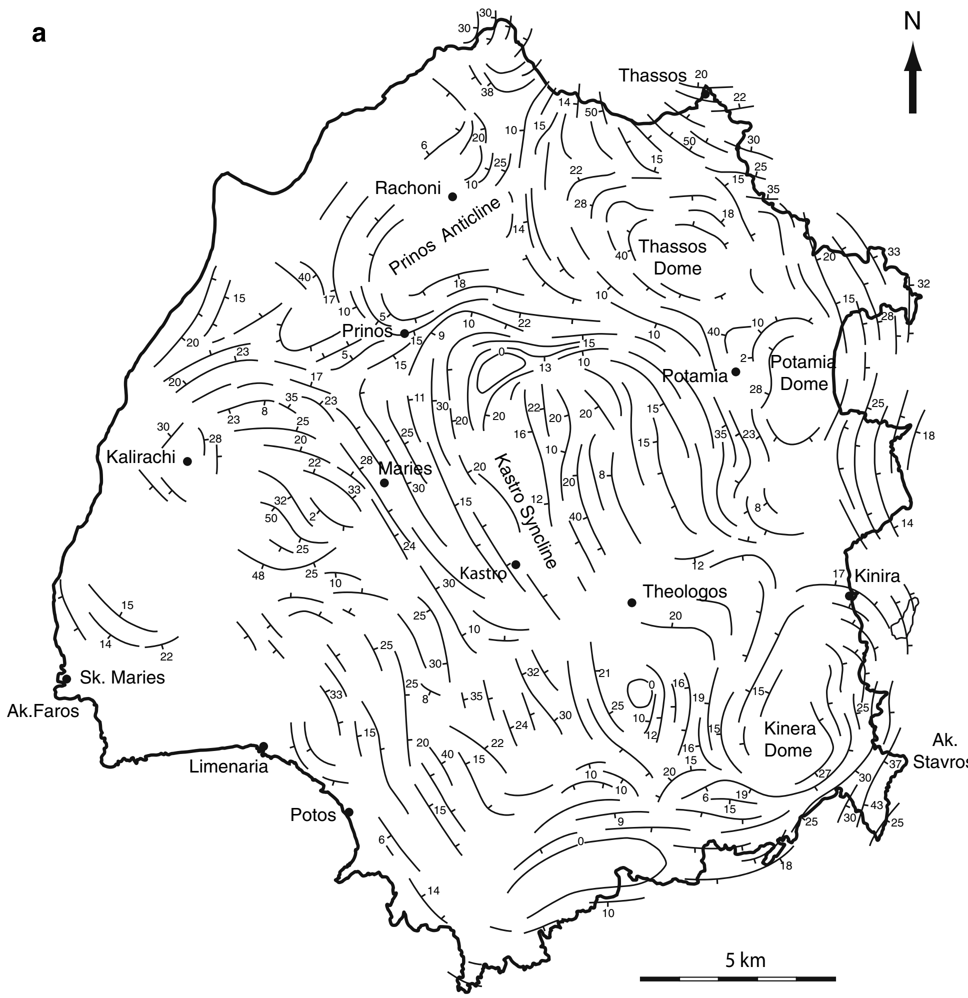


Fig. 10 Structural maps: **a** foliation trajectories (numbers give dip values). **b** Stretching lineations. The *arrowhead* indicates the sense of shear. *Numbers* correspond to plunge values located on the direction of lineation plunge

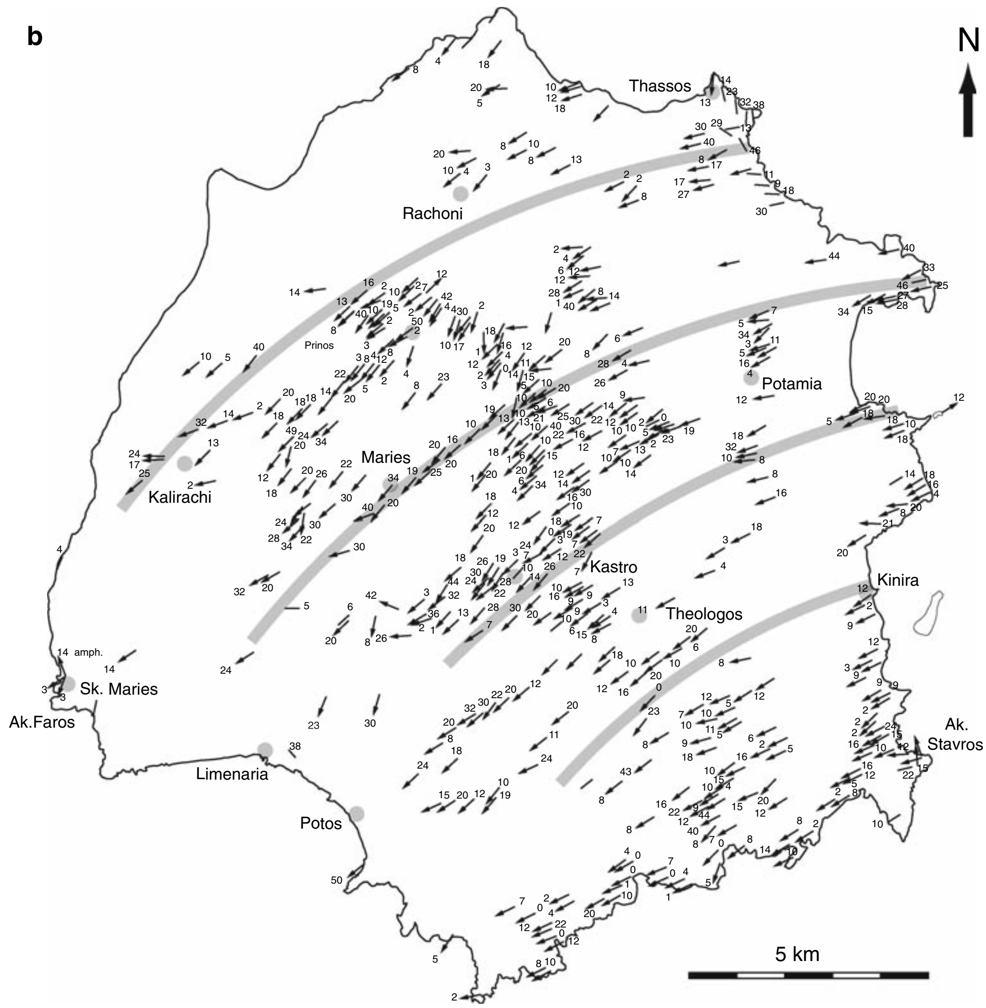
15 Ma for the formation of discrete detachment surfaces that decoupled lower and intermediate units.

