Multiple generations of extensional detachments in the Rhodope Mountains (northern Greece): evidence of episodic exhumation of high-pressure rocks

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Abstract: An integrated structural and petrological study shows that exhumation of high-P rocks of the Rhodope occurred in several pulses. The structurally uppermost Kimi Complex recording an Early Cretaceous high-P metamorphism was exhumed between about 65 and >42 Ma. The Sidironero, Kardamos and Kechros Complexes that record Early Tertiary high-P metamorphism (at least 19 kbar at 700°C) were exhumed at >42-30 Ma. Exhumation occurred with isothermal decompression. Strain episodes depict thrusting of medium/high grade above lower grade high-P rocks, syn-thrusting extension and post-thrusting extension. Polyphase extension created several generations of detachment zones, which, in sum, excise about 20 km of material within the crustal profile. This reduction in crustal thickness is consistent with a reduction of the present crustal thickness from more than 40 km to less than 30 km in the eastern Rhodope. We mapped the post-thrusting Xanthi low-angle detachment system over 100 km, from its break up zone above the Sidironero Complex (Central Rhodope) into the eastern Rhodope. This detachment shows an overall ESE-dip with a ramp and flat geometry cutting across the earlier thrust structures. The Kimi Complex is the hanging wall of all syn- and post-thrusting extensional systems. On top of the Kimi Complex, marine basins were formed from the Lutetian (c. 48-43 Ma) through the Oligocene, during extension. Successively, at c. 26 to 8 Ma, the Thasos/Pangeon metamorphic core complexes were exhumed. In these times representing the early stages of Aegean back-arc extension, the Strymon and Thasos detachment systems caused crustal thinning in the western Rhodope. Renewed heating of the lithosphere associated with magmatism and exhumation of hot middle crust from beneath the Sidironero Complex occurred. We focus on the geometry, timing and kinematics of extension and contraction structures related to the >42-30 Ma interval and how these exhumed high-P rocks. We interpret high-P rocks exhumed in this interval as a window of the Apulian plate beneath the earlier (in the Cretaceous) accreted Kimi Complex.

Exhumation of continental material that has been earlier buried to depths corresponding to 20 kbar and more is associated with reduction of at least 60 km of material from above the high pressure (high-P) rocks. Various tectonic mechanisms have been suggested, describing different mass movement paths that result in exhumation of high-P rocks. (i) 'Late-/post-collisional extension'. The buoyant thick continental crust and/or the hot lithospheric mantle cause buoyancy forces and surface uplift; the uplifted thick continental domain exerts a force on the surrounding and tends to extend ('collapse'). Surface uplift may also be caused by convective removal of the cold and heavy lithospheric mantle (e.g. Platt et al. 1998). (ii) 'Back-arc extension'. Drag on retreating subduction boundaries initiates profound extension tectonics in continental areas above the subducting plate (e.g. Royden 1993). (iii) 'Upward extrusion'. Detachment and ascent of tectonic wedges from a continually subducting continental plate occurs on concurrently active deeply rooted thrusts and higher level normal faults. Ascent is essentially controlled by buoyancy forces of the subducted material during ongoing collision tectonics (e.g. Chemenda et al. 1995).

Such processes may explain the close association of extensional and contractional structures reported in several high-P terrains. However, each mechanism demands substantially distinct driving forces.
forces and mechanical properties of the lithospheric wedge. Thus, detailed structural, petrological and geochronological investigations of high-P metamorphic terrains are a key for understanding the kinematics of large-scale mass movements associated with exhumation of deep rocks.

In this article we present results of our integrated structural and petrological research on Alpine high-P rocks in northern Greece (Rhodope Domain, Fig. 1). We will address the spatial and temporal distribution of compression and extension tectonics, the role of both in the exhumation history of high-P rocks and the magnitude of displacements on the respective detachment/shear zone systems.

Geological context and scope of work

Structural setting

Exhumation mechanisms of high-P rocks have been intensely debated throughout the Mediterranean Alpine Belt that extends from southern Spain over Corsica, the western and eastern Alps, southern Bulgaria/northern Greece, the Aegean into Turkey (Fig. 1). From the Late Oligocene to Recent, in southern Spain, Corsica and the Aegean Sea, subduction of remnants of Triassic/Jurassic oceanic lithosphere has triggered back-arc extension overprinting the structures related to collision (Royden 1993). Importantly, high-P rocks were exhumed both within such sites of back-arc extension (western Alps and Rhodope in southern Bulgaria/northern Greece, Fig. 1), and also outside such sites. In either case, exhumation is linked with extensional structures. The Greek territory is assembled by largely different tectono-metamorphic complexes from this suture zone.

The Rhodope Domain (Fig. 1) comprises Variscan continental crust, Mesozoic metasediments and remnants of oceanic crust (Burg et al. 1996; Ricou et al. 1998; Barr et al. 1999). In places, grades of Alpine metamorphism exceed 19 kbar at c. 700°C (Liati & Seidel 1996). Recently, Ultra high-P metamorphism has been detected, indicated, amongst other things, by the presence of diamond inclusions in garnets of pelitic gneisses (Mposkos et al. 2001). Probably Early Cretaceous Ultrahigh-P and Early Tertiary high-P stages occurred (Wawrzenitz & Mposkos 1997; Liati & Gebauer 1999). This domain reflects Cretaceous and Tertiary episodes of crustal thickening and extension (Kilias et al. 1997; Mposkos 1989; Dinter et al. 1995; Burg et al. 1996; Barr et al. 1999, and below).

The Rhodope Domain is located to the north of the Aegean basin: a major back-arc structure in the Mediterranean sited behind the Dinaric-Hellenic thrust belt (Royden 1993; Fig. 1). From the central Rhodope (Bulgarian part) to the Aegean Sea, and the Turkish boundary (eastern Rhodope) the crustal thickness has been reduced from above 50 km to below 30 km, as estimated from gravimetric data (Makris 1985).

Previous ideas

Early ideas considered the Rhodope Domain as a pre-Alpine (Variscan or older) 'stable block' between the Dinaric-Hellenic and the Carpathian
thrust belt ('Zwischengebirge' of Kober 1928). Since the discovery of Alpine high-P metamorphism, the tectonic setting has been discussed controversially.

(i) According to Burg et al. (1996) and Ricou et al. (1998) the Rhodope Domain consists of superimposed 'mixed' (continental and ophiolitic) and continental units ('Drama continental fragment') that both accreted/collided with Europe during the Cretaceous, along the 'Axios (Vardar) suture zone' situated to the east of the Pelagonian Zone (Fig. 2, insert map).

(ii) According to Dinter (1998), the western Rhodope Domain is composed of parts of the Apulian continental plate (his 'Rhodope Metamorphic Core Complex') exposed as a tectonic window beneath an Early Tertiary accretionary complex.

The nature, timing and kinematics of tectonic movements causing exhumation of the Rhodope Domain have also been the subject of controversial discussion: Burg et al. (1995) and Ricou et al. (1998) interpret the dominant structures as to reflect Cretaceous collision and upward extrusion.

Fig. 2. New tectonic subdivision of the Rhodope Domain and location of major detachment systems. Locations of profiles (Fig. 12) are also indicated.
of high-P rocks. This was followed by Oligocene/ Miocene extension. In Dinter's (1998) view, Apulian rocks were exhumed by Miocene extension in the Aegean back-arc, following Early Tertiary thrusting and thickening.

Scope of work

We have carried out structural and microstructural investigations of the high-P rocks of the Greek part of the Rhodope Mountains (Fig. 2) in order to elucidate the mass movements associated with the exhumation of high-P rocks. Our investigations particularly focus on the geometry, kinematics and timing of multiple generations of normal detachment systems. The Rhodope Mountains were selected as a study area, because they preserve the tectono-metamorphic imprint of a long-lasting geodynamic history including Late Oligocene-Miocene back-arc extension (Dinter et al. 1995; Wawrzenitz & Krohe 1998), and exhumation of high-P rocks prior to Aegean back-arc extension (Burg et al. 1995). The Rhodope Mountains expose the structural setting of high-P rocks over large distances, contrasting to the central Aegean Sea (Fig. 1), where high-P rocks occur isolated on the Cyclades’ islands (Vandenbergh & Lister 1996).

