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Upper Cretaceous Eclogite-Facies Metamorphic Rocks from the Biga Peninsula, Northwest Turkey

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Abstract: Medium-grade metamorphic rocks crop out over a large area under the Neogene sedimentary and volcanic rocks in the central Biga Peninsula in northwest Turkey. These Çamlıca metamorphics consist dominantly of quartz-micaschists with minor calc-schist, marble, quartzite and metabasite. Some of the metabasites in the Çamlıca metamorphics preserve an early eclogite-facies mineral assemblage of garnet + omphacite + glaucophane + rutile ± paragonite, strongly overprinted by greenschist-facies mineral assemblages. The conditions of the eclogite-facies metamorphism have been determined as 510 ± 50°C temperatures and a minimum pressure of 11 kbar, based on the garnet-clinopyroxene Fe-Mg partitioning and the jadeite content of omphacite, respectively. The high phengite content of the potassic white micas in the quartz-micaschists and the close interlayering of quartz-micaschists and the metabasites suggest that the whole of the Çamlıca metamorphics has undergone regional eclogite-facies metamorphism. Rb-Sr phengite ages from three quartz-micaschist samples from the Çamlıca metamorphics range from 65 to 69 Ma and indicate a Maastrichtian age for the eclogite-facies metamorphic event. The Çamlıca metamorphics probably are a part of the Rhodope metamorphic complex, which exhibits a similar lithostratigraphy and metamorphic history.

Key Words: Eclogite facies metamorphism, Rb/Sr data, Turkey, Biga Peninsula, Rhodope Massif

Biga Yarımadası'nda Geç Kretase'de Eklojit Fasiyesinde Metamorfizma Geçirmiş Bir Birim

Özet: Biga Yarımadası'nın merkezi kesiminde metamorfik kayalar geniş bir bölgede mostra verir. Çamlıca metamorfitleri olarak isimlendirilen bu kayalar esas olarak kuvars-mika şistlerden yapılmıştır. Kuvars-mika şistler ile ardalanmalı olarak az oranlarda kalkşist, mermer, kuvarsit ve metabazitler de Çamlıca metamorfitleri içinde yer alır. Çamlıca metamorfitleri içinde yer alan bazı metabazitlerde granat + omfasit + glokofan + rutil ± paragonit'den oluşan eklojit fasiyesi parajenezleri saptanmıştır. Bu ilksel eklojit mineral topluluğu daha sonra gelişen amfibolit ve yeşilşist fasiyesi metamorfizması sonucu büyük ölçüde tahrip olmuştur. Granat ile omfasit arasındaki Fe-Mg dağılımı, ve omfasitlerdeki maksimum jadeit oranı, eklojit fasiyesi metamorfizması sırasında sıcaklığın 510 ± 50°C, minimum basıncın ise 11 kbar olduğunu gösterir. Kuvars-mika şistlerdeki beyaz mikaların yüksek fengit içeriği, ve metabazitler ile kuvars-mika şistlerin sık sık ardalanmalı olarak bulunmaları, Çamlıca metamorfitlerinin tümünün eklojit fasiyesinde metamorfizma geçirdiğine işaret eder. Üç kuvars-mika şist numunesinden elde edilen fengit Rb-Sr izotopik yaşları 65 ile 69 Ma arasına düşer, ve eklojit fasiyesindeki metamorfizmanın Maastrihtiyen yaşında olduğunu gösterir. Çamlıca metamorfitleri, benzer litolojik ve metamorfik özellikler gösteren Rodop metamorfik kompleksinin muhtemel bir parçasıdır.

Anahtar Sözcükler: Eklojit fasiyesi metamorfizması, Rb/Sr verileri, Biga Yarımadası, Rodop Masifi

Introduction

In this paper we provide new petrological and isotopic data on a large area of metamorphic rocks from the central Biga Peninsula in northwest Turkey, and show that these rocks have underwent eclogite-facies metamorphism in the Late Cretaceous. The Biga Peninsula is characterised by a poorly understood complex geology with outcrops of various metamorphic, magmatic and sedimentary rocks (Bingöl *et al.* 1975; Okay *et al.* 1991, 1996; Pickett & Robertson 1996). Okay *et al.* (1991) grouped the pre-Neogene sequences of the Biga Peninsula in two tectonic zones separated by a discontinuous northeast-trending belt of Upper Cretaceous ophiolitic mélange. Southeast of the mélange belt lies the Sakarya Zone, which consists of the Kazdağ metamorphic complex at the base overlain tectonically by the Permo-Triassic Karakaya Complex (Figures 1 & 2). The Jurassic and Lower Cretaceous sedimentary rocks lie unconformably over the Karakaya Complex. The pre-Neogene rocks northwest of the mélange belt are

