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A. I. Okay · M. Satır · O. Tüysüz · S. Akyüz · F. Chen

The tectonics of the Strandja Massif: late-Variscan and mid-Mesozoic deformation and metamorphism in the northern Aegean

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Abstract The Strandja Massif is a mid-Mesozoic orogenic belt in the Balkans build on a late-Variscan basement of gneisses, migmatites and granites. New single-zircon evaporation ages from the gneisses and granites indicate that the high-grade metamorphism and plutonism is Early Permian in age (~271 Ma). The late-Variscan basement was unconformably overlain by a continental to shallow marine sequence of Early Triassic–Mid-Jurassic age. During the Late Jurassic–Early Cretaceous (Oxfordian–Barremian) the lower Mesozoic cover and the basement were penetratively deformed and regionally metamorphosed in greenschist facies possibly due to a continental collision. An Rb–Sr biotite whole-rock age from a metagranite dates the regional metamorphism as Late Jurassic (155 Ma). Deformation involved north-vergent thrust imbrication of the basement and the emplacement of allochthonous deep marine Triassic series over the Jurassic metasediments. The metamorphic rocks of the Strandja Massif are unconformably overlain by the Cenomanian shallow marine sandstones. During the Senonian, the northern half of the Strandja Massif formed a basement to an intra-arc basin and to a magmatic arc generated above the northward-subducting Tethyan oceanic lithosphere. The Srednogorie arc closed during the early Tertiary through renewed northward thrusting of the Strandja Massif.

A. I. Okay (✉) · O. Tüysüz
Eurasian Institute of Earth Sciences,
Istanbul Technical University, 80626 Ayazağa, Istanbul, Turkey
E-mail: okay@itu.edu.tr
Phone: +90-212-2856208
Fax: +90-212-2856210

M. Satır · F. Chen
Institut für Mineralogie, Petrologie und Geochemie,
Universität Tübingen, Wilhelmstrasse 56, 72074 Tübingen,
Germany

S. Akyüz
Department of Geology, Faculty of Mines,
Istanbul Technical University, 80626 Ayazağa, Istanbul, Turkey

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Introduction

Metamorphic rocks occupy a large area of 400×200 km in the Balkans between the northern Aegean and the western Black Sea (Fig. 1). This Balkan metamorphic province, which includes the Serbo-Macedonian, Rhodope and Strandja massifs, is bounded in the south by the earliest Tertiary Vardar–Intra-Pontide suture and in the north by the Eocene–Oligocene Balkanide thrust belt (Fig. 1). Views on the tectonic significance of the Balkan metamorphic province during the Alpide orogeny range from a passive role of a Precambrian–Variscan cratonic basement (Foose and Manheim 1975; Dewey et al. 1973; Burchfiel 1980; Boncev 1988) to having actually formed during the Cretaceous to early Tertiary Alpide regional metamorphism and compressive deformation (Meyer 1968; Kronberg 1969; Dixon and Dimitriadis 1984; Burg et al. 1990, 1996; Koukouvelas and Doutsos 1990; Ricou et al. 1998). Probably the least internationally known part of this large metamorphic terrain is the Strandja Massif in the northeast, which forms a northwest-trending metamorphic belt straddling the Turkey–Bulgaria border (Fig. 1). Here, we provide new stratigraphic, structural and geochronological data from the Turkish part of the Strandja Massif and suggest a tectonic model for its post-Variscan evolution. The field data were obtained during regional mapping of the Turkish sector of the Strandja Massif in 1991 and 1994, and during a field trip to the Bulgarian part of the Strandja Massif in 1992. Although we have covered the whole of the Turkish

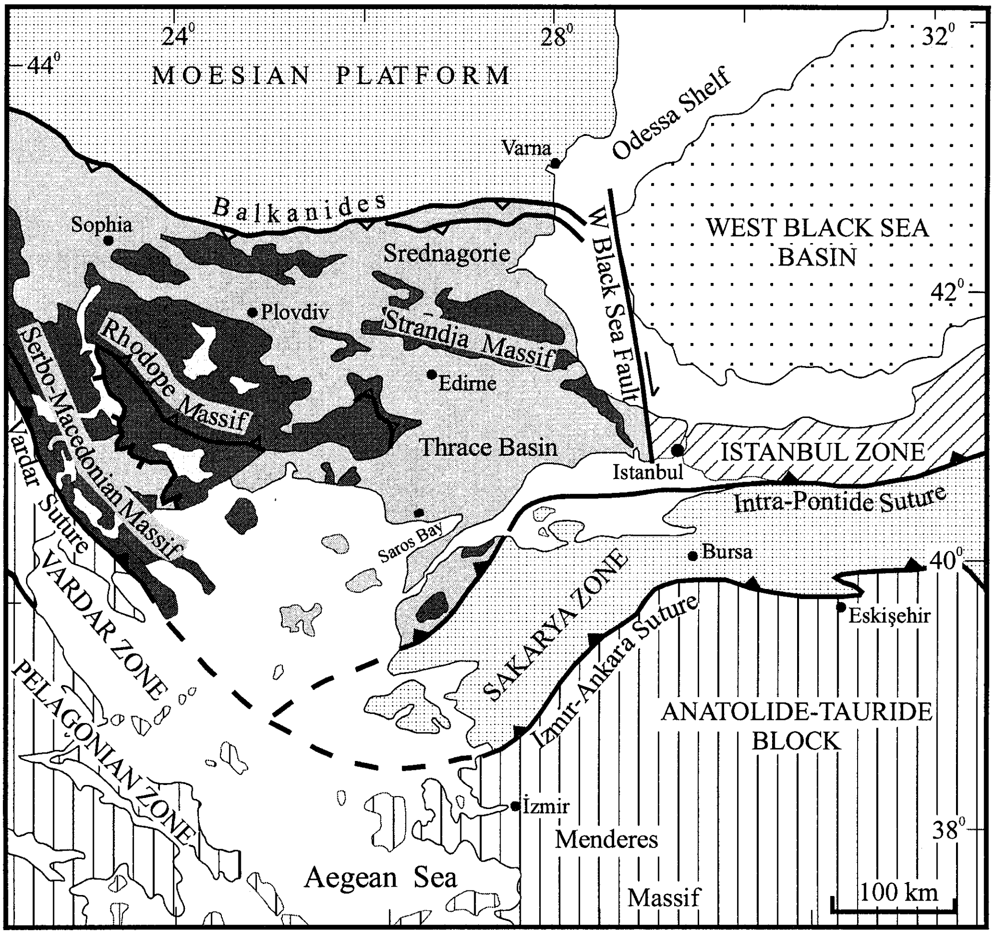

Fig. 1 Tectonic map of the northern Aegean and the Balkans showing the outcrops of metamorphic rocks (*dark areas*) between the Vardar–Intra-Pontide sutures and the Balkanide thrust belt

Strandja Massif, this paper concentrates on the central part of the Massif, where the stratigraphy and the structural relations are best exposed. Our field and geochronological results confirm that the Strandja Massif is a late-Variscan unit that underwent regional metamorphism and compressive deformation during the Late Jurassic–Early Cretaceous (e.g. Chatalov 1988; Çağlayan et al. 1988; Aydın 1982). Our study also shows that the mid-Mesozoic deformation was thick skinned and involved thrusting of the basement gneisses over the lower Mesozoic series. Furthermore, zircon geochronological data indicate that the metamorphism of the gneissic basement of the Strandja Massif, generally thought to be of Precambrian age, is most probably Early Permian coeval with the granite intrusions.

Geological setting

The Strandja Massif forms a northwest-trending mountain belt, approximately 280 km long and 40 km wide, along the southwestern margin of the Black Sea (Fig. 1). It is bounded in the south by a major Tertiary basin, the Thrace Basin, with up to 9-km-thick siliciclastic sediments of Eocene–Oligocene age (Kopp et al. 1969; Turgut et al. 1991; Görür and Okay 1996). Results from the oil wells in the Thrace Basin (Alaygut 1995) and a small outcrop of phyllites and slates north of Saros Bay (Sümengen and Terlemez 1993; Tüysüz et al. 1998) indicate that metamorphic rocks extend underneath the Tertiary sediments at least as far south as the Saros Bay (Fig. 1). In the east, the Strandja Massif is bounded by the West Black Sea basin, which has a Cretaceous oceanic crust overlain by Upper Cretaceous–Cenozoic sediments over 13 km in thickness (Letouzey et al. 1977; Finetti et al. 1988; Robinson et al. 1996). The Istanbul Zone, which borders the Strandja Massif in the southeast, comprises a continuous unmetamorphosed sedimentary sequence of Ordovician to Carboniferous age overlain unconformably by Triassic rocks (e.g. Görür et al. 1997). West of the city of Istanbul, the phyllites and slates of the Strandja Massif are separated by a strip of undeformed mid-Eocene sediments from the Carboniferous siltstones and shales, and Triassic limestones of the Istanbul Zone (Fig. 2). The pre-mid-Eocene contact between the Istanbul Zone and the Strandja Massif is believed to be a major N/S-trending dextral strike-slip fault, the West Black Sea fault (Fig. 1), which had a significant role in the formation of the West Black Sea basin. During the mid-Cretaceous opening of the