Brittle extension and development of the Limenaria basin

The layer parallel foliation is affected by late brittle deformation that is responsible for the large-scale structure of the island (Figs. 6a, 10a). Along the eastern coast, foliation defines a large-scale anticline with three internal domal-type culminations, namely the Thassos, Potamia and Kinera domes. The mean anticline axis trends NS to the south and, toward the north, bends to join the Prinos anticline whose axis is WSW–ENE. To the SW of the island, the foliation is affected by large-scale, dominantly SW-dipping normal faults (Figs. 5, 11). These faults define km-scale tilted blocks (Fig. 12) and are responsible for the mean NE-dipping attitude of the foliation (Fig. 10b). Between the eastern anticline and the southwestern tilted blocks, the foliation defines the broad Kastro syncline (Fig. 10a). Both the eastern anticline and the southwestern tilted blocks have a strong imprint on the geomorphology of the island.

Remnants of a late Neogene basin, known as the Limenaria basin, occur along the southwestern coast from Scalar Maries to the most southern island cape (Fig. 5). The largest one offers a continuous cross-section, perpendicular to the main bedding trend, along 6 km from Scala Maries to Limenaria (Fig. 11). The other smaller basin remnants allow an interpolation that shows the constant NNW–SSE bedding trend at island scale and that also offers several well-exposed sites of the basal basin contact (Fig. 11a). With the exception of the northern border of the basin, the bedding displays a very constant dip of 30° to the ENE (Figs. 11, 13). The basin is mainly filled with conglomerates with one interval of fine-grained clastics (Fig. 13b) and one interval with olistoliths close to Limenaria. The whole basin fill is intra-continental and includes lacustrine turbidites (F. Guillocheau 2003, personal communication). Two sites, 1–2 km to the west of Limenaria, have been dated with pollens as late Pliocene and early Pleistocene (Lyberis and Sauvage 1985).

Fig. 10 continued



Therefore, the oldest layers exposed along this section could be of early to middle Pliocene. Whatsoever, the sediments were deposited by the very end of, or significantly after exhumation of the metamorphic rocks (Fig. 7).

Detailed mapping does not reveal the existence of any major normal fault within the basin. The largest observed fault offsets do not exceed few meters. This means that the regular 25–30° dip of the beds toward the ENE does not result from block tilting but represents a rollover-type geometry with a minimum amplitude of 6 km (Fig. 11). The observed normal faults belong to two main families: either sub-vertical or dipping around 30° to the WSW. The bisector of the acute angle between the two fault families is perpendicular to bedding indicating that faulting started whilst the layers were still nearly horizontal. It also means that the faults rotated toward the ENE together with bedding during rollover formation.

At map-scale, the sediments deposited above of marbles with few remnant blocks of gneiss and migmatites dated around 50 Ma along the contact (Fig. 5). Where the contact of the sediments with the metamorphic rocks can be best observed at (Fig. 13a), the underlying marbles are finely brecciated and dolomitized about to a depth of nearly 2 m. Their surface that dips regularly 6° to the WSW is corrugated with crude striae trending WSW. The dip of the bedding remains at around 30° even very close to the contact (Fig. 13a) without any strong evidence of deformation in the conglomerate layers close to the contact.