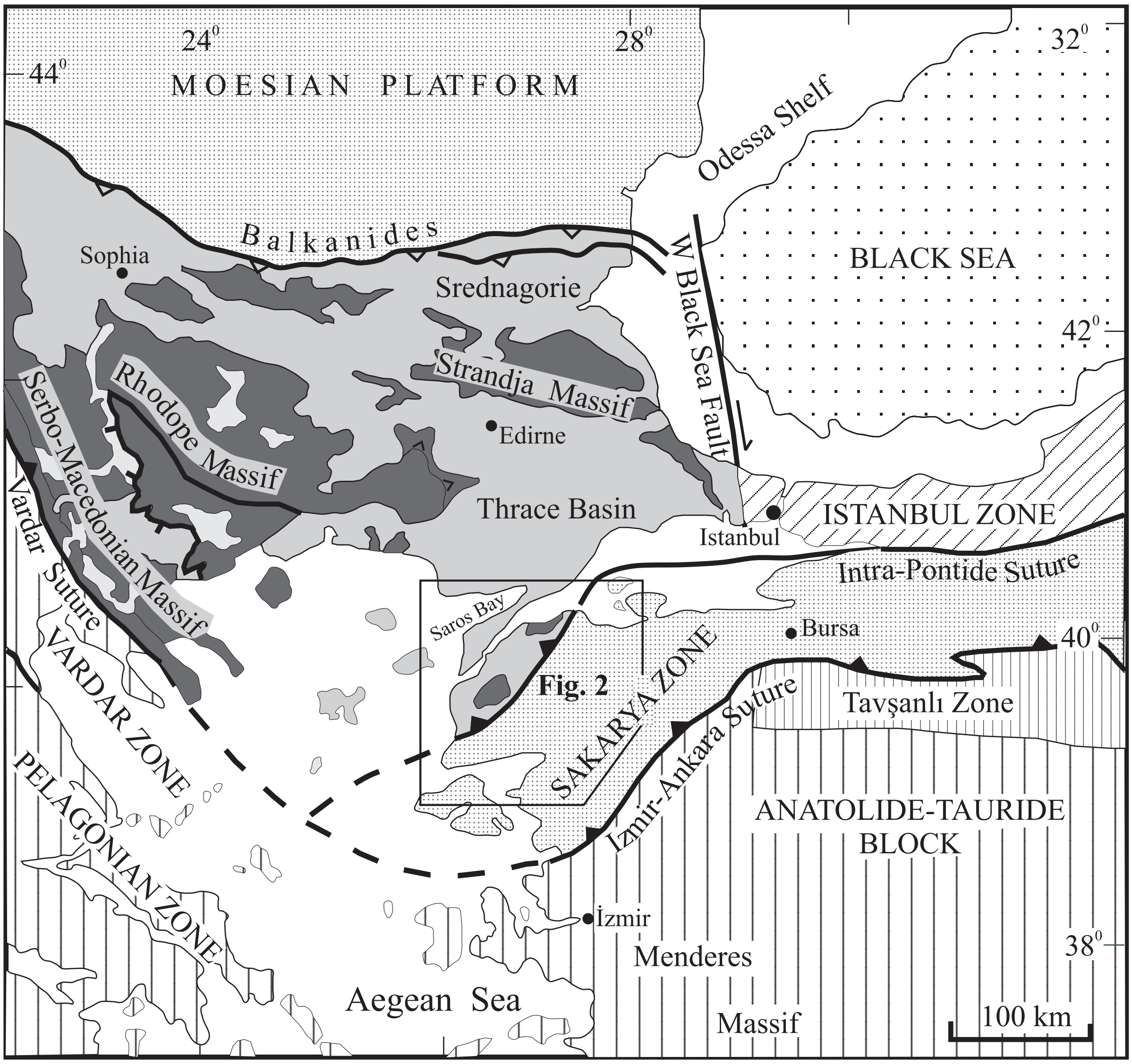

Figure 1. Tectonic map of the northern Aegean and the Balkans. The outcrops of metamorphic rocks of the Rhodope, Serbo-Macedonian and Strandja massifs are shown in black. Thick lines with solid triangles indicate sutures with original subduction polarities, those with open triangles are major intra-continental thrusts and that with the half-arrow is a transform fault.