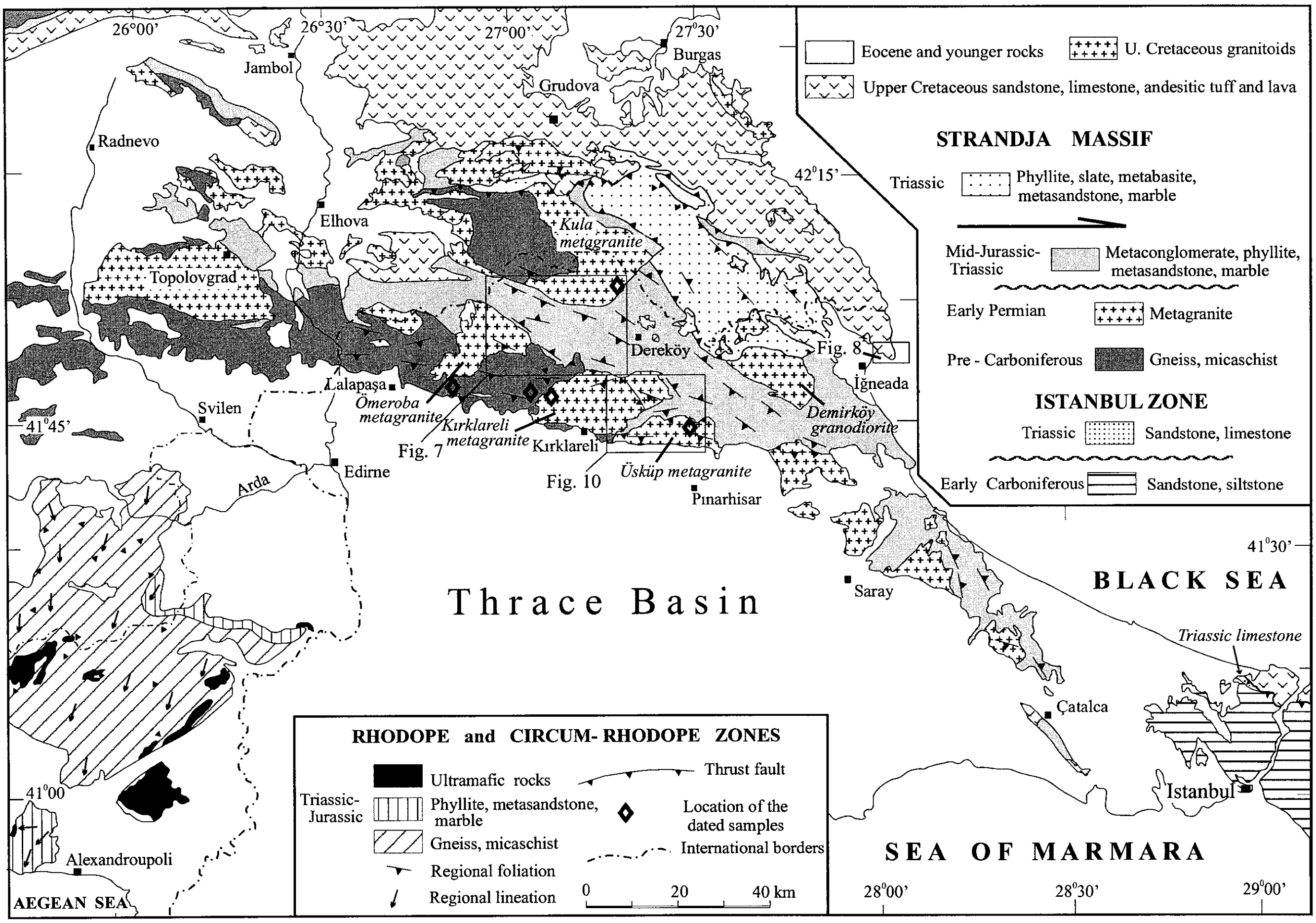

Fig. 2 Geological map of the Strandja Massif and the neighbouring regions. (Compiled from Chatalov 1988; Chestitev and Kancev 1989; Kasar and Okay, unpublished data; A.I. Okay et al., unpublished data)

oceanic West Black Sea basin, the Istanbul Zone was translated along the West Black Sea fault from its predrift position south of the Odessa shelf to its present position (Okay et al. 1994). North of the Strandja Massif is a belt of Upper Cretaceous volcano-sedimentary rocks and granodioritic plutons (Fig. 2). This Srednogorie Zone was formed in the Senonian as a magmatic arc and intra-arc basin above the northward-subducting Tethys ocean (Boccaletti et al. 1974). The contact between the metamorphic rocks of the Strandja Massif and those of the Rhodope Massif in the west are covered by the Tertiary sediments.

Stratigraphy

The Strandja Massif in Turkey consists of a late-Variscan crystalline basement of granites and gneisses unconformably overlain by a Lower Mesozoic metasedimentary sequence (Fig. 3; Pamir and Baykal 1947; Aydın 1974, 1982; Üşümezsoy 1982; Çağlayan et al. 1988; Okay et al. 1994; S. Kasar and A.I. Okay, unpublished data). This relative autochthon is tectonically overlain by allochthonous Triassic units, preserved mainly in the Bulgarian sector of the Strandja Massif (e.g. Chatalov 1988; Dabovski et al. 1991; Gocev 1991). Cenomanian sandy limestones lie unconformably over the metamorphic rocks both in the Turkish and Bulgarian sectors of the Massif and provide an upper age limit for the mid-Mesozoic regional metamorphism.

Late-Variscan basement

Granites and felsic gneisses, which make up the bulk of the basement of the Strandja Massif, form a discontinuous belt, 240 km long and approximately 13 km wide, along the southwestern rim of the Strandja Massif from near Istanbul westward to Topolovgrad (Fig. 2). They also occur in the north along the Turkish–Bulgarian border in the core of a faulted anticline. The metamorphic rocks are dominated by granitic gneisses with minor amounts of migmatite, amphibolite and micaschist, and are intruded by a large number of granitic veins, dykes, small stocks and plutons. The margins of large plutons are characterised by numerous granitic veins and stocks, and there is no

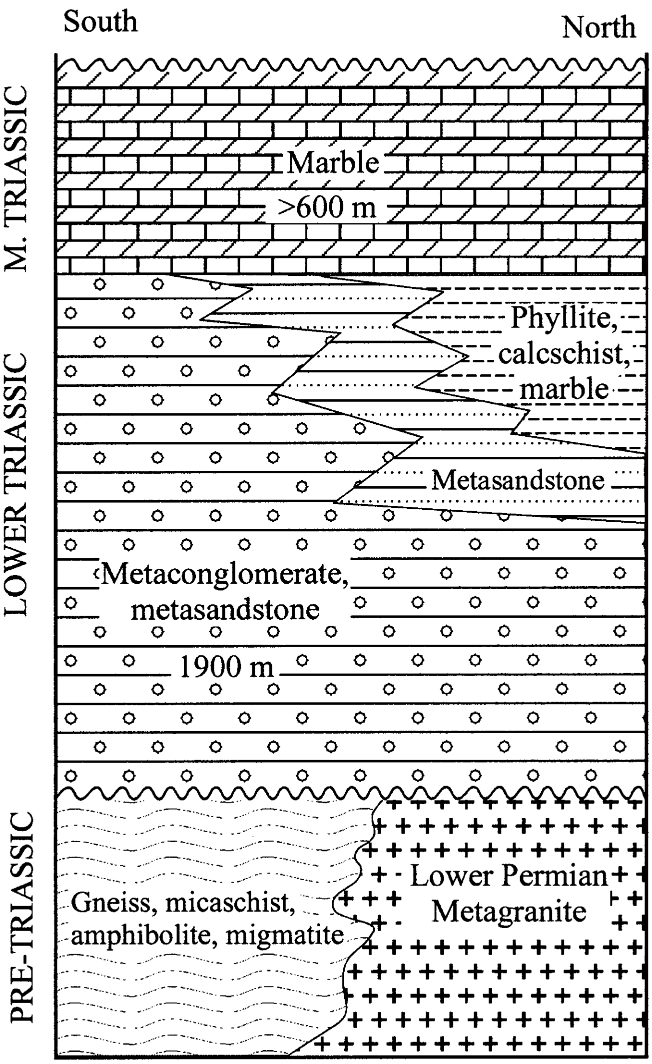

Fig. 3 Stratigraphic section of the Strandja Massif in the Kapaklı syncline

discernable contact metamorphism in the gneisses surrounding the plutons, which suggests that the granites represent deep-level intrusions. The granitic plutons show a range of petrographic and deformational features; however, there are several common traits among the plutons such as the absence of hornblende, presence of magmatic muscovite and the modal importance of microcline. Most common are porphyritic granites and monzogranites with pink K-feldspar phenocrysts up to 3 cm across. The Kırklareli and Ömeroba metagranites are examples of such plutons (Fig. 2). These granites consist of quartz (28–46 modal %), plagioclase (20–34%), microcline (15–33%), muscovite (7–13%) and minor biotite. Kırklareli metagranite, which is the only late-Variscan pluton from which geochemical analyses are available, is a uniform peraluminous granite *s.s.* with 71–74 wt.% SiO_2, 11–14% Al_2O_3, 4–5% K_2O, 3% Na_2O and 1% CaO (Aydın 1974, 1982).

The Kula metagranite, which straddles the Turkish–Bulgarian border (Fig. 2), is a little deformed, fine-grained, homogeneous, leucocratic granite that consists mainly of quartz, microcline and plagioclase with minor muscovite. Other plutons, such as the Düzorman (see Fig. 10) and Üsküp metagranites, are strongly deformed and possess a penetrative foliation. Deformation and metamorphism in the intrusive metagranites are of mid-Mesozoic age and are described later.