We newly introduce large-scale discrete low-angle detachment systems, which we mapped using the 1:50000 scale geological maps of IGME "(Institute of Geological and Mining Exploration of Greece), in the following referred to as the Xanthi, West Kardamos, East Kardamos and Kechros normal detachment fault systems (Fig. 2). We give detailed descriptions of these systems and particularly address the following questions:

1. what are the temporal and spatial relationships of these extensional structures to con-tractional structures?
2. how do the various geochronological data constrain absolute ages of inferred deformation increments?
3. how are the inferred deformation increments related to the $P-T$ path of the tectonic complexes?

General tectonic subdivision

In the eastern Rhodope Mountains, the high-P metamorphic terrain is overlain by the supracrustal eastern Circum Rhodope Zone (eastern CRZ; Fig. 2), comprising various ophiolitic sequences. K-Ar hornblende ages and apatite fission track ages both ranging between 150 and 160 Ma (review in Bigazzi et al. 1989; Hatzipanagiotou et al. 1994), indicate cooling at shallow crustal levels no later than in the late Jurassic. Associated phyllites, marbles, albite gneisses and greenschists were weakly metamorphosed to temperatures below c.400 °C (chlorite zone), indicated by the mineral assemblages Qtz-Ab-Phe-KFs-Stp (albite gneisses) and Qtz—Ab-Chl-Czo-Act (greenschists; abbreviations after Kretz 1983 and Bucher & Frey 1994). These remain undated.

We subdivide the underlying high-P metamorphic terrain into three crustal sections separated by the large scale detachment faults. A compilation of published geochronological data (Table 1; see below for references) suggests that each crustal section has a distinct geochronological record (Table 1) and that geochronological...
Section II is interpreted to have been exhumed between 26 and 10 Ma and comprises the Thasos/Pangeon Metamorphic Core Complex in the western Rhodope (Fig. 2; Wawrzenitz & Krohe 1998). This section occupies the lowermost tectonic position, underneath the Kerdilion and the Falakron/Sidironero Complex and consists of orthogneisses, metapelites, huge marble complexes and mafic rocks. Characteristic are a Late Oligocene/Miocene medium-P low to medium grade metamorphism and mineral relics of earlier high-P metamorphism. Also, this section incorporates Variscan crust as is revealed by U-Pb zircon and monazite dates from orthogneisses, Rb-Sr magmatic muscovite dates and Sm-Nd magmatic garnet data from a metapegmatite on Thasos Island (Table 1; Wawrzenitz 1997).

CRZ and Section I of the high-P metamorphic domain are overlain by Tertiary marine deposits (Fig. 3). Two major pulses of sedimentation and basin formation occurred. The first lasted from the Priabonian, locally Lutetian (i.e. from 42-50 Ma after Harland et al. 1990), through the Oligocene and mainly created the eastern and central Rhodopian basins. The second lasted through the Early/Mid-Miocene and largely created the western Rhodopian basins (Fig. 3). These two pulses temporally coincide with the c. 50-30 Ma and the 26-12 Ma exhumation episodes of Sections I and II, respectively (Table 1, Fig. 3).

Major low-angle detachment systems that separate Sections I, II and III from each other were formed during different episodes, respectively: In the 26-10 Ma interval, the Strymon and Thasos low-angle extensional detachment systems caused exhumation of the Thasos/Pangeon metamorphic
core complex (Section III, western Rhodope, Figure 2), concurrent with detachments on the Cyclades’ islands (Sokoutis et al. 1993; Dinter et al. 1995; Dinter 1998; Wawrzenitz 1997; Wawrzenitz & Krohe 1998). Section II was already exhumed in the Eocene and Oligocene. In this article, we describe for the first time in detail the Eocene and Oligocene detachment systems of the Greek Rhodope Mountains: the Xanthi, western Kardamaos, eastern Kardamos and Kechros detachment systems. These systems separate Section II from a hanging-wall unit consisting of the eastern CRZ and Section I (Fig. 2) and correlate with crustal scale detachments known from the Bulgarian Rhodope (cf. Burg et al. 1996).

**Hanging wall complex: Section (I) of the high-P metamorphic domain**

The Kimi Complex is a high-P metamorphic complex generally situated in the hanging wall of all Eocene and Oligocene detachment fault systems in the eastern Rhodope. Geothermobarometric studies on garnet-spinel pyroxenites (high-P mineral assemblage is Grt-Cpx(Sp-Ol-Hbl), former eclogites (Grt-Cpx(Jd25)-Qtz-Rt) and metaperidotites (Grt-Cpx-Opx-Ol-Spl) estimate 15.5 kbar and 770 °C (Mposkos & Perdikatsis 1989; Wawrzenitz & Mposkos 1997; Mposkos & Krohe 2000). All these rocks are boudins in migmatitic gneisses that contain phengitic muscovite (up to 6.6 Si atoms p.f.u calculated for 22 O atoms; Table 2, analyses 1 and 2). The P-T path is associated with cooling during decompression (Fig. 4; cf. Mposkos & Krohe 2000 for details on the P-T path).

A Sm-Nd garnet-clinopyroxene-whole rock age from the garnet-spinel pyroxenite yielded c.19 ±2 Ma and is interpreted as crystallization age under high-P conditions (Wawrzenitz & Mposkos 1997). An eclogite strongly deformed at granulite facies conditions also shows a U-Pb zircon SHRIMP age of c. 119 Ma (Gebauer & Liati 1997). A R-Sr magmatic mica age of 65 ± 3 Ma in a metamorphic pegmatite crosscutting the foliation of the migmatites (Mposkos & Wawrzenitz 1995) is interpreted as the crystallization age of
Fig. 4. *P–T* exhumation paths of the different tectonic complexes of the Rhodope Domain (modified after Mposkos & Krohe 2000). The petrogenetic grid is based on appropriate mineral parageneses and mineral compositions analysed in partially amphibitized eclogites, metapelites, gneisses and ultramafic rocks. Reaction curves Ctd → St + Grt + Chl, St → Ky + Chl + Grt, Grt + Chl + Ms → St + Bi, St + M → Ky + Bi + Grt, Ctd + Ky → St + Chl, are from Vuiuchard & Balleve (1988), St + Ms → Gt + Sill + Bi is from Powell & Holland (1990), Ab + Or + Qtz + W → L, is from Johannes (1985), Cpx + Opx + Spl → Hbl + Ol is from Jenkins (1981), Chl + Crn + Spl → Spr + W is from Ackerman et al. (1975), Pag + Qtz → Ab + Al₂SiO₅ + H₂O is from Chatterjee (1972), Ms₄s + Ab + Qtz → Kfs + Als + L is from Thompson & Thompson (1976), Pag → J½ + Ky + W is from Holland (1979). Isopleths Si 7, Si 6.8, 6.4 and Si 6.2 are from Massonne & Szpurka (1997). The triple point for the aluminosilicates is from Bohlen et al. (1991). The reaction curve Chl + Czo + Qtz → Grt + Hbl is calculated with the THERMO-CALC program. The remaining reaction curves were calculated with the GEOCALC program (Brown et al. 1988) and the database of Berman (1988), using analysed compositions of coexisting mineral phases. Abbreviations of mineral names after Kretz (1983) and Bucher & Frey (1994).
mica and hence as a minimum age for the migmatitic stage (Mposkos & Wawrzenitz 1995).

In the eastern Rhodope, the overall thickness of the hanging wall unit (Kimi Complex and CRZ) does not exceed a few hundred metres. Both are transgressively overlain by Lutetian/Priabonian (48-42 Ma) conglomerates (1GME unpublished maps, 1999). Thus, Late Eocene-Oligocene clastic basins are situated almost immediately above Section II that was still at great depths and exposed to high temperatures at the time of sedimentation. This means that extension on these normal detachment fault systems cut out several tens of km of crustal material between the crustal Sections I and II.

**Sidironero Complex (Section II):**

**Bounding detachment system**

In the central Rhodope, the Xanthi Detachment System separates the Kimi Complex from the underlaying Sidironero Complex (Section II, Fig. 5a, b). This system consists of a discrete detachment surface underlain by a 0.5-2 m thick cataclastic zone (Fig. 6a). It trends NE-SW and dips 25-45° SE (Fig. 2) and truncates at intermediate to high angle the older mylonitic foliation, the lithological layering, and the metamorphic profile of the underlying Sidironero Complex. Microfabrics suggestive of dynamic recrystallization of calcite in the cataclastic zone indicate that translation on the detachment occurred above c. 200-250 °C. Deformation continuing at lower temperatures is indicated by cataclastic calcite. In quartzfeldspar rocks, catalastic flow created an interconnecting system of narrowly spaced shear fractures and microbreccias defining a weak macroscopic cataclastic foliation (Fig. 6b). Locally, particularly around the Kentavros Granodiorite (Fig. 3), limited plastic elongation and rotation recrystallization of quartz are present (Fig. 6c).