All available data clearly demonstrate that this contact cannot be considered as a core-complex detachment, in the most classical sense, contrary to the Wawrzenitz and Krohe's (1998) conclusion. The underlying marbles show no evidence of a finite strain gradient of ductile deformation. The two meters of marble breccias result from layer-parallel brittle shear. Sediments even close to the contact are not deformed. Available geochronological and palynological data show that sediments were deposited mostly after exhumation of the metamorphic rocks (Fig. 7). Away from the contact, marbles and underlying orthogneisses are affected by steeply dipping normal faults, trending perpendicular to the strike of the basin sediments (Fig. 11)

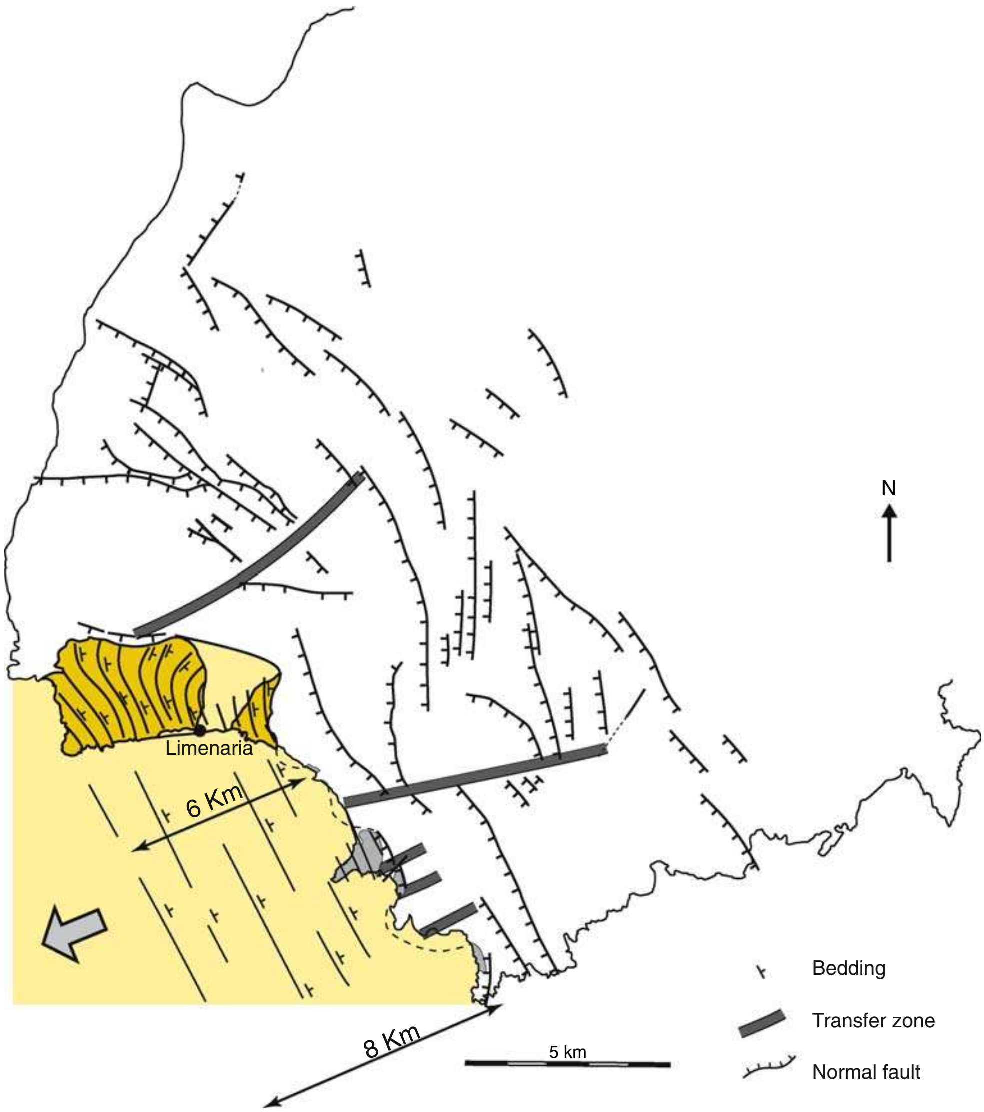


Fig. 11 Map of the Limenaria Basin with bedding trends, normal faults and transfer zones

Fig. 12 Tilted blocks represented in the 3D diagram of Fig. 6b looking towards the West

showing that they were part of the brittle crust at the time of sediment deposition.

Instead of a detachment—i.e. a major shear zone cutting down section and bringing upper crustal rocks on top of middle to lower crustal rocks—faulting and associated basin development are more likely related to a flat-ramp-type extensional system (Fig. 14). The lower metamorphic unit plays the role of a décollement between an upper