Zircon geochronology

Up to now, the only available isotopic age data from the basement of the Strandja Massif was an Rb/Sr whole-rock isotope age of 244±11 Ma based on three rock samples from the Kırklareli metagranite (Aydın 1974). During the present study three samples from three different granitic bodies and two samples from the basement metamorphic rocks were dated using the single-zircon stepwise evaporation technique of Kober (1986, 1987). The sample locations are shown in the geological map in Fig. 2. The petrographic features of the dated zircons and the analytical results are given in Table 1 and are summarised in the histograms in Figs. 4 and 5. The single-zircon stepwise Pb evaporation dating method has the advantage that only small zircon samples are needed, no chemical procedures are involved and therefore there is no blank contamination, and one knows precisely which grain is being dated. It has given results that agree with the conventional dating techniques (e.g. Cocherie et al. 1992). The analytical technique was the same as described by Okay et al. (1996). Data collection started at a zircon evaporation temperature of approximately 1450 °C. The temperature was increased by steps of 20–30 °C to approximately 1520 °C. Isotopic measurements were done after each temperature step.

Zircons from the metagranites

Zircons from three samples from the Kırklareli, Kula and Üsküp metagranites (Fig. 2) were dated. All three samples consist essentially of quartz, K-feldspar and plagioclase, and additionally magmatic biotite and muscovite occur in minor amounts in the Kırklareli and Kula metagranite, respectively. The sample from the Üsküp metagranite shows a penetrative foliation and development of metamorphic muscovite ascribed to the mid-Mesozoic orogeny.

Zircons from all three samples are dominantly colourless, transparent and prismatic, with no or very few inclusions. They show generally fine growth zoning typical for igneous zircons (Fig. 6). According to the morphological classification of Pupin (1980), the zircons from all the three metagranites are dominantly

Table 1 Isotopic data from single grain zircon evaporation

Lithology and sample number	Grain	Zircon morphology	Mass scans[a]	Mean $^{207}Pb/^{206}Pb$ ratio and error[b]	$^{207}Pb/^{206}Pb$ age (Ma)
Kirklareli metagranite 1346B	1	Colourless, long and Prismatic	147	0.051661±211	270±9
	2		131	0.051718±192	273±9
	3		126	0.051692±151	272±7
	4		101	0.051701±176	272±8
	5		126	0.051687±185	271±8
	Mean		406	0.051679±37	271±2
Kula metagranite 1142B	1	Colourless, clear and prismatic	108	0.051715±361	273±16
	2		46	0.051589±428	267±19
	Mean		96	0.051674±250	271±11
Üsküp metagranite 837B	1	Rose, prismatic and long	42	0.052541±554	309±24
Gneiss 1323A	1	Rose, prismatic and turbid	70	0.051560±317	266±14
			64	0.050968±348	239±16
	2	Colourless, small and prismatic	36	0.051833±433	278±19
Migmatite 1335A	1	Colourless, prismatic and large	30	0.052314±332	299±15
			44	0.051788±271	276±12
			28	0.050959±267	239±12
			48	0.050566±316	221±14

[a] Number of $^{207}Pb/^{206}Pb$ ratios evaluated for age assessment
[b] Observed mean ratio corrected for non-radiogenic Pb where necessary

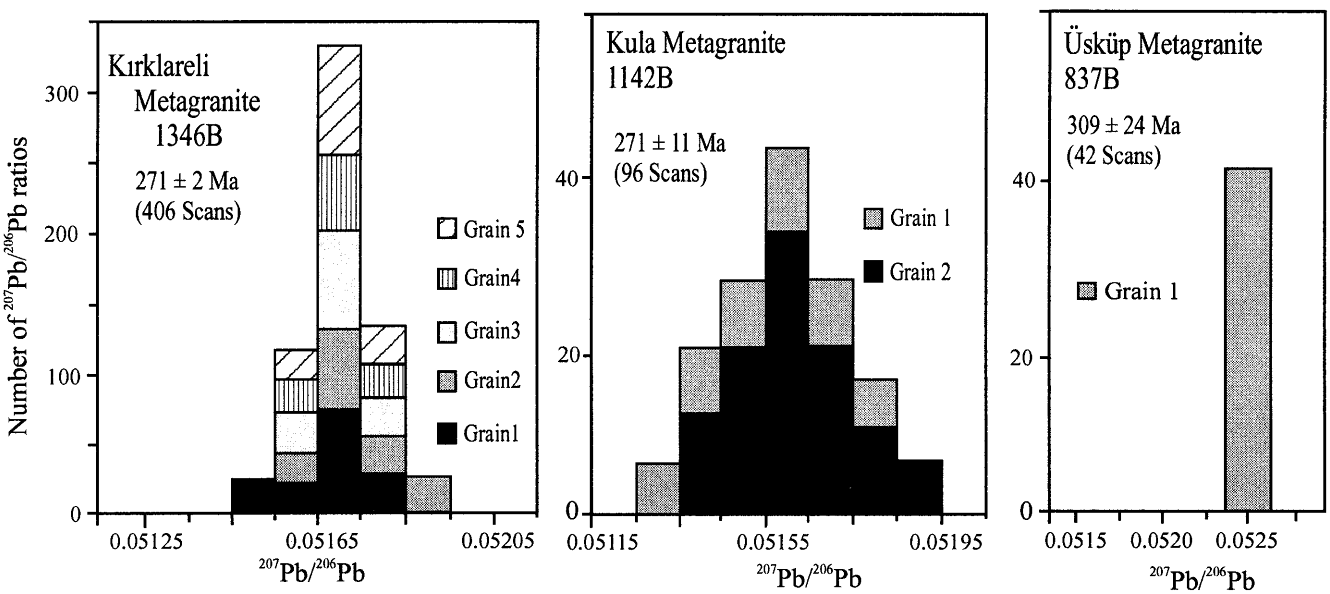

Fig. 4 Histograms show the distributions of radiogenic Pb-isotope ratios derived from evaporation of individual zircon grains from the metagranites of the Strandja basement

S-type, typical for zircons from the crustal melt granites.

Five zircon grains from the Kırklareli metagranite sample gave a precise age of 271±2 Ma (Fig. 4a). A very similar but less precise age of 271±11 Ma was obtained from two grains from the Kula metagranite (Fig. 4b). A single-zircon grain from the Üsküp metagranite sample gave a slightly older age of 309±24 Ma (Fig. 4c). These metagranites have undergone greenschist facies regional metamorphism during the Late Jurassic–Early Cretaceous under metamorphic temperatures of less than 500 °C. Considering that zircon has an isotopic closure temperature of above 900 °C for U and Pb (e.g. Kober 1986), the zircon ages from the metagranites should represent magmatic crystallisation ages of the plutons, and indicate that the granites have intruded the gneissic basement during the Early Permian. Plutonism during the Variscan orogeny in central Europe spanned a period of 340 to 270 Ma (e.g. Schaltegger 1997); therefore, from a temporal and most probably also from a spatial aspect, the Early Permian metagranites in the Strandja Massif can be considered as part of the late-Variscan plutonism.

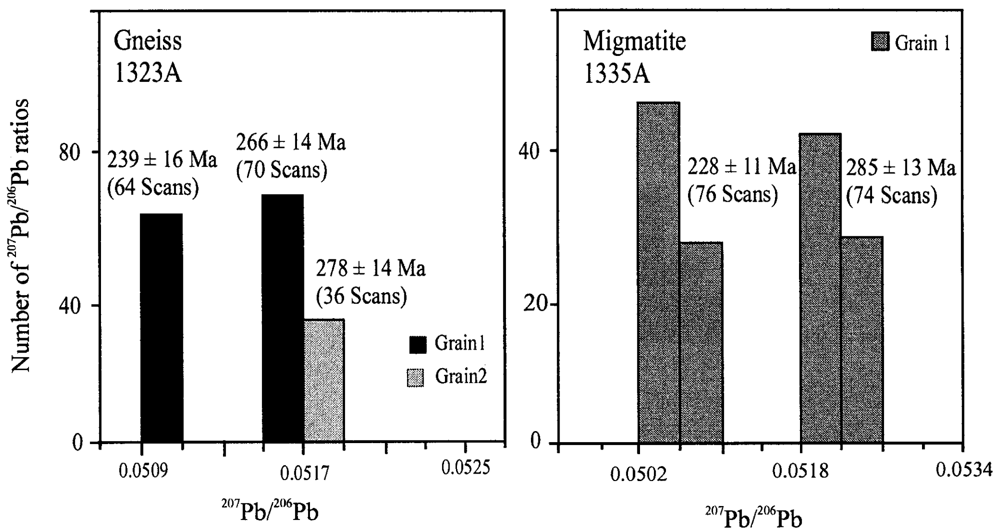

Fig. 5 Histograms show the distributions of radiogenic Pb-isotope ratios derived from evaporation of individual zircon grains from the gneiss (1323A) and migmatite (1335A) of the Strandja basement