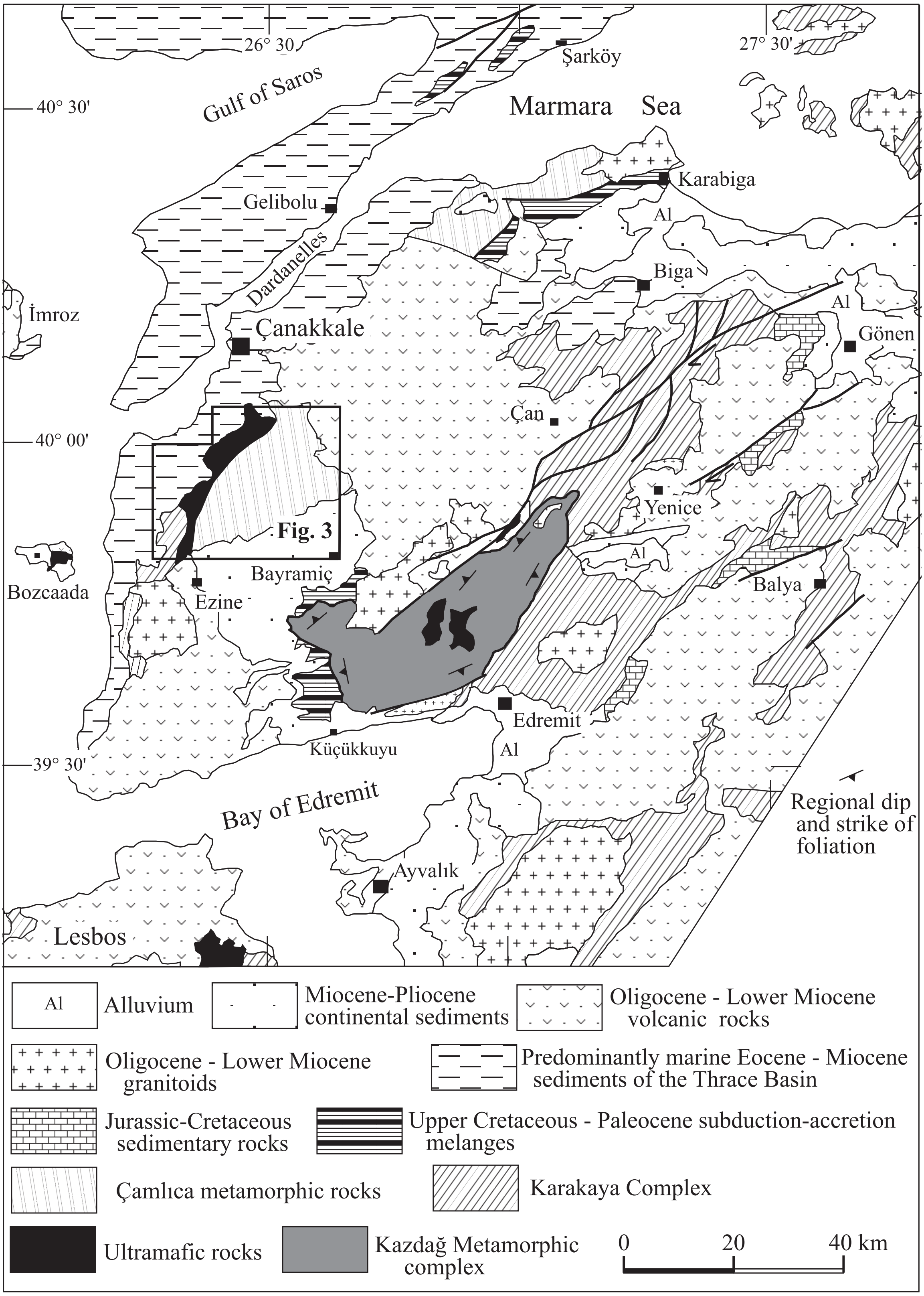

Figure 2. Geological map of the Biga Peninsula showing the tectonic setting of the Çamlıca metamorphics.