Lineation trends show variations probably caused by later folding and reactivation of the detachment during the early Miocene. To the west of Xanthi in the Falakron marble, striations plunging SSW at low angle on SE dipping planes (Fig. 7) are defined by elongated quartz segregations. There, recrystallized calcite grains oblique to the shear plane indicate top down-dip movement to the SSW or dextral oblique normal faulting. To

![Image](Fig. 5. Xanthi detachment fault surface near the town of Xanthi. (a) The detachment surface behind Xanthi town viewed looking to the west - is bounded to low grade Falakron Series marble (lower part of Section II) forming the large mountain range in the background. Relics of the upper plate (black arrows) containing eclogite amphibolites of the upper plate (attributed to the Kimi Complex) are transgressively overlain by Eocene to Oligocene sediments. The basin (left side of photograph) consists of Miocene to Pliocene deposits that in turn transgressively overly the Eocene to Oligocene sediments, suggesting Neogene reactivation of segments of the detachment surface. The Oligocene Xanthi granodiorite (mountains in the foreground) intruded into the detachment surface. White arrows show where the detachment surface emerges from the eastern margin of the granodiorite. (b) Closer view on the detachment surface (D) bounded to weak Falakron Series marble north of Xanthi town. White broken line indicates a corrugation axis; D’ is the part of the detachment surface in the corrugation synform. White arrows indicate eclogite amphibolites of the upper plate Kimi Complex preserved in a corrugation synform.)
Fig. 6. Xanthi-detachment, microfabrics. (a) Outcrop of the Xanthi detachment surface D (3 km south of Kenntavros). C denotes foliated cataclastic zone beneath the detachment surface. Arrow points into the direction of movements of the hanging wall defined by long axis orientation of fractured fragments and secondary ('Riedel') shear zones cross-cutting the detachment surface in the lower part of the photograph. Scale: ? ? (b) Foliated cataclasites immediately beneath the Xanthi Detachment Surface (Echinos area) indicate totally brittle deformation. Narrow-spaced cataclastic shear fractures, microbreccia (M) and probably pseudotachylites (P) cut across quartz fabrics showing characteristics of dynamic recrystallization and static annealing (QZ). Note the straight boundaries between P and M domains (arrows). Scale: long side of photo is 6 mm. (c) Low temperature shear zones beneath the Xanthi Detachment Surface (area around the Kentavros Granodiorite); quartz shows plastic elongation and local rotation recrystallization; plagioclase behaves rigidly, a-clasts of plagioclase show top to the right sense of shear indicating eastward normal faulting in this area. Scale: long side of photo is 6 mm.

the east of Xanthi, a lineation trend is poorly defined; striation/lineation trends, the configuration of shear fractures and shear zones show (Fig. 6a) top down-dip movement predominantly to the SSE, locally to the east (Fig. 7).

Previously, the Kimm Complex was considered as a part of the upper Sidironero Complex, as both are typified by a high-r-high-P metamorphism (summarized as upper tectonic unit; e.g. Mposkos & Liati 1993). However, we have separated the two complexes (Mposkos & Krohe 2000) because:

1 the Kimm Complex was earlier (between 65 and 48 Ma) exhumed than the Sidironero Complex indicated by the oldest transgressive conglomerates (Lutetian) and the Rb-Sr muscovite age of the pegmatites;
2 the Kimm Complex and the Tertiary sediments are separated from the Sidironero-, Kardamos and Kechros Complexes by this detachment system (Fig. 2);
3 the $P-T-t$ path of the Kimm Complex suggests an episode of cooling during exhumation/decompression (Mposkos & Krohe 2000), contrasting with that of the underlying Sidironero Complex.

The structurally higher levels of the Sidironero Complex record the highest $P-T$ conditions during high-P metamorphism in Section II. In the
Thermes area (Fig. 2), migmatic orthogneisses and pelitic gneisses enclose lenses of kyanite eclogites indicating minimum peak pressures of c. 19 kbar and at least 700 °C (Liati & Seidel 1996, Thermes' curve, Fig. 4b). Crystallization of migmatites was within the stability field of sillimanite + K-feldspar (Mposkos & Liati 1993). This suggests near isothermal decompression from the maximum depth (>19 kbar) to depths corresponding to c. 6-7 kbar (Mposkos & Liati 1993; Mposkos 1998, Fig. 4b). Crystallization of muscovite in migmatitic pegmatites, showing the mineral assemblage Ms + Bi + Kfs + PI + Qtz, and the low Si content of white mica (Si = 6.2, Table 2, analysis 3) constrain subsequent cooling into the stability field of Ms + Qtz below 6 kbar (using the phengite barometer of Massonne & Szpurka 1997, 'Thermes' area in Fig. 4b). In migmatites, kyanite was preserved through these stages probably as a result of rapid decompression followed by fast cooling.

In amphibolites underneath these migmatite series ('Xanthi area', Fig. 2), hornblende (K2.6Na0.3Ca0.7Mg2.58Fe1.1Ti0.14Al2.6Si6.49O22) formed after the eclogite facies metamorphism and produced An-rich plagioclase...
(An 67%) and clinopyroxene (Cao.90Mgo.74 Feo.3iAlo.o9Si.95CV) (Fig. 8b). According to the experimental results of Spear (1981), the reaction hornblende —> clinopyroxene + plagioclase occurred above 700 °C in accordance with decompression at high temperatures (Fig. 4b, 'Xanthi'-curve).

The structurally lower levels of the Sidironero Complex consisting of alternating metapelites and orthogneisses (Albite Gneiss Series), plus marble layers and thick marble of the Falakron Series (Fig. 2), record significantly lower P-T conditions of 11 kbar and 500 °C (Fig. 4b; 'Ab-Gneiss'). In metapelites temperatures were within the stability field of the mineral assemblage Grt + Ctd + CM. Minimum pressures are confined by the intersection between the Si = 7.0 isooleth of Massonne & Szpurka (1997) corresponding to the analysed amphibolite of the Falakron Series (Fig. 2), and the reaction curve Ctd + Chi + Qtz —> Grt + H2O calculated from compositions of Grt core (Grs.24Prpo.5Almo.69 Sps.o.is), Ctd (Mgo.26Fei.69Alo.48Osii.99 cations to 12 O) and Chi (Mg4.58Fe4.48Ai5.4gSi5.26 cations to 28O) in metapelites (Fig. 4b). Garnets from metapelites show decreasing grossular composition and increasing Mg/Mg + Fe ration from the core to the rim (Grt rim Grs.o6Ppo.i7Alnio.75 Sps.o.i, Grt) indicating a temperature increase during the (earlier stages of) decompression. Generally in this work, the phengite barometer from Massonne & Szpurka (1997) is applied to white K-micas associated with the critical mineral assemblage Phen + Bi + Kfs + Qtz.

### Strain associated with decompression
Within the Sidironero Complex, mineral assemblages of high-P metamorphism are essentially relics preserved in boudins of (ultra) mafic rocks, or as relic grains in quartzo-feldspatic mylonites. Thus, the pervasive foliation planes, lineation trends, grain scale fabrics, and shear sense indicators postdate peak pressures and therefore potentially depict the kinematics and deformation mechanisms related to exhumation of high-P metamorphic rocks. Typical mineral assemblages reveal downward-decreasing P-T conditions through the complex.

At the structurally higher levels of the Sidironero Complex, migmatites and, particularly the strained rims of amphibolitized eclogite boudins, amphibolites are deformed with microfabrics typical of high-7° mylonites. Hornblende and the coexisting post-eclogitic clinopyroxene of amphibolites of the Xanthi area (see above) show characteristics of dynamic recrystallization (Fig. 8a, b) inferring deformation at high temperatures during decompression. S-C fabrics defined by elongated hornblende grains asymmetrically aligned to the compositional layering indicate top-to-SW movements during high-T shearing (Fig. 4b).
8b). Through cooling, strain localized into biotite, white mica and quartz rich domains; top to SE sense of shear at that stage is indicated by secondary shear zones.