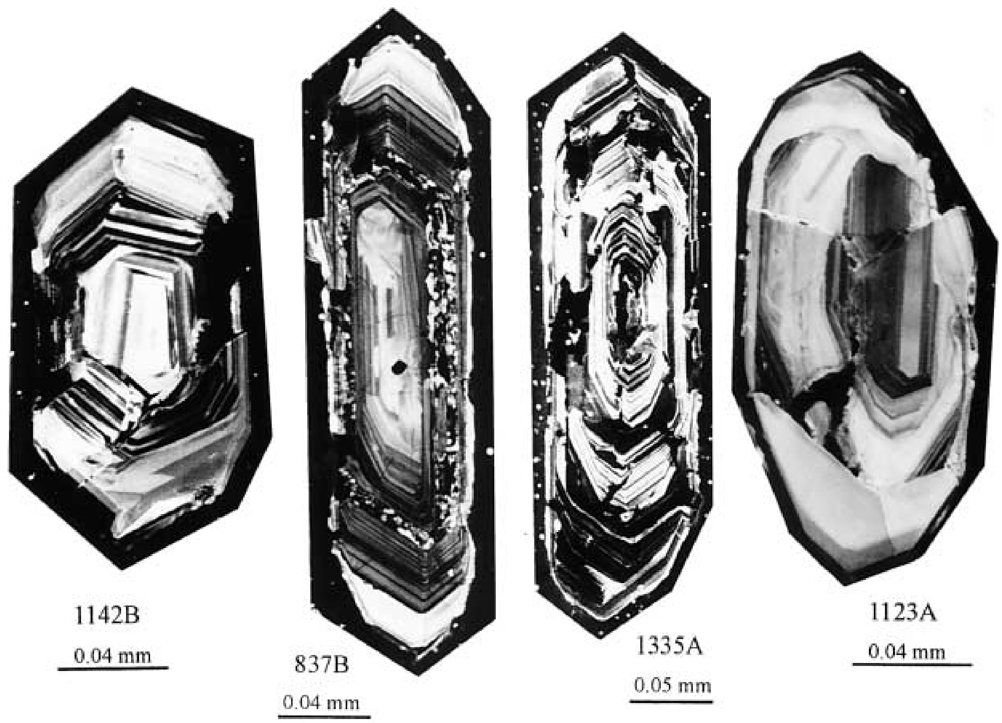

Fig. 6a–d Cathodoluminescence photographs of zircons from the Strandja Massif. **a** Prismatic, colourless, transparent magmatic zircon shows sector zoning, Kula metagranite, sample 1142B. **b** Prismatic, elongate, colourless, transparent zircon with igneous sector zoning, Üsküp metagranite, sample 837B. **c** Prismatic, elongate, colourless, transparent zircon with igneous sector zoning, leucosome from a migmatite, sample 1335A. **d** Prismatic zircon with a magmatic core and a homogeneous (metamorphic ?) overgrowth, gneiss, sample 1323A

The isotopic ages obtained from the Strandja metagranites confirm the Late Paleozoic ages assigned previously to the granitic intrusions on the basis of regional geology (e.g. Chatalov 1988).

Zircons from the gneiss and migmatite

Two samples from the basement metamorphic rocks were dated. Sample 1323A is a fine-grained, finely banded gneiss of quartz, microcline, plagioclase, biotite and muscovite. Rare, poorly preserved feldspar porphyroclasts suggest a granitic origin, which is supported by the oscillatory zoning and prismatic habit of the zircons. However, some zircon grains from this sample have homogeneous overgrowths possibly formed during the late-Variscan metamorphism (Fig. 6). Two zircon grains from this sample were dated (Fig. 5; Table 1). The first grain gave two peak ages of 266±14 and 239±16 Ma, corresponding to high and low evaporation temperature ages, respectively, while the second grain gave a single peak age of 278± 19 Ma. The older ages are similar to those documented in the Kırklareli and Kula metagranites, and indicate that the orthogneiss was deformed and metamorphosed during or very soon after its intrusion.

The other dated sample (1335A) comes from the granitic leucosome of a migmatite. It consists of quartz, microcline, plagioclase and minor muscovite. Zircons from the sample are dominantly prismatic, colourless and transparent with strong oscillatory igneous zoning (Fig. 6), although there are also turbid, milky grey to pale-brown zircons. Two grains were dated. Like the previous orthogneiss sample, the results show two age peaks, one at 285±13 Ma and the other at 228±11 Ma. The 285-Ma age is similar to that obtained from the orthogneiss and the metagranites and indicates high-grade metamorphism and partial melting during the earliest Permian. The Triassic isotopic ages from both samples are more difficult to interpret, especially since the sedimentary sequence, which lies stratigraphically on the exhumed and eroded basement of the Strandja Massif, have been dated palaeontologically as earliest Triassic to mid-Jurassic in age (Chatalov 1988); therefore, these Triassic ages from the gneiss and migmatite are regarded as being due to Pb loss during the Late Jurassic–Early Cretaceous metamorphism.

An important result of the zircon geochronology is that the age of the basement metamorphic rocks of the Strandja Massif is similar to that of the intrusive granites. This result is consistent with the absence of contact metamorphism at the granite gneiss contacts and indicates high-grade metamorphism, migmatisation and formation of crustal melts during the Early Permian in the Strandja Massif.

Mesozoic metasedimentary cover

The late-Variscan metamorphic rocks and metagranites are unconformably overlain by a transgressive continental to shallow marine metasedimentary sequence, over 2.5 km in thickness, which is best preserved in the central Strandja Massif in the core of the northwest-trending Kapaklı syncline (Figs. 2, 3, 7). The metasedimentary sequence consists of metaconglomerates and metasandstones at the base, which are overlain by carbonates in the core of the syncline.

The unconformity between the basement gneisses and the overlying metaconglomerates can be clearly observed 1 km northwest of the village Erikler (Fig. 7). Metaconglomerates dominate the lower part of the metaclastic sequence. The well-rounded and poorly sorted clasts in the metaconglomerate are usually 3–10 cm across but may reach up to 50 cm and consist mainly of granite, gneiss, aplite and quartz in a sandy-silty matrix. The metaconglomerate beds, 1–5 m thick, alternate with thinner arkosic to quartzitic metasandstone and metasiltstone beds. In some cases metaconglomerate occurs in the erosional channel fills in the metasandstones. Upwards in the metaclastic sequence, the metaconglomerate beds become scarce, and the sequence is dominated by metasandstones, metasiltstones and phyllites. Occasionally graded bedding and current bedding are preserved in the metasandstones, and show that the sequence is right way up. In the northern limb of the Kapaklı syncline there is a gradual upward transition from these medium-grained metaclastic rocks to a carbonate-rich sequence of calc-schist, phyllite, slate and thin marble horizons. Some of the black marble horizons around the village of Taştepe (Fig. 7) contain abundant undetermined lamellibranch and gastropod fossils. This mixed carbonate–siliciclastic sequence is overlain by a calcitic and dolomitic marble series of over 600 m in thickness preserved in the core of the Kapaklı syncline (Fig. 7). The marble is white to grey, medium to thickly bedded and represents recrystallised neritic limestone.

Carbonates are stratigraphically the youngest unit preserved in the core of the Kapaklı syncline. However, northeast of a complex fault zone, east of the village of Kula, there is a sequence of black, dark-grey slates with minor intercalated metasiltstones, over 400 m in thickness, which lie stratigraphically over dark recrystallised limestones (Fig. 7). These fine-grained metaclastics extend to Bulgaria, where they are palaeontologically dated as Mid-Jurassic (Chatalov 1988).

The abundance of metaconglomerates, erosional channels in the metasandstones, and large-scale cross-bedding in the lower part of the metaclastic sequence indicate a fluviatile environment, whereas the shelly faunas in the carbonates suggest shallow marine conditions for the upper part of the sequence. The cover series exhibits some lithological variation between the two limbs of the Kapaklı syncline. In the southern limb of the syncline the metaclastics are dominated by metaconglomerates, which pass up abruptly to the marbles, whereas in the northern limb arkosic to quartzitic metasandstones are more abundant than the metaconglomerates, and there is a thick siliciclastic–carbonate transitional interval between the metasandstones and the marbles (Figs. 3, 7). These lithological variations suggest a southerly source for the clasts in the conglomerates and a northward deepening sedimentary environment.

Palaeontological ages of the cover series in the Turkish Strandja are not known. In contrast, the conodont and bivalve ages of the cover units in the Bulgarian Strandja are relatively well determined (Chatalov 1985a, 1988, 1990). Geographic and lithological correlations with the Bulgarian sector of the Strandja Massif indicate an Early Triassic age for the basal metaclastic unit and for the overlying phyllite–calc-schist–slate sequence, and a mid-Triassic (Anisian) age for the overlying marbles. The slates, which outcrop southeast of the Kula metagranite, are probable equivalents of the Jurassic phyllites which occur immediately across the Bulgarian border (Chatalov 1988). The Triassic sequence in the Strandja autochthon can be compared with the Germanic Triassic series of central and eastern Europe (e.g. Schröder 1982) with the