assigned to the Ezine Zone (Okay *et al.* 1991). They crop out widely north of Ezine and west of Karabiga (Figure 2). The north- to northeast-trending Ovacık Fault divides the pre-Neogene rocks north of Ezine in two distinct sequences. West of the Ovacık Fault there is a thick epicontinental Permo-Carboniferous sequence regionally metamorphosed at low greenschist-facies conditions. This Karadağ sequence is made up of a basal clastic unit of shale, quartzite, and sandstone overlain by neritic limestones, ~1600 m thick. The upper parts of the limestone series contain Late Permian fusulinids (Kalafatçıoğlu 1963; Okay *et al.* 1991). The neritic limestones are overlain by a syn-orogenic clastic series of shale, siltstone, calci-turbidite, pelagic cherty limestone and olistoliths of limestone and basalt. A large slab of ultramafic rocks, the Denizgören ophiolite, tectonically overlies the syn-orogenic clastic sequence (Figure 3). The Karadağ sedimentary sequence was initially thought to signify a latest Permian to Triassic ophiolite obduction (Okay *et al.* 1991). However, 117 ± 2 Ma $^{40}Ar/^{39}Ar$ hornblende ages from an amphibolite sliver from the base of the Denizgören ophiolite point to an Early Cretaceous (Aptian) rather than a Permo-Triassic ophiolite obduction (Okay *et al.* 1996).

East of the Ovacık Fault there is another metasedimentary sequence, which differs from the Karadağ sequence in lithology and metamorphic grade. These Çamlıca metamorphics, which include eclogite lenses, form the object of this paper.

The Çamlıca Metamorphics

The Çamlıca metamorphics cover an area of ~250 km^2 between the Ovacık and Karıncalı faults and form a westward dipping structural sequence of over seven kilometres in thickness (Figure 3). The type section of the Çamlıca metamorphics is along the road to the village of Çamlıca, which branches off from the Ezine-Çanakkale highway. Over 80% of the Çamlıca metamorphics are made up of grey, brown, greenish brown, well-foliated quartz-micaschists with the common mineral assemblage of quartz + white mica + carbonate + albite ± chlorite ± clinozoisite ± garnet. Apart from these monotonous quartz-micaschists, there are yellowish calc-schists, white, yellow, black marbles, white quartzites, amphibolites and albite-chlorite schists, which occur as one to ten metre thick horizons within the quartz-micaschists. In the east around the village of Kayacık, the Çamlıca metamorphics are tectonically overlain by small bodies of serpentinite (Figure 3). Contact relations of these ultramafic bodies illustrate that the emplacement of the ultramafic rocks postdated the regional metamorphism of the Çamlıca metamorphics. The Çamlıca micaschists are also cut by small granitoid intrusions most probably of Oligo-Miocene age.

The Çamlıca metamorphics have an apparently simple internal structure. The foliation surfaces in the micaschists generally trend north-south and dip to the west at 20° to 50° (Figure 4). A large number of mesoscopic isoclinal folds with axial surfaces parallel to the foliation occur in the micaschists. The metamorphic rocks also contain a north- to north-northeast -trending subhorizontal mineral lineation, defined largely by elongated quartz grains. The mineral lineation is particularly strong in the vicinity of the Ovacık Fault and becomes weaker eastward.

The Çamlıca metamorphics are separated in the west from the Denizgören ophiolite by the Ovacık Fault, which forms a broad north- to northeast-trending arc, 33 km long. In the extreme north, where the flysch sequence crops out under the Denizgören Ophiolite, the Ovacık Fault forms the tectonic contact between the Çamlıca metamorphics and the flysch sequence of the Karadağ unit (Figure 3). The Ovacık Fault dips west to northwest with the dip angle increasing from 30° in the north to 80° in the south. The steep dip of the fault plane north of Ezine and the outcrop pattern of the Neogene sediments in the region suggest that the southern part of the Ovacık Fault is rejuvenated as a normal fault defining the western margin of the Bayramiç Neogene basin (Figure 2). In the vicinity of the Ovacık Fault the Çamlıca metamorphics have a strong protomylonitic overprint with a thickness of 5-6 m. The lineation and foliation data suggest either that the Ovacık Fault is a north-south directed thrust that has been subsequently strongly tilted westward, or that it is a transpressional strike-slip fault.