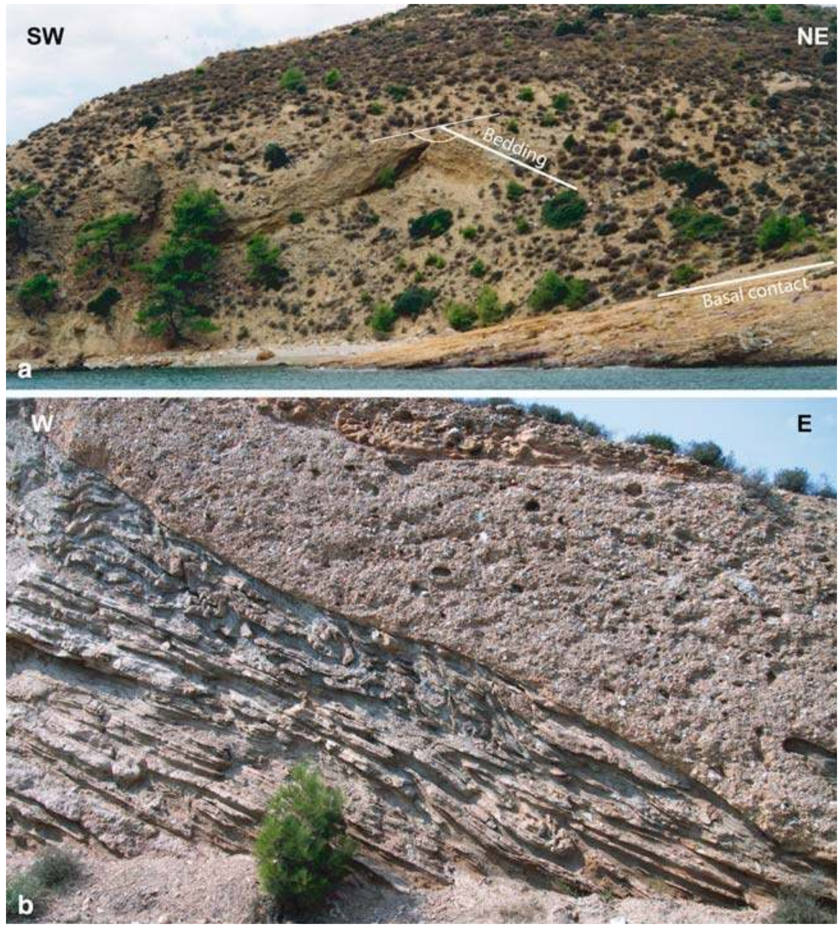


Fig. 13 **a** View of the basal contact of the Limenaria Basin, close to Potos. The conglomerates have a 30° dip to the ENE, close to the basal contact. that is parallel to the foliation of the underlying marble. **b** Conglomerates and fine grain sediments with a 30° dip toward the ENE, close to Limenaria. Folds developed in unconsolidated fine-grain sediments as a result of top to W horizontal shear during conglomerate mass-flow emplacement, prior to eastward tilting

brittle slab, made of the intermediate and upper metamorphic units, and a deeper high-strength layer that, however, does not outcrop. The décollement occurred within the lower unit that is dominantly composed of marbles. As indicated by the mineralogical and geochemical analysis of hydrothermal deposits along and around large steep faults of the upper unit, the décollement was likely accompanied by fluid circulation at temperatures of around 200°C (Boulvais et al. 2007). At the onset of displacement, steep normal faults define ramps in the brittle units connected by layer-parallel shear within the décollement layer (Fig. 14). The resulting flat-ramp-type displacement pattern leads to the formation of an anticline in the merging ramp area and of a syncline above the blind ramp. With increasing displacement, sediments deposited within the piggy-back-type syncline basin with rollover geometry. As the décollement layer undergoes combined layer-parallel shearing and layer-perpendicular shortening, normal faulting and block tilting develops in the upper unit at the back of the basin. One direct implication of such a flat-ramp-type extension is that the basin width provides a direct estimate of the amount of displacement, around 6 km for the Limenaria basin (Fig. 11).

At regional scale, the Limenaria basin is connected to the SW to the Orfanos basin (Fig. 1) whose asymmetric structure results from a major SW-dipping normal fault that controls a more than 3,000 m thick depocentre above the Messinian salt (Fig. 15). This is well documented by industry seismic lines (Mascle and Martin 1990). The Thassos décollement is expected to be connected with the major Orfanos normal fault, combining into flat-ramp-type geometry at upper crustal scale (Fig. 15).

In summary

In the Thassos metamorphic rocks, ductile extension started in mid-Oligocene times (Wawrzenitz and Krohe 1998) at a temperature close to 600°C and at a depth of around 25 km. Finite strains result from a combination of layer-perpendicular shortening and layer-parallel shearing with a sense of shear consistently top to W or SW. During extension, deforming rocks cooled reaching higher crustal levels. Consequently, rocks deformed earlier in a ductile manner display a broad range of fabrics from high-temperature plastic flow to cataclastic flow that accommodated the same kinematics. Extension ends with brittle