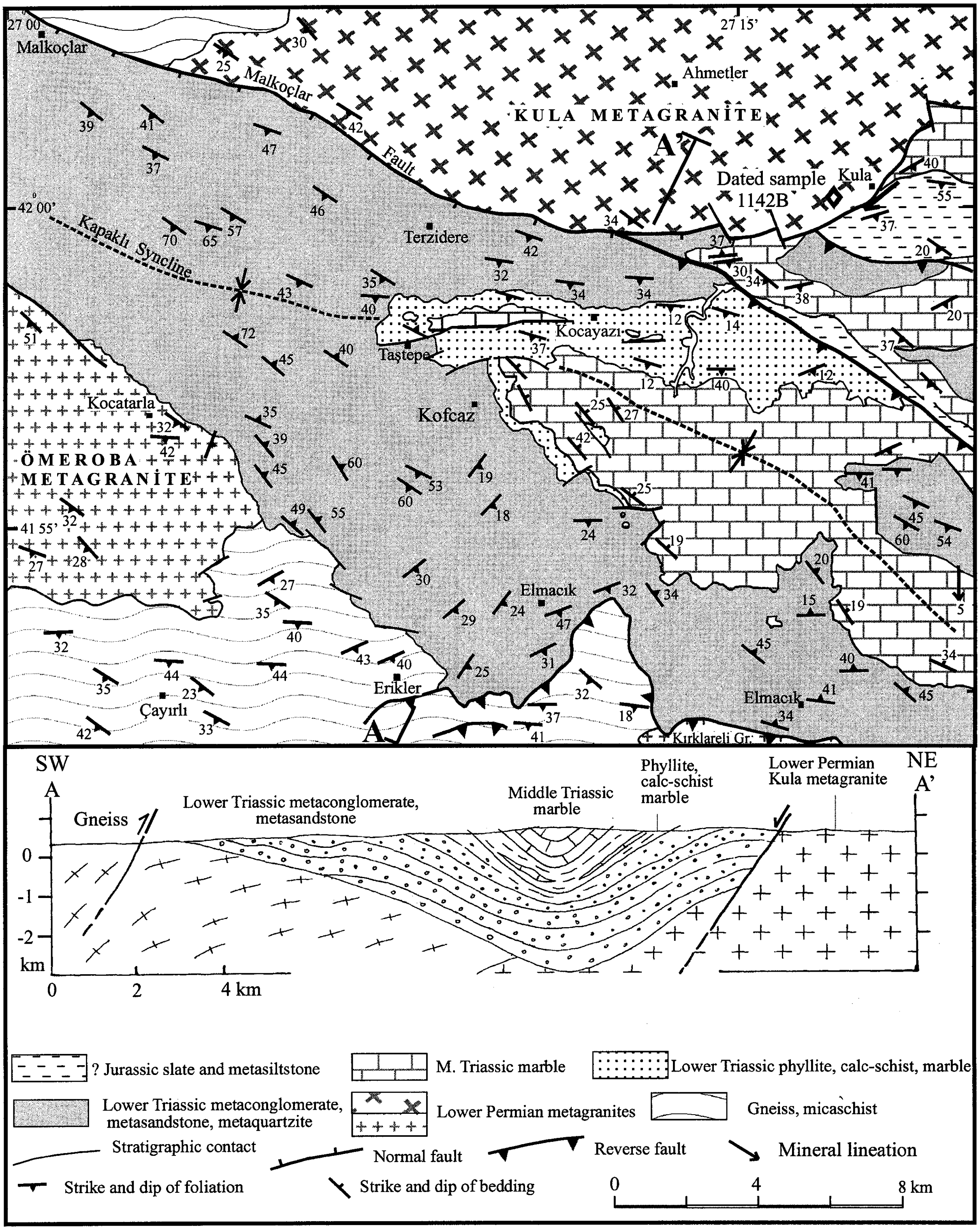

Fig. 7 Geological map and cross section of the central Strandja Massif around the Kapaklı syncline. For location see Fig. 2

basal metaclastic series corresponding to Buntsandstein, and the overlying marbles to the Muschelkalk. In the Bulgarian part of the Strandja Massif, the age of the authochthonous cover series of the Strandja Massif extends up to the Mid-Jurassic (Bathonian) with an unconformity between the Carnian and Hettangian series (Chatalov 1988).

Triassic allochthons of the Strandja Massif

The allochthonous Triassic metasedimentary and metavolcanic rocks, which lie tectonically over the Jurassic metasediments of the Strandja autochthon, are known as the Strandja-type Triassic as opposed to the stratigraphically, lithologically and structurally different Balkanide-type Triassic of the Strandja autochthon (Chatalov 1980, 1988; Dabovski and Savov 1988). The allochthonous Triassic is found mainly in a large klippe in Bulgaria (Fig. 2), and consists dominantly of phyllite, slate, marble, metabasite, metakeratophyre, metasandstone and metasiltstone, including thick packages of turbidite sequences. The Strandja-type Triassic shows intense deformation, which has largely disrupted the stratigraphic continuity. Conodont ages from the Strandja-type Triassic range from the earliest Triassic (Griesbachian) to Norian (Chatalov 1985b, 1988). With its lithological features, chaotic internal structure and allochthonous tectonic position, the Strandja-type Triassic may represent a subduction–accretion complex (Şengör et al. 1984); however, ultramafic rocks or ophiolites are conspicuously absent from the whole of the Strandja Massif.

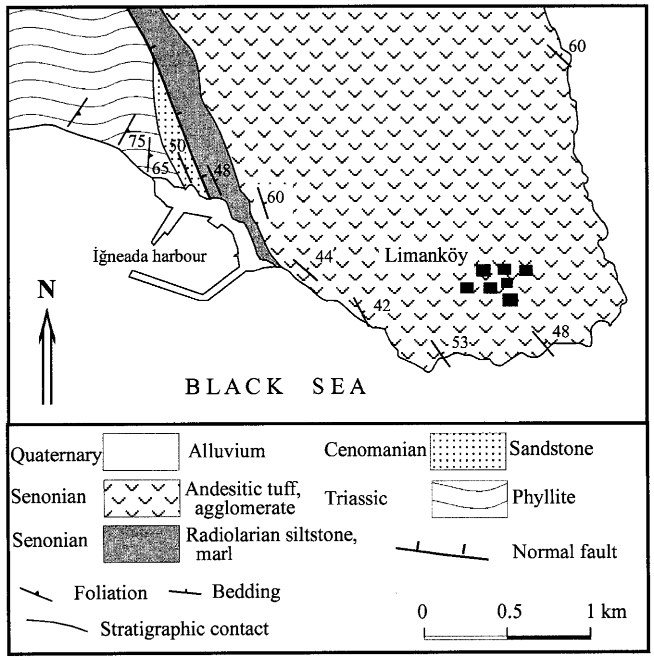

Fig. 8 Small-scale geological map of the area immediately east of the town of İğneada illustrates the Cenomanian unconformity over the metamorphic rocks of the Strandja Massif. For location see Fig. 2

Cretaceous–Tertiary volcano-sedimentary cover of the Strandja Massif

Along the Black Sea coast the metamorphic rocks of the Strandja Massif are unconformably overlain by widespread Upper Cretaceous sedimentary and volcanic rocks, which constitute the Srednogorie Zone. In the Turkish sector the base of the Cretaceous is well exposed west of İğneada (Fig. 8), where shallow marine carbonate-rich sandstones, 40 m thick, lie over the phyllites of the Strandja Massif with an angular unconformity. The sandstones contain abundant *Orbitolina* sp. and *Orbitolina concava* indicating an age range of Aptian to Cenomanian (Pamir and Baykal 1947; O. Sungurlu, unpublished data). They are followed up by hemipelagic siltstone and marl, and by andesitic tuffs and agglomerates, over 250 m in thickness (Fig. 8). The more widespread Cretaceous series in Bulgaria also start with Cenomanian conglomerate, marl, and sandstone with coal lenses and pass up into Coniacian to Campanian andesitic tuffs, agglomerates, lava flows intercalated with marl and siliciclastic turbidites, more than 3 km in thickness (Aiello et al. 1977; Boccaletti et al. 1978; Nachev 1993; Nachev and Dimitrova 1995). Maastrichtian is unconformable over the volcanoclastic rocks and is represented by shallow marine limestones. The Upper Cretaceous volcano-sedimentary sequence was deposited in an intra-arc basin above the northward-subducting Vardar-Intra-Pontide ocean (Boccaletti et al. 1974). South of the intra-arc basin there is a belt of Upper Cretaceous sills, dykes, stocks and plutons related to the Srednogorie magmatic arc (Fig. 2). The largest Cretaceous pluton in the Turkish Strandja is the Demirköy granodiorite (Fig. 2, Aykol and Tokel 1991) with biotite and hornblende K/Ar ages of 78±2 and 79±2 Ma, respectively (Moore et al. 1980). A small microdiorite stock northeast of Dereköy has also yielded similar K/Ar biotite ages of 83±3 Ma (Aydın 1982). Similar isotopic ages are obtained from plutons in the Srednogorie Zone in Bulgaria (e.g. Zagorcev and Moorbath 1987). These Cretaceous calc-alkaline intrusive rocks are abruptly terminated southwest of Dereköy, which marks the magmatic arc front, and there are no Cretaceous intrusions in the southern basement strip of the Strandja Massif.

Along the southwestern margin of the Strandja Massif the metamorphic rocks are unconformably overlain by Eocene shallow marine limestones (Fig. 2; Kopp et al. 1969). The Thrace basin south of the Strandja Massif started to form in the mid-Eocene and was filled by Eocene–Oligocene siliciclastic sediments over 9 km in thickness (Turgut et al. 1991; Görür and Okay 1996).

Structure

The Strandja Massif comprises penetrative structures of Early Permian, and Late Jurassic–Early Cretaceous age, and largely brittle post-Cenomanian structures. The late-Variscan structures, which are found in the gneissic basement, must have been overprinted by the mid-Mesozoic deformation; however, it is difficult to

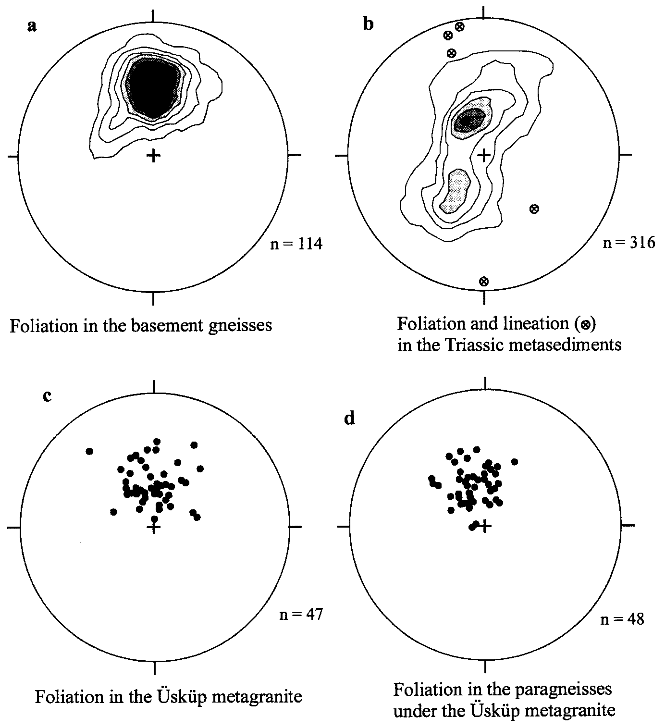

Fig. 9a–d Structural data from the Strandja Massif plotted on equal area streonets. In the contoured streonets the contours are at 1, 3, 5, 7, 9 and 11%. **a** Foliation planes from the late-Variscan gneisses. **b** Foliation planes from the Triassic metasediments overlie the late-Variscan basement. **c** Foliation planes from the Üsküp metagranite. **d** Foliation planes from the Triassic metasediments tectonically underlie the Üsküp metagranite

differentiate these two structure generations in the gneissic basement, where the dominant structure is a south-dipping compositional banding and foliation (Figs. 2, 9a). This gneissic banding is discordant with the generally northeast-dipping foliation in the overlying cover series (Figs. 7) and is also cut by the granitic veins and stocks of the Early Permian Kırklareli and Ömeroba metagranites. These two observations indicate that the south-dipping foliation and compositional banding in the basement metamorphic rocks are pre-Triassic.