In the Albite Gneiss Series, in the structurally lower part of the Sidironero Complex, pre-mylonitic phengitic white mica grains from orthogneisses and metapelites show decreasing Si content from core to rim (Table 2, analyses 4c, 5r). The mica grains recrystallized during deformation have a low Si content (Si — 6.4-6.3, Table 2, analysis 6re) consistent with deformation/recrystallization (Fig. 8c) during decompression to 5-6 kbar (Fig. 4b). In amphibolites, syn-deformational hornblende oriented with long axes parallel to the lineation, show compositional zoning from tremolitic in the core (Nao.igCauoMga.gsMno.osFei.^Alo.ve Siy.49 cations to 23 O) to tschermakitic hornblende in the rim (Nao.3gCai.65Mg2.7oMno.o3Fei5oAl2.i4 Si6.52 cations to 23 O) in accordance with increasing temperature during decompression. Thus, importantly, deformation took place at increasing temperature during decompression (albeit at generally lower temperatures than in the higher Sidironero Complex) and continued during successive cooling (Fig. 4b). Within the lower Sidironero Complex, shear sense indicators such as S-C relationships and fishes of relic phengitic mica also consistently indicate top to SW (updip) shearing.

We interpret formation of mylonites to be associated with thrusting in the deeper crust (Fig. 7; cf. Dinter et al 1995; Burg et al 1996; Kilias et al 1997, 'Nestos thrust' zone), and thus to have formed before formation of the Xanthi detachment system. Consistent with this are (i) shear senses indicating updip SW movements, (ii) downward-decreasing maximum pressures and temperatures during high-P metamorphism (previous to mylonite formation) within the Sidironero Complex and (iii) downward decreasing temperatures during the deformation/decompression stage, indicating thrusting of hotter on top of cooler crustal sections and/or cooling from below within the Sidironero Complex. The Xanthi-detachment system cross-cutting this mylonitic foliation brought the Kimi Complex into contact with the high and low grade parts of the Sidironero Complex. This system was
clearly formed after juxtaposition of high grade upon low grade units and after emplacement of both at a shallow depth.

Kardamos Complex (Section II)

Bounding detachment systems

Detachment surfaces bounding the Kardamos Complex show structural variations.

(i) The eastern Kardamos detachment surface that separates the structurally higher (eastern) parts of the Kardamos Complex from the Kimi Complex (Section I) is underlain by a shear zone a few hundred metres thick (Fig. 9) formed at greenschist facies conditions. This detachment surface trends at low angle to the orientation of the foliation of such shear zones that shape a gently NE-plunging dome structure (see below, Fig. 7).

(ii) The western Kardamos detachment that bounds the western Kardamos Complex (Section II, Fig. 7) is, like the Xanthi detachment system, a discrete detachment surface underlain by a 0.5-2 m thick cataclastic zone. This detachment surface and the cataclastic zone trend approximately north-south, dip at low angle to the west and cut across the mylonitic foliation, the lithological succession and metamorphic profile of the footwall Kardamos Complex. Thus, the western part

P-Thistory: general

The structurally higher parts of the Kardamos Complex, beneath the eastern Kardamos detachment system, comprises migmatites, meta-blastic gneisses, metapelites and metabasites that record upper amphibolite facies metamorphism. In metapelites, this is indicated by the mineral assemblages Grt-Ky-Bi (Fig. 4c). Retromorphic staurolite and sillimanite coexist with muscovite and biotite. According to the petrogenetic grid of Vuichard & Ballevre (1988), coexisting Grt + St + Bi and St + Bi + Als and the absence of chlorite in the metapelites indicates minimum temperatures of 600-650 °C during this stage of decompression (Fig. 4c). In metabasites, synmylonitic mineral assemblages include plagioclase (An2o-25) and hornblende.

The western Kardamos Complex exposes structurally lower parts beneath the cross-cutting western Kardamos detachment. This part is composed of a sequence of ortho- and paragneisses, metapelites (albite gneisses), metabasites and intercalated marbles, which are overlain by the Tapikion Mt. Metagranodiorite' (Figs 2 and 3). Gneisses locally preserve the high-P mineral assemblage Grt-Ky-

Fig. 9. Detachment surface (D) separating brecciated marbles of the upper plate Kimi Complex (A) from plastically flowing marble of the eastern Kardamos Complex (B), 10 km NE of Komotini. The marble of the Kardamos Complex contains quartz veins (qz) that were also plastically deformed and boudinaged subparallel to the extension of the detachment surface. Boudinage asymmetry indicates dextral sense of shear (dextral oblique normal faulting in the outcrop). Scale: (long side of photo is 9.4 mm.)
Zo-Chl-Pl (An$_{19-25}$). The reaction Grt + Ky + Qtz \rightarrow An calculated for the analysed mineral compositions (Fig. 4c) yielded 13 kbar for garnet core and 12 kbar for garnet rim compositions, assuming 600 °C (Mposkos & Krohe 2000), indicating garnet growth during decompression.

The retrogressive mineral assemblages are Grt-Ms-Bi-Ab-Pl(i5–2o) ± Kfs-Qtz in pelitic gneisses and Grt-Hbl-Bi—Czo-Ab—Pl(i4—2i)—Qtz in metabasites characterizing the P-T conditions during decompression. Albite (AiiQ-4) has a rim of coexisting oligoclase (An$_{4-2i}$). Staurolite that replaced garnet or kyanite coexisted with chlorite, constraining the decompression path within the garnet—Staurolite-chlorite stability field and limiting the peak temperature between 580 °C and 620 °C (Fig. 4c). This suggests that decompression was near isothermal but at lower temperatures than in the structurally higher part, and thus downward-decreasing temperatures within the Kardamos Complex (Fig. 4c).

**Strain partitioning associated with decompression**

The Kardamos Complex also experienced shearing during decompression. Mineral assemblages recording maximum P- T conditions predate shearing and are only locally preserved. Directions of shear planes and lineations in mylonitic gneisses vary over the Kardamos Complex due to a complex tectonic history (Fig. 7). Detachment surfaces bounding the Kardamos Complex show structural variation.

**Structurally higher part.** Only in the uppermost parts, within shear zones close to the eastern Kardamos detachment surface, are pre-mylonitic phengitic white micas preserved. In granodioritic orthogneisses immediately beneath the detachment surface, the maximum phengite component is Si = 6.5 atoms p.f.u. (Fig. 10, sample K31, Table 2, analysis 9c). At c.SOOm beneath the detachment surface it increases to Si = 6.7 atoms p.f.u. (Fig. 10, sample K33, Table 2, analysis 7c). This is interpreted as representing an increase in pressure from 8 to 10 kbar (at temperatures of 600 °C) over that short distance and is in accordance with higher level extension. Pre-mylonitic phengites tend to have accommodated to lower pressures during deformation. Pre-mylonitic phengites are frequently intergrown with biotite and have low phengite components. This suggests decomposition of an older, pre-mylonitic, phengitic mica during deformation. Thus, in this part, the record of peak pressures has been almost entirely erased during amphibolite-facies metamorphism. The formation of St and Sil (coexisting with Ms and Bi) was coeval with shearing, indicating syn-deformational temperatures above 600-650 °C (see above, Fig 4c). Characteristic in metabasites are recrystallization of plagioclase and hornblende that form elongated aggregates subparallel to the stretching lineation. Deformation was outlasted by annealing, producing grain growth and straight grain boundaries (Fig. 11c).

This is consistent with extension-related juxtaposition of the cold Kimi Complex above the upper Kardamos Complex.

In mylonites at distances of c. 500 m and more from the eastern Kardamos detachment surface, white K-mica is frequently intergrown with biotite and has low phengite components. This suggests decomposition of an older, pre-mylonitic, phengitic mica during deformation. Thus, in this part, the record of peak pressures has been almost entirely erased during amphibolite-facies metamorphism. The formation of St and Sil (coexisting with Ms and Bi) was coeval with shearing, indicating syn-deformational temperatures above 600-650 °C (see above, Fig 4c). Characteristic in metabasites are recrystallization of plagioclase and hornblende that form elongated aggregates subparallel to the stretching lineation. Deformation was outlasted by annealing, producing grain growth and straight grain boundaries (Fig. 11c).