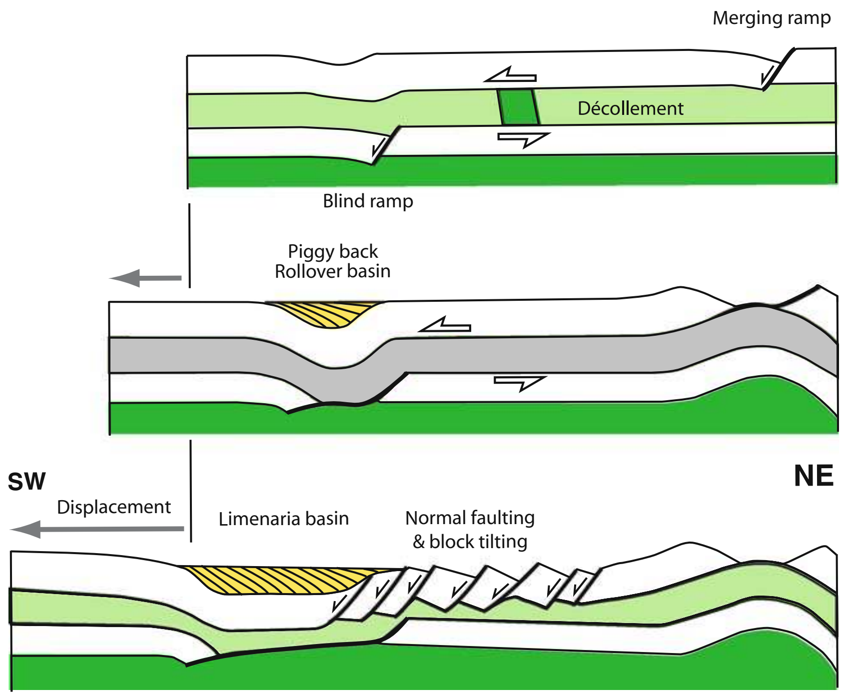


Fig. 14 Suggested model for the development of the Limenaria basin. The displacement system is of flat-ramp type. In *white* are two competent units separated by a weak layer, in *grey*, acting as a décollement. The *white arrows* indicate the sense of shear within the décollement. The sediments are deposited within a flexure of the upper competent unit above a blind ramp of the lower competent unit. The basin therefore is transported on top of the upper competent unit—i.e. piggyback basin—as it displaces above the décollement layer. Compares with the 3D diagram of Fig. 6b

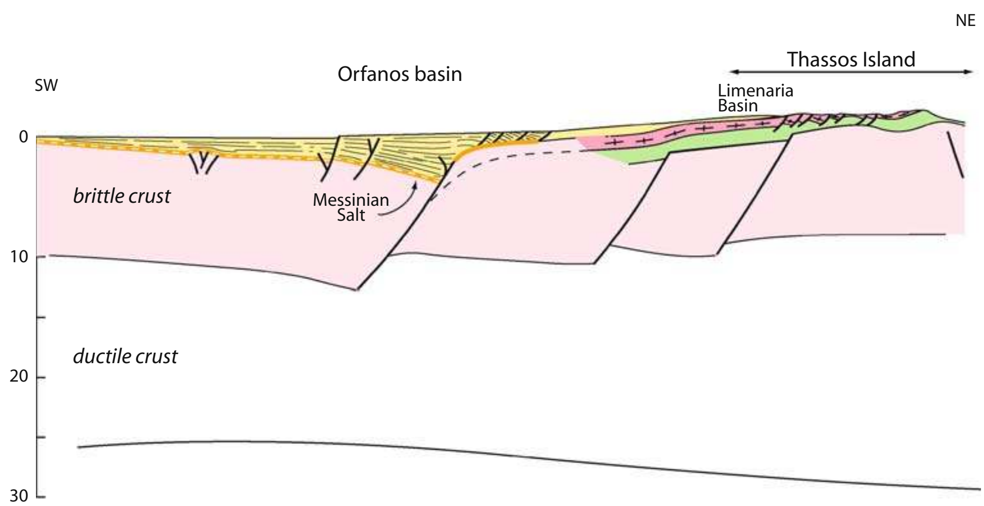


Fig. 15 Regional cross section showing the possible relationship between the onshore Limenaria basin and the offshore Orfanos basin. The geometry of the Orfanos basin corresponds to a line drawing of a seismic section presented in Martin and Mascle (1989) and Mascle and Martin (1990)

deformation during Pliocene–Pleistocene time producing km-scale tilted blocks to the Southwest of the island and a large-scale open anticline to the East. Field evidence point out that the Limenaria basin is of piggy-back-type, controlled by a flat-ramp-type décollement within already exhumed and eroded metamorphic rocks. Correlation with the offshore Orfanos basin through seismic evidence (Martin and Mascle 1989) indicates that late Neogene basins mainly developed after Messinian salt deposition.

From what has been stated above, it is obvious that the island of Thassos does not correspond to a separated core complex as proposed by Dinter (1998) and Wawrzenitz and Krohe (1998) but is a part of the larger SRCC (Fig. 1b, c). The isolation of Thassos results from the Prinos Basin development mostly in post-Messinian times, significantly after the exhumation of the metamorphic rocks.

40 My of Aegean extension recorded in the Southern Rhodope Core Complex

Our data lead to the evolutionary model depicted in Fig. 16 for the Southern Rhodope Core Complex. The onset of extension is difficult to precisely date with the available geochronological data. However, the youngest age of HP metamorphism of 42 Ma obtained by Liati (2005) provides