The deformation in the Triassic–Jurassic metasediments in the central Strandja Massif shows a marked increase in intensity, defined by the development of foliation, from the relatively little deformed Kapaklı syncline in the northwest to a highly strained thrust belt in the southeast. Although foliation of varying intensity is present throughout the Strandja Massif, mineral lineation is only very rarely observed. The general absence of lineation is a structural feature that distinguishes the Strandja Massif from the strongly lineated Rhodope Massif (e.g. Burg et al. 1996).

The large-scale post-Variscan structure of the west–central Strandja Massif is a broad, symmetrical syncline, the Kapaklı syncline (Figs. 2, 7). The metaconglomerates and metasandstones in the limbs of the Kapaklı syncline show a rough spaced fracture cleavage subparallel to the bedding. The original sedimentary features, such as graded and current bedding, are commonly preserved in the metasandstones. The shapes of the clasts in the metaconglomerates suggest weak strain intesity. In contrast, phyllites and calcschists in the Kapaklı syncline exhibit a penetrative foliation, and very rarely a weak subhorizontal north-trending mineral lineation. They are deformed into mesoscale north-vergent folds with east-trending subhorizontal axis. Crenulation cleavage subparalel to the east-west fold axial planes has developed widely in the fine-grained metaclastic rocks.

The Kırklareli and Ömeroba metagranites on the southern limb of the Kapaklı syncline and the Kula metagranite on the northern limb show clear effects of recrystallisation, although penetrative foliation, apart from that in the rare shear zones, has not been observed in these plutons.

The Kapaklı syncline is an open, symmetrical, non-cylindrical fold with a half wavelength of ~10 km (Figs. 7, 9b). It is modified by faulting along its southwestern and northeastern limbs. On the southwestern limb the Kırklareli metagranite and the gneisses have been thrust along a steeply south-dipping reverse fault over the Mesozoic metasediments. Along the northeastern limb of the Kapaklı syncline there is a major dextral transtensional fault between the Triassic cover rocks and the underlying basement granites and gneisses. This Malkoçlar fault (Fig. 7) extends for over 60 km in the Bulgarian and Turkish sectors of the Strandja Massif and has a curved pattern (Fig. 2). In the east between the village of Kula and the Bulgarian border, the Malkoçlar fault is subvertical. The steep attitude of the fault and the mapped offset in Bulgaria (Fig. 2) suggest dextral strike-slip movement along this section of the fault. The western part of the Malkoçlar fault dips at 45–60° to south and is a normal fault.

The large-scale structure in the eastern central Strandja Massif is a strongly deformed, probably rootless granitic thrust sheet, the Üsküp metagranite, which lies over strongly strained Mesozoic metasediments (Fig. 10). The Üsküp metagranite shows a strong mylonitic foliation and compositional banding, and a very weak subhorizontal north-trending lineation. The foliation in the Üsküp metagranite dips consistently south at 35° and is parallel to the basal thrust plane, and to the foliation in the underlying Mesozoic cover series (Figs. 9c,d). The deformation intensity in the metagranite, as defined by the intensity of foliation, increases downwards towards the basal thrust. Near the basal thrust the metagranite is completely transformed into banded gneisses which are difficult to distinguish from the underlying paragneisses. The paragneisses under the Üsküp metagranite occur in a shear zone between the Kırklareli-Düzorman metagranites at the base and the Üsküp metagranite at the top (Fig. 10). They consist of fine-grained, white quart-

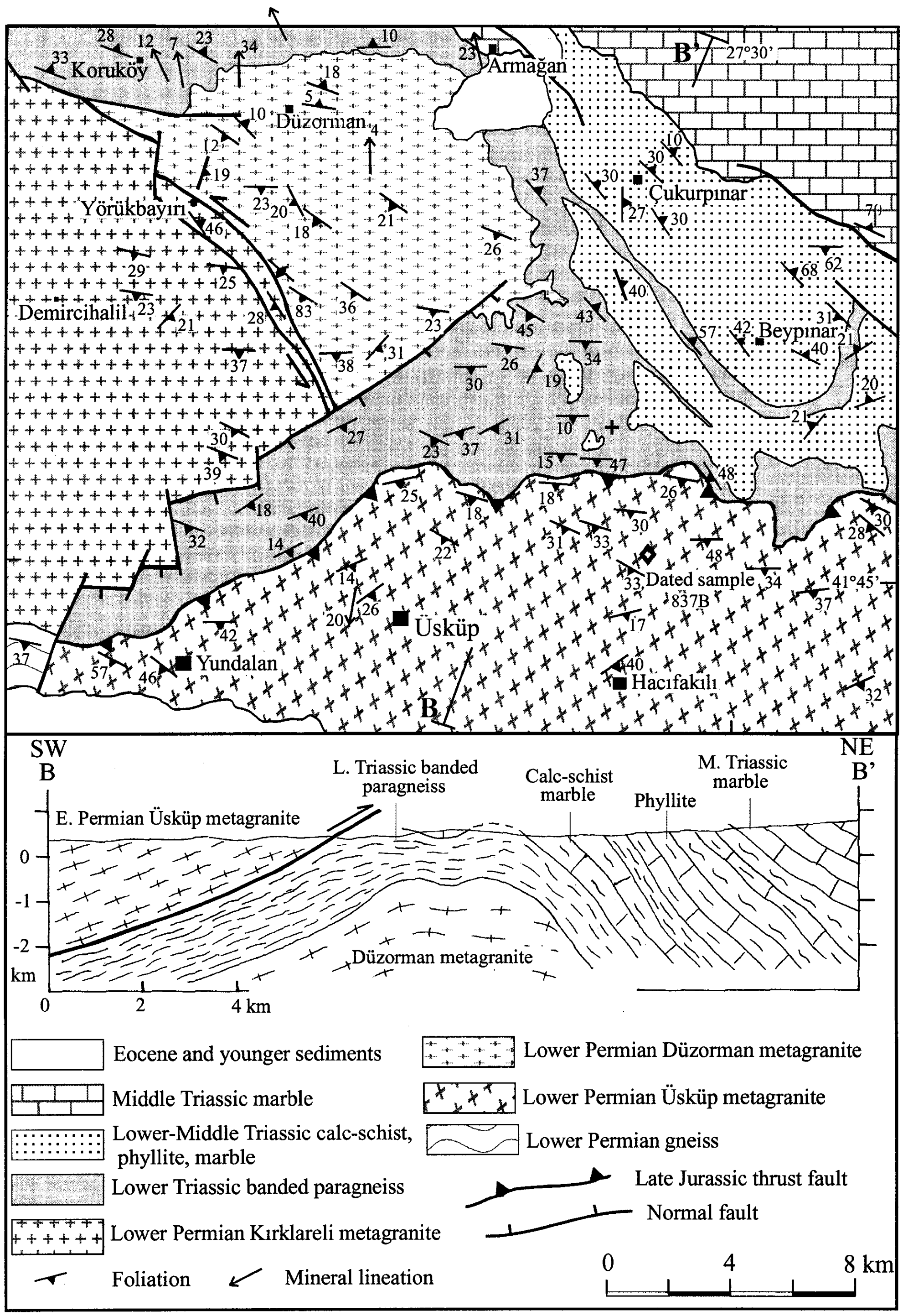

Fig. 10 Geological map and cross section of the region around the allochthonous Üsküp metagranite. For location see Fig. 2

zo-feldspathic gneisses and rare biotite micaschists which show fine mylonitic banding but no mineral lineation. Only the rare clasts in the paragneisses reveal their sedimentary origin. The thrust contact between the Üsküp metagranite and the underlying Mesozoic metasediments can, therefore, be regarded as a deep-seated greenschist facies shear zone.

Several lines of evidence indicate that the deformation and thrusting during the mid-Mesozoic orogeny in the Strandja Massif was north-vergent. The mineral and streching lineation in the cover series, although weak and rarely preserved, is consistently north–south. The paragneisses directly under the Üsküp metagranite show intense micro- and mesoscale folds with a consistent northward vergence. Similar overturned folds are described from the cover metasediments in the Bulgarian sector of the Strandja Massif (e.g. Dabovski and Savov 1988). North-vergent character of the mid-Mesozoic orogen is also supported by the Triassic palaeogeography of Bulgaria. The Triassic sequences north of the Strandja Massif are continental to shallow marine with no evidence of an intervening deep marine Triassic basin, from which the Triassic allochthons could be derived.