In all parts of the eastern Kardamos Complex, the shear zone has a normal component. In the
Fig. 11. (a) Quartz feldspar LT-mylonite in the carapace shear zone, a few metres beneath the eastern Kardamos detachment surface; phengitic white mica (M) is preserved; feldspar behaves by brittle fracturing (arrow) and plastically stretched quartz (Qz) shows a low degree of recovery/recrystallization. Scale: long side of photo is 2.3 mm. (b) Low temperature plastic strain of quartz in the carapace shear zone, a few centimetres beneath the eastern Kardamos detachment surface; extreme elongation of grains and low degree of recovery/rotation recrystallization. Scale: long side of photo is 9.4 mm. (c) Quartz feldspar high-T mylonite in the carapace shear zone, c. 300 m beneath the eastern Kardamos detachment surface; relict phengitic white mica; feldspar shows dynamic recrystallization and grain growth at low differential stresses and high temperatures (annealing). Scale: long side of photo is 2.3 mm. (d) Albite gneiss mylonite in the structurally deepest (western) Kardamos Complex. Albite overgrew an internal foliation defined by biotite and quartz aligned at high angle to the external foliation. Asymmetric strain shadows in albite clast (arrows) indicate top-to-the-left sense of shear (SW-directed in the outcrop). Scale: long side of photo is 6 mm. (e) Eastern Rhodope. Low temperature mylonite a few metres beneath the detachment surface separating the Kechros from the Kimi Complex. Low temperature plastic strain of quartz (QZ) is indicated by strong elongation of host grains and low degree of recovery/rotation recrystallization. Top left sense of shear is indicated by prism subgrain walls oblique to the elongations of quartz ribbons (arrow) and phengitic white mica (M) forming fishes consistent with SSW-ward translation of the hanging wall. Scale: long side of photo is 2.3 mm.
southern limb of the dome the foliation trends NE-SW, dips moderately SE and bears low angle SW to SSW plunging lineations. Shear sense is top to the SW indicating dextral oblique normal faulting (Fig. 7). Further to the east, toward Komotini (Fig. 7), the plunge of lineations changes to south and ESE; top-to-the-south and -ESE movements indicate normal faulting. In the northeastern Kardamos Complex (in the NE-plunging hinge of the antiform) the mylonitic foliation swings to a north-south trend, dips at intermediate angle to the east and bears east to ENE plunging lineations. Shear senses indicate top down-dip movements to the east and ENE, respectively (Fig. 7).

Structurally Lower Part. The retromorphic mineral assemblages are Grt-Ms-Bi-Ab-Pl (15-20) ± Kfs-Qtz (pelitic gneisses) and Grt-Hbl-Bi-Czo-Ab-Pl (i4-2i)-Qtz (metabasics), which are syn-mylonitic. During non-coaxial strain in the mylonites of these lower parts albite-oligoclase progressively overgrew an internal foliation defined by biotite and quartz (metapelites) or hornblende (metabasics). This internal foliation is aligned at c.30-80° to the external foliation and rotates into the direction of the external foliation at the rim of the grain, in accordance with a SW sense of shear (Fig. 1d).

Beneath the cross-cutting western Kardamos detachment surface, the mylonitic foliation shows changing orientations. In the core of the Kardamos dome, both the dip of the foliation and the plunge of the lineation are to the NE. Toward the outer part of the dome (SW Kardamos Complex; Fig. 7), the dip of the mylonitic foliation successively changes to SE and the plunge of the lineation changes to (S)SSW. Yet, sense of shear invariably indicates top-to-the-SW movements (cf. Burg et al 1993, 1996; Ricou et al 1998, Fig. 7). We interpret this geometric pattern of the shear zones as follows.

Shear senses indicating updip SW movements in the core of the dome suggest deeper level thrusting in the structurally lowermost exposed metamorphic sequences. Consistent with this are upward increasing syn-deformational temperatures indicating cooling from below and/or thrusting of hotter on top of cooler crustal sections. Variations of the orientation of shear planes from the inner (lower) toward the outer Kardamos Complex suggest a continuous change from contractional to (dextral oblique) transtensional and high level extension (Fig. 7). This high level extension is the dominant structure of the eastern Kardamos Complex.

The gently west dipping western Kardamos detachment cross-cuts all the shear zones and developed after cooling of the western Kardamos complex. Hence, this detachment surface is interpreted as both genetically unrelated to the mylonites and younger than the eastern Kardamos detachment system.

Kechos Complex (Section II): metamorphism and deformation

In the eastern Rhodope, a discrete detachment (Kechos-detachment) that is underlain by a shear zone only about 50 m thick separates the Kechos Complex from the Kimi Complex (Section I) and the CRZ. This shear zone was formed at lower greenschist facies and is oriented at low angle to the detachment surface. Both, detachment and shear zone, are flat lying and shape an open antiform structure (Fig. 7).

The Kechos Complex representing the footwall unit of this detachment system largely consists of orthogneisses with intercalations of metapelites, ultramafic rocks and eclogites. In eclogites, the relict high-P mineral assemblage Grt + Omp(Jd35-55) ± Ky + Tr + Hbl + Czo + Qtz + Rt + Phe indicates minimum P-T conditions of 15 kbar (corresponding to a depth of about 53 km) at c. 550 °C (Fig. 4b, Mposkos & Perdikatsis 1989; Liati & Mposkos 1990). Kyonite occurs as inclusions in garnet cores, associated with clinozoisite and quartz, being formed during the prograde path in an earlier stage of the high-P event. In gneisses, the maximum phengite component of white micas (Si — 7 atoms p.f.u.) reflects this high-P event (Mposkos, 1989). Maximum P-T conditions and the P-T paths are close to those of the Albite Gneiss Series of the Sidironero Complex (Fig. 4b).

Upper greenschist/lower amphibolite-facies metamorphism at about 4-6 kbar overprints the high-P metamorphism. This stage is indicated by staurolite formation by chloritoid consuming reactions (e.g. Ctd + Ky -> St + Chi; Ctd + Phen -> St + Ms + Chi and Ctd + Ms -> St + Bt), inferring nearly isothermal decompression (Fig. 4b; Mposkos 1989; Mposkos & Liati 1993).

The Kechos Complex was pervasively deformed during earlier decompression, prior to development of the detachment. This is indicated by widespread post-deformational growth of St and Chi in thick mylonites. Recrystallized white mica grains aligned within the mylonitic foliation are less phengitic than pre-mylonitic white micas. Microprobe analyses of these micas from Orthogneisses (cf. Mposkos 1989, Table 2, Sample R 9A core Si — 6.51, rim Si = 6.44 and Table 2 analyses lie, 12r) suggest that shearing occurred during decompression to pressures of c.8-6 kbar.
Foliation planes dip at low angle approximately to the north; generally top-to-the-south and -SSW shear senses occur (cf. Burg et al. 1996, Fig. 7).

In the younger shear zone directly beneath the detachment surface, deformation continuing at lower greenschist facies is indicated by green, low-Ti biotite replacing garnet and muscovite and, in metabasites, by actinolite and chlorite replacing hornblende. Feldspar behaved brittlely (Fig. 6). Chloritoid is replaced by andalusite and chlorite. Sense of shear is top to the SW (Fig. 6) consistent with the orientations and shear senses of the thick shear zones (cf. Burg et al. 1996, Fig. 6).

Importantly, the upper greenschist facies Kechros Complex lies directly beneath the Kimi Complex. This contrasts with central Rhodope, where the Kimi Complex is situated directly above the medium-high grade (high-77high-P) rocks of the upper Sidironero Complex that in turn overlies the upper grebnschist facies albite gneisses of the lower Sidironero Complex. This suggests that the Kechros detachment system cuts out the medium-high grade (high-77high-P) rocks of the upper Sidironero Complex.

### Geochronological record of Eocene-Oligocene metamorphism

Upper and lower parts of the Sidironero Complex differ in geochronological records: In the structurally uppermost part (Thermes area, Fig. 2) of the Sidironero Complex, a U-Pb SHRIMP zircon age from partly amphibolitized eclogites gives 42 db 1 Ma (Table 1; Liati & Gebauer 1999). These zircons are interpreted as having crystallized at eclogite facies, and thus dating the high-P stage (Liati & Gebauer 1999) but may rather reflect a minimum age for high-P metamorphism (see discussion). A U-Pb SHRIMP zircon age from an adjacent migmatite of 40 ± 1 Ma is inferred to reflect the migmatization age (Table 1; Liati & Gebauer 1999). In this part, both K-Ar hornblende ages (Liati 1986) and R-Sr-whole rock white mica ages (Kyriakopulos pers. comm. 1999) range between 37 ± 1 and 41 ± 1 Ma, setting a minimum age for mylonitization.