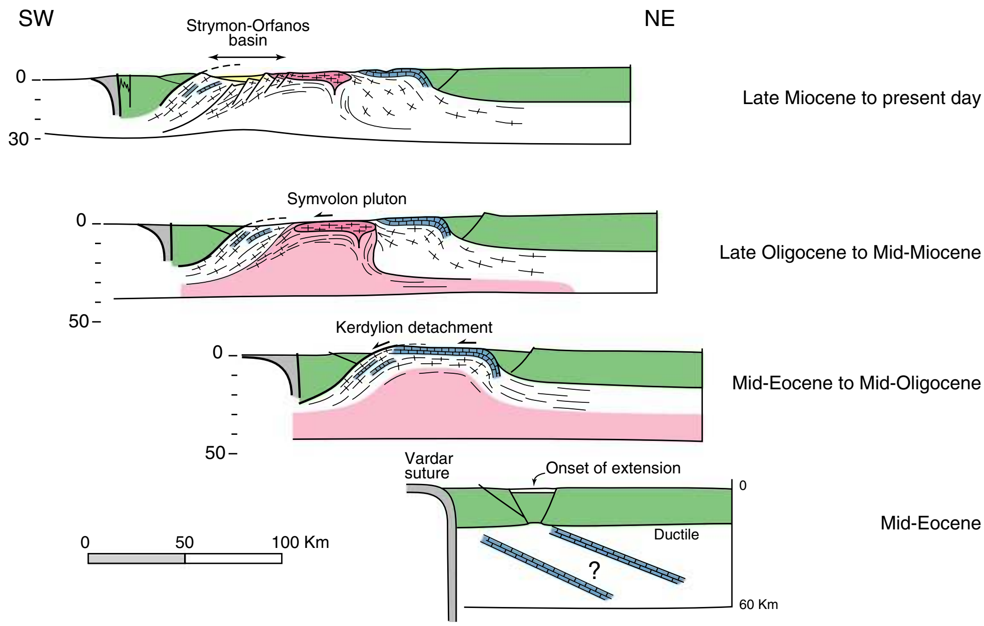


Fig. 16 Series of cross sections illustrating the main steps evolutionary of the Southern Rhodope Core Complex, from mid-Eocene to present day

an upper bound for the end of thrusting. This is in agreement with the evidence of late-Eocene extension provided by the Mesta half graben (Burchfiel et al. 2003). Therefore, the evolution that starts in middle Eocene times is still ongoing meaning that the SRCC and related late Neogene basins have recorded at least 40 Ma of extension in the north Aegean.

The model (Fig. 16) is based on restoration of the geological cross section of Fig. 3. It assumes that the Chalkidiki Peninsula and most of the Bulgarian Rhodope represent the upper brittle crust since the middle Eocene. The Moho is drawn after Papazachos et al. (1995) and Papazachos (1998). Crustal thickness at each step of the restoration is obtained from area balancing of the ductile crust estimated from the present day shape of the SRCC. The initial geometry in middle Eocene times assumes that any complex geometry of the Moho due to previous Cretaceous–early Eocene thickening was equilibrated giving a flat-Moho. However, this does not exclude that the ductile crust may contain residual inclined fabrics inherited from the piling up of thrust slices. Note that a minimum homogeneous thickness of 60 km is required at this initial stage to justify the present day cross-section geometry.

The evolution of the core complex shows three main stages. (1) The time interval from mid-Eocene to mid-Oligocene includes the exhumation of an initial metamorphic dome, made of marbles and gneisses in the Falakron and Lekani areas and of gneisses and migmatites with numerous marble layers in the Kerdylion area. (2) From late Oligocene to late Miocene, the granitic plutons of Vrondou and Symvolon were emplaced synkinematicaly in the central part of the exhuming metamorphic dome. The Menikion and Pangeon areas located between the two plutons and Thassos were exhumed during this period. (3) Since the Tortonian, normal faulting controls the development of sedimentary basins such as Orfanos-Strymon, Serres, Prinos and Drama.

Compared to other core complexes, the SRCC presents a rather unusual evolution. The most striking differences with ''classical'' core complexes are: (1) the Kerdylion detachment has no associated basin of mid-Eocene to mid Oligocene age. However, such basins exist in Bulgaria (Burchfiel et al. 2003) and may have been eroded in Greece. (2) Exhumation is not permanently located against the detachment zone; latest exhumation occurs within the previously exhumed dome. It is noteworthy that this youngest zone of exhumation corresponds to the one where granitic plutons emplace. It is also remarkable that no real detachment controls this late exhumation of ''core complex in a core complex''. As observed in Thassos, the detachment is replaced by flat-ramp-type structure where marble layers intercalated between gneisses act as décollement. (3) The sedimentary basins are younger than the entire exhumation history of the metamorphic and plutonic rocks and they extend over the entire SRCC form north (Drama) to south (Strymon–Serres). It is remarkable that they are located on both sides of the late axis of exhumation Vrondou–Thassos; however, more to the SW. This suggests that, since Tortonian times, no longer metamorphic rocks were exhumed in the SRCC but extension remained active, but likely at a lower rate where the brittle crust was weakest, i.e. around the youngest zone of exhumation.

Thermo-mechanical numerical models of core complex evolution have recently shown phenomena directly comparable to the SRCC (Tirel 2005). In models with an elevated initial Moho temperature, i.e. around 1,000°C at large amounts of extension the incremental zone of extension and exhumation moves back from the detachment zone toward the centre of the previously exhumed dome. The numerical models illustrate that, as extension increases, the decrease in thickness of the whole crust reduces the effectiveness of lower crustal material to flow below the dome. As a consequence, the zone of exhumation migrates toward the centre of the dome. The unusual evolution of the SRCC, which corresponds to the initial conditions of numerical models, could accordingly be a consequence of the large amount of extension—i.e. 120 km—and related crustal thinning.