Metamorphism

All the pre-Cenomanian rocks of the Strandja Massif have undergone one or two periods of regional metamorphism. The late-Variscan metamorphism has affected only the basement, whereas the mid-Mesozoic regional metamorphism affected both the basement and the cover series.

The widespread Triassic metapsammites and conglomerates in the cover series typically contain quartz+albite+K-feldspar+muscovite assemblage. The original sandstone fabric with poorly sorted quartz and feldspar grains in a sparse matrix is petrographically recognisable in the rocks of the Kapaklı syncline. The only metamorphic effects in these metasandstones is the recrystallisation of quartz into smaller polygonal grain aggregates, and the formation of sericitic white mica along grain boundaries. In contrast, in the southwest in the thrust belt under the Üsküp metagranite, the metapsammites are strongly recrystallised and show compositional banding. The mineral assemblage in these rocks is quartz+albite+K-feldspar+muscovite±biotite±epidote. The compositional bands in the metapsammites consist of approximately 1-mm-thick alternating muscovite-rich and quartzo-feldspathic layers. Rare coarse feldspar grains with a mantle structure are the only relics from the original sandstone.

Deformation and metamorphism in the late-Variscan granites are likely of mid-Mesozoic age. This is obvious in the case of the allochthonous Üsküp metagranite, where the marked compositional banding is parallel to the basal thrust plane and to the foliation in the underlying Mesozoic series (Fig. 9c,d). The Kırklareli and Ömeroba metagranites on the southern limb of the Kapaklı syncline and the Kula metagranite on the northern limb show clear effects of recrystallisation. The magmatic quartz crystals have recrystallised into aggregates of polygonal grains with straight grain boundaries. Feldspar porphyroclasts show recrystallisation into smaller grains at their margins. Newly formed metamorphic minerals in the metagranites include muscovite, epidote and chlorite. The more strongly deformed metagranites, such as the Düzorman and the Üsküp metagranites, show a compositional banding defined by millimetre-thick alternations of quartz+feldspar, and muscovite+biotite+epidote layers. The only magmatic relics are the larger feldspar and very rarely muscovite porphyroclasts, the latter showing extensive recrystallisation to smaller grain aggregates at their margins. The quartz and feldspar in the matrix of these metagranites form equant and equal-sized grain aggregates largely free from the effects of deformation features such as undulose extinction, bending or fracturing of the grains.

The mineral assemblages in the metapsammites and in the metagranites indicate that the Strandja Massif was metamorphosed in low greenschist facies at temperatures of less than 500 °C and pressures of <8 kbar (e.g. Yardley 1989), as also deduced by Chatalov (1988) for the neighbouring areas in Bulgaria. There is no marked areal change in the grade of metamorphism in the Turkish Strandja Massif. The age of the regional metamorphism is stratigraphically bracketed between Bathonian, the youngest palaeontological age from metamorphic rocks in the Bulgarian Strandja (Chatalov 1988), and Cenomanian, the age of the oldest sedimentary rock that lies unconformably on the metamorphic rocks (Fig. 8). K/Ar biotite ages from three samples of the Kırklareli metagranite yielded isotopic ages ranging from 155 to 149 Ma (Aydın 1974, 1982). During the present study Rb–Sr isotopic data were obtained from the biotite and whole rock of the Kırklareli metagranite sample (1346B), which was dated by zircons as Early Permian (271 Ma). The analytical techniques were the same as described in Okay et al. (1993). The biotite whole-rock age of the Kırklareli metagranite is 155±2 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.71673±18 (Table 2). Considering that the biotite from the Kırklareli metagranite is texturally magmatic, this Late Jurassic Rb/Sr age gives a maximum age for the mid-Mesozoic greenschist facies metamorphism in the Strandja Massif.

The common mineral assemblage in the micaschists in the late-Variscan basement is quartz+plagioclase+biotite+muscovite+garnet±staurolite. Staurolite occurs only to the west, north of Lalapaşa (Fig. 2). Rare amphibolites consist essentially of plagioclase and green hornblende. The voluminous gneisses in the basement are made up of quartz, plagioclase and K-feldspar with minor muscovite, biotite and epidote. Several gneiss samples comprise rounded feldspar porphyroclasts, which may be relics from a granitic protolith. The mineral assemblage in the micaschists indicates upper greenschist to lower amphibolite facies metamorphism. Migmatites indicate a high amphibolite facies metamorphism during the Early Permian, although mineral assemblages characteristic for this

Table 2 Rb–Sr data from the sample 1346B from the Kirklareli metagranite, Strandja massif

	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Apparent age (Ma)
Rock	205	104,00	5,7152	0.72935±12	155.4±1.5
Biotite	1024	2,04	2111	5.378±6	

high-grade metamorphism have not been found, possibly because of the scarcity of the metapelitic lithologies.

Geological evolution

Late-Variscan orogeny

The close spatial and temporal association of granites and gneisses in the Strandja basement, the high alkali feldspar content (high K/Na ratio) of the granites, the scarcity of hornblende and the zircon typology suggest that the granites formed by partial melting of crustal material during the Early Permian. An older crystalline basement or Paleozoic metasediments has not been identified. These Early Permian granites and metamorphic rocks are regarded as the eastward extension of the central European Variscan belt, especially since the overlying post-orogenic Triassic sequences bear close stratigraphic resemblance to those found in central Europe. Terrigeneous Lower Triassic sequences, similar to the Central-European Triassic, occur also widely in the rest of Bulgaria (e.g. Mader and Chatalov 1988), where they lie unconformably over terrigeneous Permian sediments or older formations. However, in the Balkanides and in the Moesian Platform the Variscan deformation was of Late Carboniferous and earliest Permian in age (Tenchov 1989; Haydoutov and Yanev 1997), somewhat earlier than that in the Strandja Massif. The vergence of the late-Variscan orogen in the Strandja Massif is not known directly. However, the presence of deformed but unmetamorphosed Paleozoic sequences in the Moesian platform north of the Strandja Massif (e.g. Foose and Manheim 1975), possibly forming a foreland belt, implies a northward vergence.

Late-Variscan metamorphism and plutonism can be traced as far north as the Balkanides, where Lower Triassic continental sandstones and conglomerates lie unconformably over the Upper Paleozoic granites and metamorphic rocks (e.g. Jubitz 1960). Metamorphism and plutonism are not present in the Moesian Platform in the north and in the Istanbul Zone, to the southeast of the Strandja Massif (Fig. 1), which show uninterrupted Paleozoic sedimentation from Ordovician to the Carboniferous followed by minor Carboniferous deformation. This suggests a major tectonic break, a Variscan suture or a major fault, between the Strandja Massif in the south and the Moesia-Istanbul block in the north (cf. Burchfiel 1980). On the other hand, the basement of the Strandja Massif appears to be similar to that of the Pelagonian Zone in Greece, which has a metamorphic basement of quartzo-feldspathic micaschist and amphibolites intruded by Late Carboniferous granites and unconformably overlain by Triassic to Jurassic metasedimentary rocks (e.g. Yarwood and Aftalion 1976; Nance 1981; Schermer et al. 1990).

Triassic–Jurassic epicontinental sedimentation and the mid-Mesozoic orogeny

By the end of the Permian the late-Variscan metamorphic and granitic rocks of the Strandja Massif were exhumed and continental sedimentation started by the Early Triassic. The detritus for the 2-km-thick Lower Triassic coarse clastic rocks came from the late-Variscan gneisses and granites. By the mid-Triassic the clastic sedimentation in the Strandja Massif was succeeded by neritic carbonate deposition (Fig. 11a). The Triassic sedimentation is similar in facies to that of central and northern Bulgaria and central Europe, where an initial continental clastic series of Early Triassic age is succeeded by a shallow marine carbonate platform. This suggests that the Strandja Massif continued to be part of the Variscan Europe during the Triassic. In the Bulgarian Strandja the shallow marine sedimentary sequence is known to extend up to the Bathonian with a possible break in sedimentation during the Norian and Rhaetian (Chatalov 1988). North-vergent, Late Triassic folds are recorded in the seismic sections in the Moesian Platform (Tari et al. 1997); however, this latest Triassic compression appears to have been not important in the Strandja Massif, as the sedimentation continued during the Early and mid-Jurassic with the deposition of shallow marine sequences (Chatalov 1988).

In the Late Jurassic–Early Cretaceous interval the authochthonous Strandja sequence was overthrust by allochthonous sedimentary and volcanic rocks, probably representing a subduction–accretion complex, and the whole package of Mesozoic sediments and the underlying basement were penetratively deformed and regionally metamorphosed (Fig. 11b). The north-vergent deformation involved folding, generation of foliation and thrusting of the basement granites over the Mesozoic metasediments.