In structurally deeper levels (but still above the Albite Gneiss Series; northern Xanthi area, Figs. 2 and 3), a quartz vein yielded a slightly older U-Pb SHRIMP zircon age of 45±1 Ma; this age is interpreted as reflecting quartz vein formation during dehydration at low temperatures (c.300 °C) along the prograde P-Tpath (Table 1; Gebauer & Liati 1997). However, in the structurally deeper levels, K-Ar-hornblende dates of amphibolites without relics of eclogites are significantly older, yielding 45 ± 1 to 47 ± 1 Ma (beneath the marble horizon, northern Xanthi, Table 1, Liati 1986, see discussion). K-Ar biotite and white mica ages of 36 ± 1 and 37 ± 1 Ma indicate cooling below 350 °C and 300 °C, respectively (Table 1; Liati 1986) and are thus a maximum age of frictional slip on the Xanthi detachment surface. This late stage is also reflected by a zircon date from a pegmatite cross-cutting the mylonitic foliation of 35 Ma ± 1 (Gebauer & Liati 1997).

In the Kechros Complex a mica sieve fraction of large (>500 m) (largely pre-mylonitic) phengitic white mica grains from a mylonitic orthogneiss yielded a R-Sr age of 37 ± 1 Ma (Table 1, Wawrzenitz & Mposkos 1997). In contrast to the upper Sidironero Complex, P— T conditions of the Kechros Complex did not exceed the stability field of Ms + Qtz and the suggested 550 °C closure temperatures of the R-Sr white mica systems. Thus, Wawrzenitz & Mposkos (1997) interpreted this date as a minimum age of high-P metamorphism in the Kechros Complex. Moreover, c. 37 Ma is a maximum age of mylonitization and juxtaposition of the Kechros Complex next to the Kimi Complex (Wawrzenitz & Mposkos 1997).

As no geochronological data from the Kardamos Complex existed, samples of white mica and biotite from an orthogneiss of the eastern Kardamos Complex were analysed for K-Ar age determination by Geochron Labs (Massachusetts). K-Ar ages of 42 ± 1 and 39 ± 1 Ma, were found, respectively (Table 3), indicating cooling below 350-300 °C, significantly before the upper Sidironero and Kechros Complexes. Thus, according to these ages, the eastern Kardamos detachment

| Table 3. K-Ar data of muscovite and biotite from the eastern Kardamos Complex |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                                 | 40Ar/39Ar       | Avge. 40Ar ppm  | Ave. K [%]      | 40K ppm         | Age [Ma]       |
| Muscovite (80-200 jam)          | 0.002473        | 0.2234          | 7.570           | 9.030           | 42.1 ± 1       |
| Biotite (80-200 fkm)            | 0.002316        | 0.2042          | 7.394           | 8.820           | 39.4 ± 1       |

Age=1/λt+(λe+λw)/ln [λt+(λe+λw)/(λe+λw)] X 40Ar/39ArK+1] [167]
cooled prior to the footwall units of Xanthi detachment.

Granitoids associated with detachments

Most granitoid intrusions of the Rhodope Mountains are spatially linked to detachment fault systems (Fig. 3). The ages and intrusion depths of these granitoids provide further constraints on depths and time intervals over which the discrete, brittle detachments were active.

The highly sheared Kentavros granodiorite, about 10 km to the north of Xanthi (Fig. 2) is a syn-detachment intrusion into the upper Sidironero Complex, immediately beneath the Kimi Complex and the Xanthi detachment surface. K-Ar hornblende ages of 38 ± 1 Ma (Table 1, Liati 1986) match the R-Sr white mica-whole rock ages of the Sidironero Complex, indicating concurrent cooling of the pluton and enclosing metamorphic rocks. Hornblende geobarometry (Schmidt 1992) yielded estimated pressures of 5.1-5.4 kbar (Al$_{tot}$ in Hbl is 1.70-1.76 atoms p.f.u.; Pangeon Mountains, Table 2, analyses 13c, 14r). Pressures of 9 kbar were attained at temperature of c. 490 °C. This is constrained by the intersection of the isopleths Si = 6.8 of Massonne & Szpurka (1997) and the reaction curve Chi + Czo + Qtz ⇔ Grt + Hbl calculated with the Thermocalc program, using the analysed mineral compositions Grt (Grs 0.3gAlmo.52Prpo.06 Fe$_2$3+$^2$ Fe$^{3+}_{0.36}$Tio.$^6$Si$_{2.07}$Si$_{0.44}$ cations for 23 O), Chl (Mg7.6iFe$_2$0.36$^2$ Al$_{20}$Si$_{3.48}$ cations for 28 O) and Czo (Ps - 20%).

However, pervasive shearing and exhumation of the Thasos/Pangeon Complex occurred during the Miocene. R-Sr dates of white mica and biotite between 23 ± 2 and 15 ± 1 Ma in the Pangeon Mountains (Table 1, Del Moro et al 1990) and on Thasos Island reflecting cooling and constrain in part the age of deformation (Wawrzenitz 1997, Wawrzenitz & Krohe 1998). Calc-alkaline granitoid intrusions interpreted as syn-deformational (Symvolon granodiorite, Fig. 3) yielded U-Pb titanite and $^{40}$Ar/$^{39}$Ar hornblende dates of 22 ± 1 to 23 ± 1 Ma (Table 1; Dinter et al 1995). On Thasos Island the metamorphic grade increases downward. Also the R-Sr dates of white mica and biotite decrease downward from 23 ± 1 and 15 ± 1 Ma to 18 ± 1 and 12 ± 1 Ma, respectively (Table 1). The later interval is interpreted as extensional exhumation of a deeper crustal level on a second detachment system ('dome bounding detachment' in Figs 2 and 3; Wawrzenitz & Krohe 1998). According to Wawrzenitz (1997) and Wawrzenitz & Krohe (1998), the Thasos metamorphic core complex was formed during early Aegean back-arc extension. So far, no accurate geochronological data exist to constrain the age of high-P metamorphism of the Pangeon Mts.

Unroofing the Thasos/Pangeon Complex

(The Thasos/Pangeon Complex mylonites in the western Rhodope (Dinter et al. 1995; Sokoutis et al 1993; Wawrzenitz & Krohe 1998; Fig. 2) were formed during exhumation. They show predominant SW-NE-trending lineations with mainly top-to-SW- and locally top-to-NE-directed shear senses (Fig. 7). In metabasites the mineral assemblage Hbl-Ab(Anol)- Pl(An$_{12}$)- Grt-Czo-Chl + Qtz-Rt-Ttn indicates epidote—amphibolite facies. In orthogneiss mylonites, the Si content in white K-micas decreases from the pre-mylonitic to the recrystallized white micas from c.6.85 to 6.35 atoms p.f.u. (Pangeon Mountains, Table 2, analyses 13c, 14r). Pressures of 9 kbar were attained at temperature of c. 490 °C. This is constrained by the intersection of the isopleths Si = 6.8 of Massonne & Szpurka (1997) and the reaction curve Chi + Czo + Qtz ⇔ Grt + Hbl calculated with the Thermocalc program, using the analysed mineral compositions Grt (Grs 0.3gAlmo.52Prpo.06 Fe$_2$3+$^2$ Fe$^{3+}_{0.36}$Tio.$^6$Si$_{2.07}$Si$_{0.44}$ cations for 23 O), Chl (Mg7.6iFe$_2$0.36$^2$ Al$_{20}$Si$_{3.48}$ cations for 28 O) and Czo (Ps - 20%).

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From c. 15 Ma until 8 Ma, low angle normal (Strymon and Thasos) detachments associated with mylonite zones were active (Dinter & Royden 1993; Wawrzenitz & Krohe 1998). Early/Mid-Miocene basins developed on the hanging walls of these younger detachment faults. The basins are interpreted to represent supra-detachment basins of the Strymon and Thasos detachment systems (Dinter et al. 1995). The extent of such basins increases toward the western Rhodope (Figs 2 and 3). The earlier exhumed metamorphic complexes (including Sidironero Complex etc.) are in the hanging-wall position of these detachments (Fig. 12a, b).