In terms of sequence and timing of events, our model is not strikingly different from the one of Krohe and Mposkos (2002). However, these authors refer to a complicated sequence of ''multiple detachments'' among which, in particular, the so-called ''Strymon detachment'' is highly questionable. The map contour of this S-SW-dipping detachment corresponds to the boundary between late Miocene–Pliocene sediments and plutonic and metamorphic rocks of the core complex as represented on geological maps published by the IGME (Greek geological survey). Most often, instead of being a low angle detachment it is in fact a steeply dipping normal fault like in the Serres and Siderocastro basins. At several places the sediments are deposited directly on top of the metamorphic rocks without any fault or detachment in between. Finally, in the Drama fault area in the neighbourhood of Alistrati a more than 8-km-wide rollover basin structure is controlled by a listric fault dipping northward, exactly oppositethe supposed detachment. We therefore propose to definitely abandon the concept of ''Strymon detachment'' introduced by Dinter and Royden (1993) and further used by Wawrzenitz and Krohe (1998) and Krohe and Mposkos (2002).

The flat-ramp-type mode of upper crustal extension exemplified in Thassos is likely typical of a thin and hot brittle crust with a strong horizontal anisotropy. First, thrusting is responsible for the slicing and piling up of the superposition of sedimentary cover above granitic basement. This gives the numerous repetitions of orthogneisses and marbles that characterize the Southern Rhodope. Then the pile is stretched horizontally by ductile extension and is exhumed close to the surface with a flat-lying attitude. In late Miocene–Pliocene times, soon after the exhumation, the crust is still hot and therefore the upper crust rather thin, likely in a range of 5–10 km. In such a hot crust, the temperature may be about 200°C at only few kilometres' depth making the marbles ductile with low strength whereas the orthogneisses are brittle with higher strength. Marble layers therefore provide efficient décollement horizons between orthogneisses layers. This results in the flat-ramp geometry of movement surfaces being accommodated by steeply dipping normal faults in the hanging wall that control the deposition of sediments. In places where two décollement levels are connected by a blind ramp, the hanging wall undergoes flexuration that controls the deposition of piggyback basin with rollover-type geometry.

Block rotation during core complex exhumation

In the north Aegean domain, numerous paleomagnetic data demonstrate clockwise, up to 30–35° block rotation since early Oligocene time (see reviews by Kissel and Laj 1988; Dimitriadis et al. 1998). To the SW of the SRCC, the Eocene plutons of the Chalkidiki Peninsula have undergone a mean clockwise rotation of 30° (Kondopoulou and Westphal 1986). To the north of the SRCC, Eocene–Oligocene granite plutons have undergone 11° clockwise rotation (Haubold et al. 1997) that is likely accommodated in the Bulgarian Rhodope by brittle faulting. A minimum differential clockwise rotation of around 20° has therefore been taken up by the emplacement of the SRCC.

The pattern of stretching lineations displays at the scale of the SRCC an overall curvature (Fig. 1a) with the mean direction varying from 40°E in the Lekani, to 60° in the Pangeon and to close to EW in the Kerdylion. Stretching lineations record the shearing deformation undergone by ductile rocks during exhumation. Ductile rocks first flow horizontally from below the two separating blocks A and B (Fig. 17a) and rise almost symmetrically in the area of separation where the detachment zone is located. In general, the metamorphic dome growth displays a simple asymmetry with the oldest exhumed rocks located opposite to the detachment zone (Fig. 17a). In the course of exhumation, the rocks cross the transient brittle–ductile transition and foliations and lineations created in the ductile crust are ''frozen'' and incorporated in the brittle crust (Brun and Van Den Driessche 1994). If the separating blocks rotate, lineations ''fossilized'' in the successive fringes of metamorphic dome growth have recorded the progressive differential block rotation. They consequently form concentric arcs around a pole of rotation.

The asymmetry of dome growth pattern (Fig. 17a) can be perturbed by a late domal rise within the core complex (Fig. 17b), as observed in the SRCC (Fig. 16). However, because stretching lineations develop perpendicular to the borders of the actual exhuming zone, lineations still form concentric arcs around the pole of rotation, if the rotation pole remain unchanged even if the sequence of growth fringes is not regular (Fig. 17b).

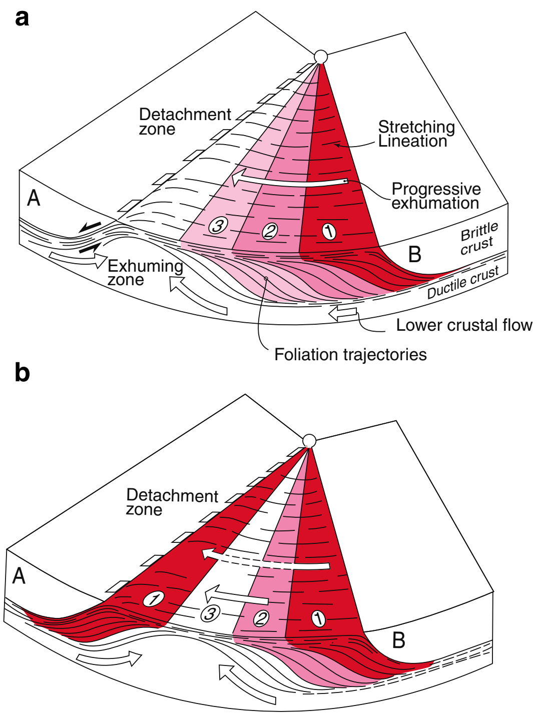


Fig. 17 Progressive exhumation of a core complex between rotating upper crustal blocks (inspired from numerical modelling by Tirel 2005; Tirel et al. 2004): **a** the exhuming zone remains close to the detachment all along the process. **b** The exhuming zone is at a late stage of evolution, located in the inner part of the core complex. Metamorphic rocks observed at surface correspond to successively ''frozen'' fringes (variable *grey* patterns). Foliations are flat lying on dome *top*. The curvature of stretching lineation trajectories reflects the progressive block rotation