The age of the mid-Mesozoic orogeny in the Strandja Massif is stratigraphically bracketed between Bathonian and Cenomanian. Its age can be further narrowed using the age of the foreland basin in the north (Şengör and Natalin 1996, p 579). During the Oxfordian a narrow east/west-trending siliciclastic basin developed between the Strandja-Rhodope massifs and the Moesian platform (Fig. 11b). This foreland basin, called the Nish-Trojan trough, received siliciclastic and carbonate turbidites from the south (Tchoumatchenko et al. 1989, 1990; Tchoumatchenko and Sapunov 1994; Harbury and Cohen 1997). The Nish-Trojan trough migrated northwards and persisted until the Barremian. The thick turbidite sequences in the Nish-Trojan trough contrast with the neritic carbonates deposited on the Moesian platform in the north during the Oxfordian-Barremian (Tchoumatchenko et al. 1989, 1990; Harbury and Cohen 1997). Data from the Nish-Trojan foreland basin indicate that the compression in the Strandja Massif started in Oxfordian and continued until the Barremian. This

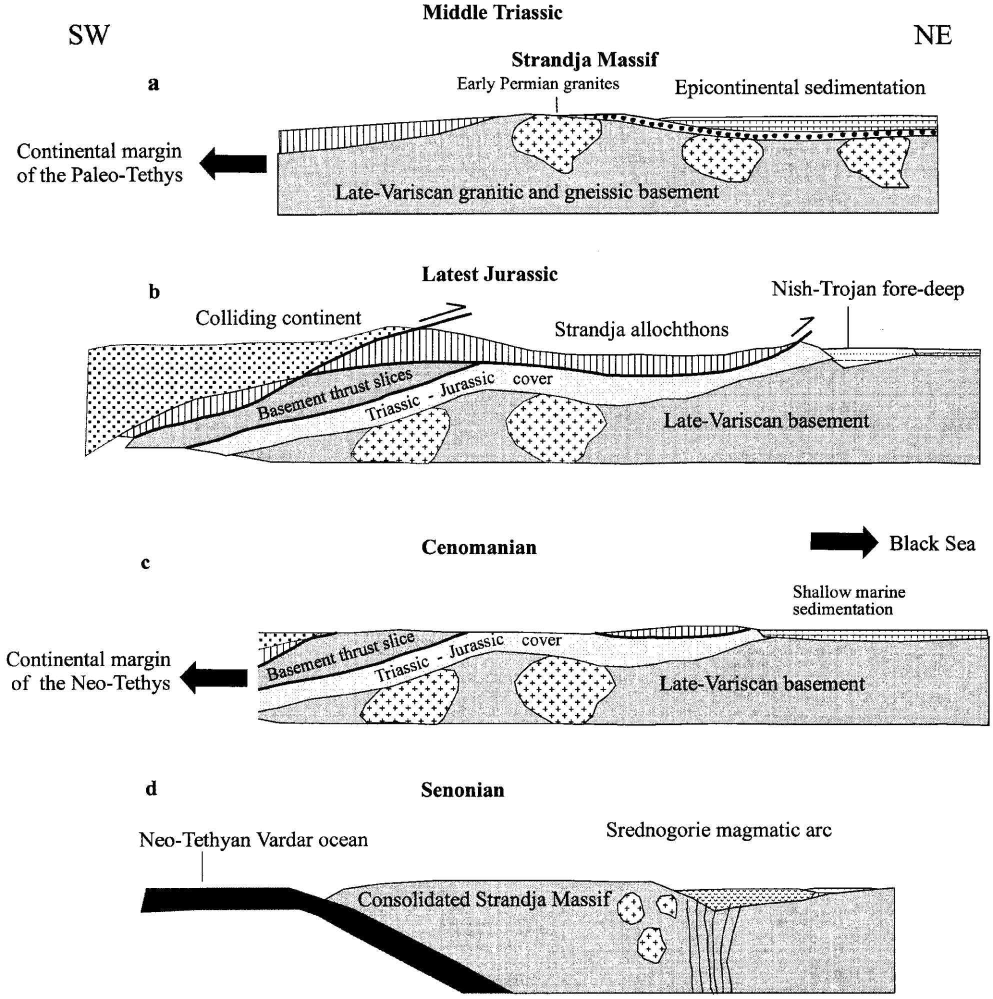

Fig. 11a–d Cross sections illustrate the geological evolution of the Strandja Massif during the Mesozoic. **a** Middle Triassic, shallow marine limestone deposition over a peneplained late-Variscan basement. **b** Latest Jurassic, deformation and metamorphism due to continental collision; development of the Nish-Trojan fore-deep basin in front of north-vergent thrust slices. **c** Cenomanian, shallow marine transgression over a peneplained surface. **d** Development of a magmatic arc and an intra-arc basin over the northward subducting Neo-Tethyan ocean with the Strandja Massif occupying a compressional fore-arc setting

157- to 125-Ma period is compatible with the scarce Rb/Sr and K/Ar age data on the mid-Mesozoic regional metamorphism (155 to 149 Ma; Aydın 1974, 1982, this study).

The mid-Mesozoic orogeny in the Strandja Massif is characterised by prolonged thick-skinned deformation associated with regional metamorphism. The northward vergence is perpendicular to the main structural trend of the Strandja Massif (cf. Fig. 2). These features are hallmarks of an important orthogonal continental collision. The main tectonic problem with the mid-Mesozoic collisional orogeny in the Strandja Massif is the apparent absence of the colliding block.

Before collision, the Strandja Massif was part of the passive margin of Laurasia, and it formed the footwall of the orogen during deformation. It must be separated through a pre-Cenomanian oceanic suture from a continental block that had an opposing active margin during the Late Triassic to Middle Jurassic (Fig. 11b). This continental block may be buried under the Thrace Basin.

Late Jurassic–Early Cretaceous deformation or regional metamorphism are not present in the Istanbul and Sakarya zones. In the Sakarya Zone sedimentation was continuous throughout Late Jurassic–Early Cretaceous and the Alpide deformation occurred during the Paleocene (Okay and Tüysüz 1999). In the Istanbul Zone, the weak Alpide deformation also took place during the Paleocene–Eocene. Similarity in this point is again with the Pelagonian Zone in Greece (e.g. Mountrakis 1984).

Late Cretaceous–Tertiary history

The northern margin of the Strandja Massif was exhumed by the mid-Cretaceous after the enigmatic Late Jurassic–Early Cretaceous orogeny, and Cenomanian shallow marine sandy carbonates were deposited with angular unconformity over the Mesozoic metamorphic rocks (Figs. 8, 11c). By early Senonian a magmatic arc and intra-arc basin, characterised by granodioritic plutons, stocks, dykes and voluminous andesitic lavas and tuffs, were established over the northeastern half of the Strandja Massif (Boccaletti et al. 1974). This Srednogorie magmatic arc, which can be traced along the whole length of Bulgaria, was generated during the northward subduction of the Tethyan ocean along the Vardar and Intra-Pontide sutures (Fig. 11d). The southern part of the Strandja Massif may have been in a fore-arc position during the Late Cretaceous. The absence of Cretaceous deposits in the southern Strandja or in the Rhodope massifs indicates either that the magmatic arc was compressional, or that such deposits were eroded during the subsequent continental collision (Fig. 11d). Continental collisions leading to the generation of the Vardar, Intra-Pontide sutures occurred during the Paleocene to Eocene. The ensuing compression resulted in north-vergent thrusting of the Strandja Massif over the Cretaceous deposits leading to the closure of the Srednogorie intra-arc basin (Fig. 2). The compressional structures propagated northward producing the Balkanide fold and thrust belt, which is mainly of Eocene and Oligocene age (Fig. 1; e.g. Sinclair et al. 1997).

Conclusion

The Strandja Massif is a composite orogenic belt deformed and regionally metamorphosed during the late-Variscan and Late Jurassic–Early Cretaceous orogenies. The Early Permian orogeny in the Strandja Massif involved amphibolite facies regional metamorphism, crustal anatexis, and generation and emplacement of crustal melt granites. Early Permian zircon ages are obtained from both the deep-level granites and the surrounding gneisses and migmatites.

During the earliest Triassic the basement was overlain by fluviatile coarse-grained sediments with abundant detritus derived from the basement granites and gneisses. The transgressive cover reach up to the mid-Jurassic and is characterised by continental to shallow marine sedimentation similar to that in central Europe. During the Late Jurassic–Early Cretaceous, both the cover series and the basement of the Strandja Massif were penetratively deformed and regionally metamorphosed in greenschist facies. Rb/Sr biotite whole-rock ages of the metamorphism is Late Jurassic (~155 Ma). Compression involved north-vergent thrusting of the basement granites over the mid-Mesozoic cover series, and the emplacement of the Triassic allochthons including basic volcanic rocks and deep marine turbiditic sequences, over the epicontinental Jurassic cover series of the Strandja Massif. An upper age limit for the mid-Mesozoic orogeny in the Strandja Massif is given by the Cenomanian shallow marine sandstones, which lie unconformably over the metamorphic rocks.

During the Senonian the northern half of the Strandja Massif was the site of a magmatic arc and an intra-arc basin, where over 3-km-thick calc-alkaline volcanic and volcanoclastic rocks accumulated, and several Senonian granodiorites intruded the metamorphic rocks of the Strandja Massif. The magmatic arc ceased by the Maastrichtian, and the intra-arc basin closed during the Early Tertiary by north-vergent thrusting leading to the formation of the Eocene–Oligocene Balkanide mountain chain.

A major unsolved problem is the geological relation between the Strandja Massif and the Rhodope Massif *s.l.*, which includes the Rhodope *s.s.*, Serbo-Macedonian, and Circum-Rhodope massifs. There are many similarities but also major differences between these two large metamorphic terranes. The presence of a late-Variscan gneissic and metamorphic basement in the Rhodope Massif *s.l.*, strongly overprinted by the Late Tertiary heating, is indicated by some isotopic data (Borsi et al. 1965; Wawrzenitz and Krohe 1998) and there is stratigraphic evidence for a second period of metamorphism and deformation during the Late Jurassic and Early Cretaceous especially in the Circum-Rhodope Zone. However, the Rhodope Massif includes eclogites and metamorphosed ophiolites possibly of Early Cretaceous age (Liati 1988; Kolceva and Eskenazy 1988; Wawrzenitz and Mposkos 1997) absent in the Strandja Massif. Furthermore, the Mesozoic compressive deformation in the Rhodope Massif *s.l.* is generally south- to southwest-vergent in stark contrast to the northward vergence found in the Strandja Massif.

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