Discussion: kinematic and dynamic model

Geochronological constraints on the tectonic evolution (<42 and 30 Ma interval)

In summary, Section II (Sidironero, Kardamos and Kechros Complexes) is a part of a high-P crustal domain that, within the 42-30 Ma interval, experienced strong pervasive deformation during decompression at temperatures of 500-700 °C and during cooling. This history contrasts with those of the over- and underlying complexes, which show older and younger metamorphic histories, respectively. At its top and bottom, this crustal section is bounded by detachment systems formed in the <42-30 Ma and 23-8 Ma intervals, respectively (Fig. 12a-d). Exhumation of the high-P rocks was concurrent with transgression in the Lutetian or Priabonian and basin formation continued to the Late Eocene-Oligocene, particularly in the eastern Rhodope. We interpret this sedimentation as related to movements on detachment systems bounding this crustal section at its top.

According to Liati & Gebauer (1999), the sequence of U-Pb SHRIMP zircon ages from quartz vein, to eclogite and migmatite of the Sidironero Complex brackets the subduction-exhumation history of the entire Rhodope high-P terrain within a short period of time between 45 and 35 Ma. However, the Rhodope high-P terrain does not show a homogeneous P-T and exhumation history. Even among different parts of the Sidironero Complex, P-T histories and deformation mechanisms vary. Such variations seem to correlate with differences of geochronological data that show a broadly downward-increase in age. This sets important constraints on the reconstruction of differential mass movements in the <45-30 Ma time span.

The uppermost migmatitic part of the Sidironero Complex (Thermes area) had already exhumed into the middle crust (stability field of sillimanite) at cAO Ma. This is shown by the 40 ± 1 Ma U-Pb zircon SHRIMP date constraining the age of migmatization. Pegmatoids associated with migmatites contain muscovites that show low phengite components. In deeper parts of the higher Sidironero Complex, above the marble horizon north of Xanthi (Fig. 2), R-Sr muscovite ages and K-Ar hornblende ages, which both range between 37 ± 1 and 41 ± 1 Ma (Table 1), reflect a minimum age for recrystallization during mylonitization associated with thrusting of this part over the Albite Gneiss Series. In this part, mylonitization was at high temperatures and succeeded migmatization and syn-migmatic deformation.

In the lower Sidironero Complex, beneath the marble horizon north of Xanthi (Fig. 2), K-Ar ages of hornblende from amphibolite mylonites yielding 45 ± 1 Ma (Liati 1986) are interpreted as dating (re)cristallization of hornblende during mylonitization of the lower Sidironero Complex, after high-P metamorphism. Mylonitisation is interpreted to continue through cooling below the supposed closure temperatures of the K-Ar hornblende system of 550 °C. The c. 45 Ma hornblende data are also a minimum age for high-P metamorphism in the lower Sidironero Complex as mylonitization developed after high-P metamorphism (registered by the Si contents of recrystallized white mica). Downward increasing ages might reflect cooling of the footwall due to thrusting on top of cold Falakron Series (Fig. 2; Dinter 1998). The abrupt increase in hornblende ages toward the lower Sidironero Complex also suggests that thrusting continued along discrete faults at temperatures lower than closure of these isotope systems.

Frequently, excess Ar is observed in hornblende of high-P metamorphic complexes. However, when excluding samples that preserve distinct textural remnants of the eclogite stage ('eclogitogenic amphibolites' of Liati 1986), there is a clear correlation of the higher ages with the lower part (beneath the marble horizon north of Xanthi) and of the lower ages with the high-grade higher part of the Sidironero Complex (Table 1). In the case of excess argon, a scatter of various values throughout the Sidironero Complex would rather be expected.

The 45 ± 1 Ma U-Pb age of the quartz vein from the lower Sidironero Complex (Liati & Gebauer 1999) approximates the K-Ar hornblende ages within this part. Thus, alternatively, this age may be related to metamorphic reactions and zircon crystallization associated with deformation and hydration during decompression prior to cooling. So far, the age of high-P metamorphism in this part is poorly constrained.
**Kardamos Complex.** PCooling of the (structurally higher) amphibolite facies of eastern Kardamos Complex below 350-300 °C at c.41-39Ma is interpreted to result from its emplacement beneath the cold Kimi Complex on the extensional eastern Kardamos detachment fault. Importantly, these K-Ar data also show that extensional unroofing in the higher Kardamos Complex was contemporaneous with contractional deformation in the lower Sidironero Complex. Besides, cooling, shearing in low-T mylonites, and frictional slip on detachment systems in the higher Kardamos Complex roughly occurred within the same time span as the high-T deformation in the upper Sidironero Complex. Presently, no geochronological data exist from the underlying upper greenschist facies western Kardamos Complex.

**Kechros Complex.** A R-Sr white mica date of 37 ± 1 Ma is interpreted to reflect a maximum age of mylonitization (Wawrzenitz & Mposkos 1997). In the analysed sample, syn-mylonitic white micas indicate pressures (6-8 kbar) higher than those indicated by the pegmatite muscovites crystallized at 41 Ma in the upper Sidironero Complex. This has the following implications:

1. **mylonitization of the Kechros Complex is younger (<37 Ma) than that of the Sidironero Complex;**
2. **at c. 37 Ma, the Kechros Complex was at greater depth than the Sidironero Complex;**
3. **high-P metamorphism of the Kechros Complex may postdate high-P metamorphism in the Sidironero Complex, i.e. the Kechros Complex was part of a deeper crustal segment during exhumation of the Sidironero Complex.**

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Fig. 12. Profiles through the Rhodope domain. Vertical scale is two times horizontal scale. See Figure 2 for location of profiles, Figures 2 and 3 for unit fillings and Table 1 for ages.
Thrusting within the Sidironero Complex occurred during decompression. This means continuous removal of material from the top of (i.e. exhumation of) the Sidironero Complex in close association, or even simultaneously, with thrusting. The main removal mechanism was extension. This is evident from preservation of a metamorphic hanging wall consisting of pre-Late Eocene metamorphic rocks (Kimi Complex) and transgressive Late Eocene to Oligocene marine (eastern Rhodope) sediments. Migmatites of the footwall Sidironero Complex also have Late Eocene/Early Oligocene ages (Fig. 12a-d). Thus, several tens of kilometres of crustal material have been removed along the contact of the Kimi and Sidironero Complex, which is indicative for normal faulting. Yet, kinematic reconstruction requires juxtaposition of these two complexes on two successive detachment systems formed in two successive extension stages for reasons summarized as follows.

Lutetian marine sedimentation (c.48 Ma) occurs almost directly upon migmatites that were at the time of deposition hotter than 700 °C. However, transgression of marine sediments upon the Kimi Complex predated formation of the Xanthi detachment surface about 10 Ma (north of Xanthi).

The Xanthi detachment is associated with cataclastic deformation and clearly developed after the migmatic stage of the Sidironero Complex. Thus, the high grade high-P upper Sidironero Complex must have been emplaced in the middle crust by exhumation episodes older than the Xanthi detachment.

We suggest that early extension (c.42-30 Ma), coeval with thrusting of hot over cold meta-
morphic rocks, excised a crustal section between the Sidironero and Kimi Complex. However, at the contact between these two complexes, in the Xanthi area, no mylonites related to such earlier, syn-metamorphic extension are recognized. Therefore, these structures have probably been cut out by the Xanthi detachment (Fig. 13). In our structural interpretation (Fig. 13), the eastern Kardamos system that is associated with shearing represents an older detachment system that was excised by the Xanthi detachment system between the Kimi and upper Sidironero Complexes. The eastern Kardamos detachment system is clearly older than the western Kardamos detachment (situated east of Xanthi-Echinos, see Fig. 13, see above).

The structure of the western Kardamos detachment surface is similar to that of the Xanthi detachment (Xanthi area) that ramps through the thrust structures, from the upper, high grade to the lower, low grade Sidironero Complex (Fig. 13). We interpret the western Kardamos detachment fault as a satellite fault rooting into the Xanthi master detachment fault. Both excise the Kardamos Complex between the Kimi Complex and the deeper Sidironero Complex (or even deeper crustal sections, Figure 13). In this interpretation (i) the Kardamos Complex forms part of the hanging wall of the Xanthi master detachment; (ii) the deeper Kardamos Complex with hot rocks thrust over cold is equivalent to the lower and upper Sidironero Complex (symbolized in Figure 12 by indentation of the specific signatures); (iii) the higher Kardamos Complex contains syn-thrusting extensional structures between Kimi and upper Sidironero Complex cut out by the Xanthi detachment (Fig. 13).