Figure 18a, illustrates the best-fit circular arcs that can be obtained from the pattern of lineations at the scale of the SRCC. They correspond to a pole located about 230 km to the north of Thessaloniki. The arcuate pattern of lineations in Thassos (Fig. 10b) corresponds to an anticlockwise rotation with a pole located at around 30 km to the SE of the island. This suggests that the SRCC terminates at the SE of Thassos but longer discussion is beyond the scope of the present paper.

Using the main pole of clockwise rotation deduced from the curvature of the lineation trends and the amounts of block rotation from paleomagnetism, the Chalkidiki Peninsula has to be rotated backward (anticlockwise) by 30° and the northern boundary of the SRCC by 11° (Fig. 18b). The restoration shows that the Chalkidiki block covers almost entirely the SRCC in agreement with the mechanical models of core complexes (Tirel et al. 2004). The distance between the present day and the restored position of the Kerdylion detachment is approximately 120 km giving a minimum amount of extensional displacement. The mean extensional rate calculated from this value for 40 My is 0.30 cm/year. However, the rate of displacement has not necessarily been neither permanent nor constant during 40 My.

Conclusions

The Southern Rhodope Core Complex has accommodated at least 120 km of extension during a long history of

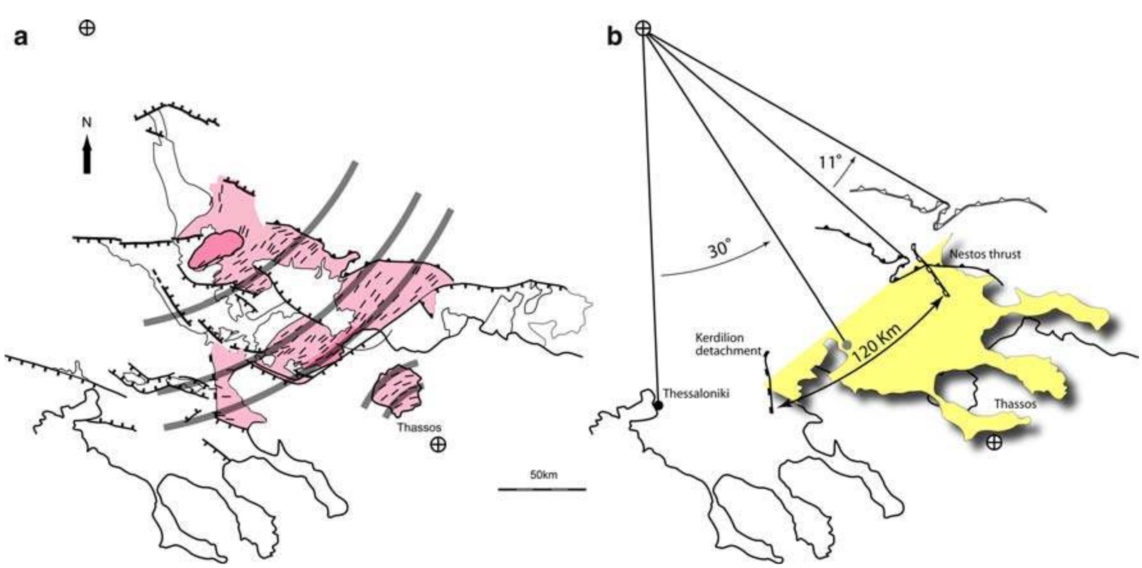


Fig. 18 Restoration of block rotation at the scale of the Southern Rhodope Core Complex. **a** Determination of the poles of rotation from the stretching lineation pattern. **b** Restoration of block rotation, taking into account the available paleomagnetic data with, in particular, mean dextral rotations of 30° for the Chalkidiki and 11° for the units located north of the Nestos thrust, respectively. The restoration shows the likely position of Chalkidiki prior to the exhumation of the SRCC. The maximum displacement onshore is in the order of 120 km. The curvature of lineation pattern in Thassos defines a secondary pole of rotation located to the SE of the island

around 40 My that can be summarized by three major steps:

1. Extension from mid-Eocene to mid-Oligocene times led to the exhumation of a metamorphic dome. The Kerdylion detachment zone that separates the SRCC from the Serbo-Macedonian units of the Chalkidiki Peninsula mainly controlled exhumation.
2. From late Oligocene to mid-Miocene, exhumation was located within the previous dome accompanied by the emplacement of synkinematic plutons (Vrondou and Symvolon).
3. Since late Miocene time, extensional basins developed above the exhumed metamorphic and plutonic rocks controlled by steep normal faults and flat-ramp-type extensional structures.

Exhumation of the SRCC is accommodated by a 30° rigid rotation of the Chalkidiki block. Ductile fabrics developed in metamorphic rocks during their exhumation have recorded the progressive rotation of Chalkidiki as illustrated, in particular, by a change in mean orientation of stretching lineations from NE to SW of the SRCC.

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