Xanthi Detachment System: large-scale extensional ramp—flat structure

According to geochronological data, the detachment juxtaposing the Kimi Complex above the Kechros Complex (eastern Rhodope), between 37 and 32 Ma, was coeval with formation of the Xanthi detachment (Central Rhodope). However, contrasting with the Xanthi detachment surface, this detachment developed at greater depth with shearing, being associated with cooling. We consider this detachment as the eastern continuation of the Xanthi detachment, which dips roughly to the SE or ESE from the brittle upper crust into the middle crust. This connected detachment system thus extends over a length of about 100km showing a ramp and flat geometry (Fig. 12c). The extensional ramp structure of the Xanthi detachment is directly observed in the central Rhodope.

It is important to note that in the eastern Rhodope, the Kimi Complex was transported above the low grade high-P rocks of Kechros Complex by detachment systems. This contrasts with the central Rhodope, where the high grade high-P upper Sidironero Complex is inserted between the Kimi Complex and the low grade high-P lower Sidironero Complex. In our structural reconstruction (Fig. 12b, c, d) the Xanthi connected detachment system excised the hot high-P rocks in the eastern Rhodope. Translation on this detachment system removed about 20 km of crustal thickness, the estimated thickness of the Kardamos and Sidironero Complexes, including Albite Gneiss and Falakron Series, from above the Kechros Complex. This is in coincidence with the reduction of the present crustal thickness from the central to the eastern Rhodope from about 50 km to below 30 km, interpreted from gravimetric data (Makris 1985).

Overall structural relationships and tectonic history of the Rhodope Domain

Based on the geochronological data and structural relationships already outlined, the tectono-metamorphic evolution of the Rhodope can be summarized as follows (cf. Fig. 14).

(1) Section I, i.e. the Kimi Complex, and probably also parts of the Vertiskos Complex and the Melivia Kotili Complex (Fig. 2) occupying the structurally high positions, show a pre-Eocene metamorphic history. They are bounded at their base by Late Eocene or Oligocene detachments (Fig. 14). In the Kimi Complex, high-\(\beta\) metamorphism is Early Cretaceous. These complexes represent a lithospheric fragment having continental crustal components and mantle fragments that accreted the European continental margin in the (Early) Cretaceous (cf. Burg et al 1996).

(2) The retrograde \(P-T\) path of the Kimi Complex, between c. 119 and c.65 Ma is characterized by decompression to depths larger than 30km (medium-\(\beta\) stage), formation of migmatites and metamorphic pegmatites, cooling, and continuous hydration of former high-P rocks and granulites. Hydration and exhumation at that time has been linked to subduction of oceanic material beneath the European plate margin that included the Kimi Complex (Mposkos & Krohe 2000). A final stage of exhumation occurred after 65 Ma, but before the middle Eocene.

(3) The Sidironero, Kechros, Kardamos and Keridilion Complexes generally occur beneath either Late Eocene (Kardamos and Vertiskos detachments, Fig. 2) or Oligocene detachments (Fig. 14). Geochronological data essentially indi-
Fig. 13. Sketch illustrating the emplacement of the tectonic complexes in the central Rhodope. Two stage extension tectonics emplaced the Kimi Complex and the Eocene sediments on top of the high grade Sidironero Complex: C. 42-38 Ma: thrust emplacement of high grade high-P rocks (Section II) was accompanied by high level extension associated with a broad shear zone on top of the migmatic rocks (eastern Kardamos detachment system), exhumation of high grade high-P rocks and transgression of basins on the upper plate (Section I; Kimi Complex). Approx. 38-32 Ma: post-contractional extension ('out of sequence') low angle normal faults cut through the earlier formed thrust and extensional structures and emplaced Eocene sediments immediately above high grade high-P rocks migmatized at the time of sedimentation. Approx. 26-10 Ma: Miocene metamorphic core complexes were formed between 26 and 10 Ma, substantially after the exhumation stage of high-P rocks.
cate Early Tertiary metamorphic histories. Fligh-P metamorphism indicates maximum burial depths of 53 km (15 kbar) in eastern Rhodope and over 68 km (min. P 19 kbar) in central Rhodope (Thermes area) at temperatures of c. 550 °C and c.700°C respectively. Nearly isothermal decompression from the maximum depth up to depths of <20 km infers rapid exhumation.

(4) In the Late Eocene/Early Oligocene, two episodes of extension created two sets of detachment systems.

(5) The older is clearly coeval with deeper level thrusting of hot over cold high-P rocks (eastern Kardamos detachment system, between 42 and 39 Ma) separating the Kimi Complex from the eastern Kardamos Complex. This detachment is probably linked with the detachment system separating the Vertiskos Complex from the Kerdilion Complex (Fig. 14).

(6) The younger detachment is the Xanthi (-Kechros) detachment system (37-30 Ma) that dismembered the Vertiskos Complex from the Kerdilion Complex (Fig. 14).

(7) The crustal thickness excised by the Xanthi connected detachment system is larger in the eastern Rhodope than in the central Rhodope. In the eastern Rhodope, this system emplaced the upper plate Kimi Complex upon a structurally much lower level of the previous thrust structure (Kechros Complex, Figure 14). Hence, in the eastern Rhodope, crustal thinning, inferred from gravimetric data, occurred in the Oligocene on the eastern dipping Xanthi-Kechros normal detachment system (Fig. 14).

(8) Ages of detachment systems are constrained from structural relationships and geochronological data of sheared metamorphic rocks and granitoids (Fig. 14). In the Lutetian/Priabonian and Oligocene, simultaneous with detachment formation, several pulses of sedimentation occurred. Transgression of basins linked to both detachment systems is generally upon Vertiskos, Melivia-Kotili, and Kimi Complexes, forming the upper plate (Fig. 14).

(9) After exhumation of high-P rocks in the Sidironero/Kardamos and Kechros Complex,
Correlation -with the Bulgarian Rhodope

The tectonic complexes in the Greek Rhodope, presented in this article, correlate with the tectonic units of the Bulgarian Rhodope, which earlier subdivisions did not allow. The Kimi Complex correlates with the Krumovica Unit, and the Koti-li-Melivia Complex probably with the Madan Unit of the Bulgarian Rhodope (Burg et al. 1996; Ricou et al. 1998; Z. Ivanov pers. comm. 1999). Upper Sidironero, Kardamos and Kechros complexes correspond to the Central Rhodopian Gneiss Dome, Kecebir Dome and Biela Recka Unit in the Bulgarian Rhodope, respectively. Xanthi, western and eastern Kardamos detachment systems, and also the detachment system bounding the Kechros Complex, deeply extend into Bulgaria, where they represent prominent structures (cf. Burg et al. 1996; Ricou et al. 1998; Z. Ivanov pers. comm. 1999).

Conclusions

Our data show first that the predominant NE-SW trend of stretching lineations in mylonites and top-to-SW senses of shear were formed during principally different events and thus do not in general reflect progressive thrusting (cf. Burg et al. 1993; Burg et al. 1996; Ricou et al. 1998), secondly that several phases of extension from the Late Eocene to the Miocene had a major impact on the metamorphic fabrics and on the large-scale structures of the Rhodope Domain (Dinter et al. 1995; Wawrzenitz & Krohe 1998), this work) and thirdly that a large proportion of tectonic contacts juxtaposing various superimposed metamorphic complexes are extensional. In the individual tectonic complexes, the lineation trends of the mylonites do in fact depict spatial partitioning of flow within the crust and a succession of compression and extension events. Syn-thrusting extension was followed by post-thrusting extension. All these different episodes contributed to exhumation of high-P rocks and are genetically linked with formation of basins on the hanging wall (downthrown) blocks of detachments.

Our kinematic/geodynamic model sketches out that:

1. most parts of the west, central and east Rhodope domain in Greece expose high-P rocks that were exhumed in the Eocene/Oligocene beneath a thin lid of material that had been exhumed earlier;
2. except for this thin lid, the dominant pervasive structures and tectonic boundaries reflect Early Tertiary tectonic processes (compression and extension);
3. low-angle detachments had already formed as early as the Late Eocene, thus preceding Aegean back-arc extension;
4. such older detachment systems connect to a principal large-scale tectonic boundary that caused exhumation of a high-P terrain in their footwall, about 10-20 Ma before the beginning of Late Oligocene/Miocene back-arc extension;
5. the structurally deeper part is interpreted as showing Early Tertiary high-P metamorphism and was a part of the Apulian plate; its P-T
history and geochronological record differ from the higher part, reflecting the Cretaceous accretion/collision history.

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