The poorly exposed Karıncalı Fault form the southeastern boundary of the Çamlıca metamorphics. Karıncalı Fault is a steeply dipping northeast-trending fault zone that juxtaposes the Çamlıca metamorphics with metashales and metasiltstones, which are assigned tentatively to the Nilüfer unit of the Karakaya Complex (Okay *et al.* 1991). These low-grade metamorphic rocks comprise thin slivers of serpentinite.

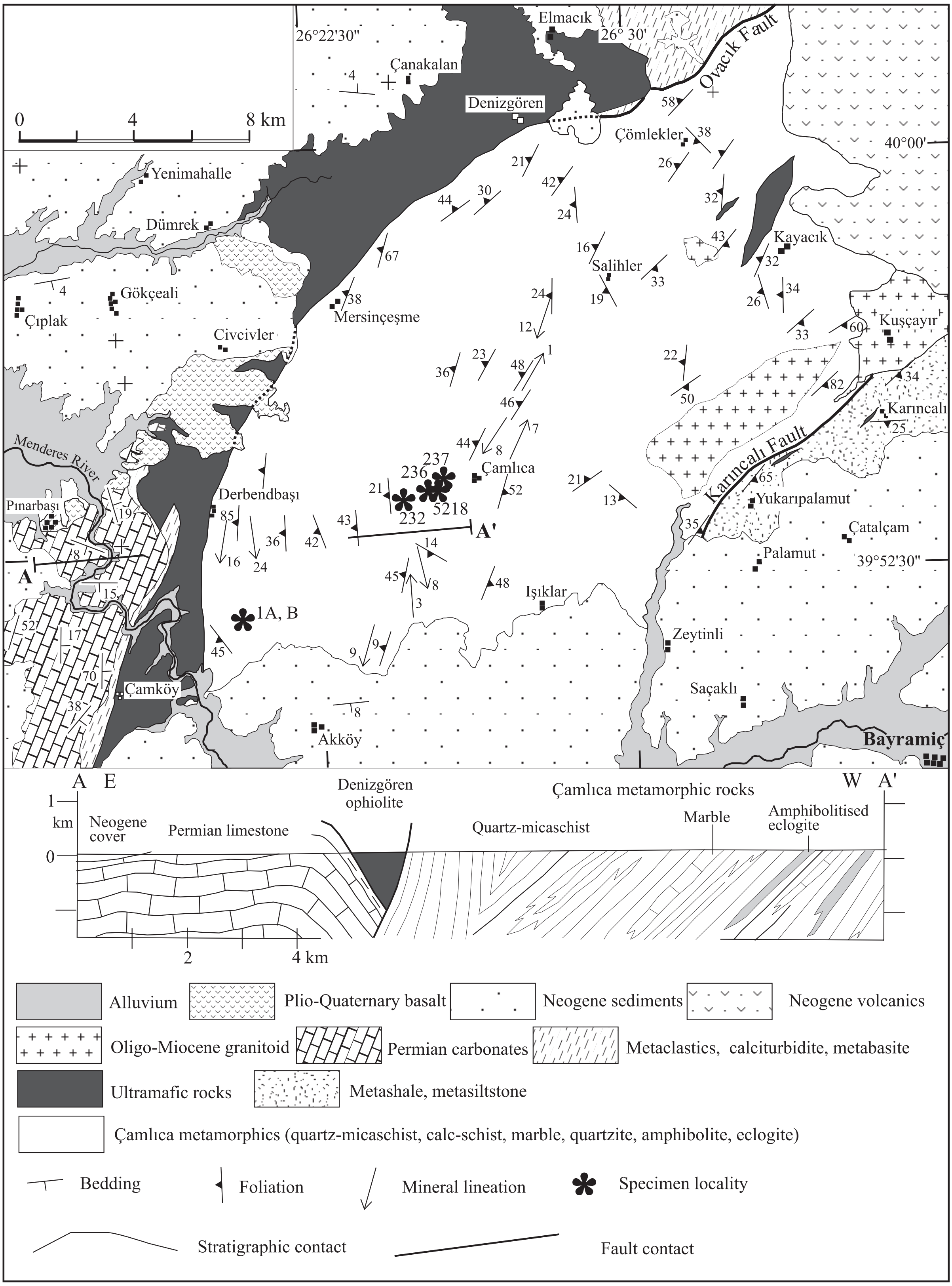

Figure 3. Geological map and cross-section of the region north of Ezine. See Figure 2 for location.

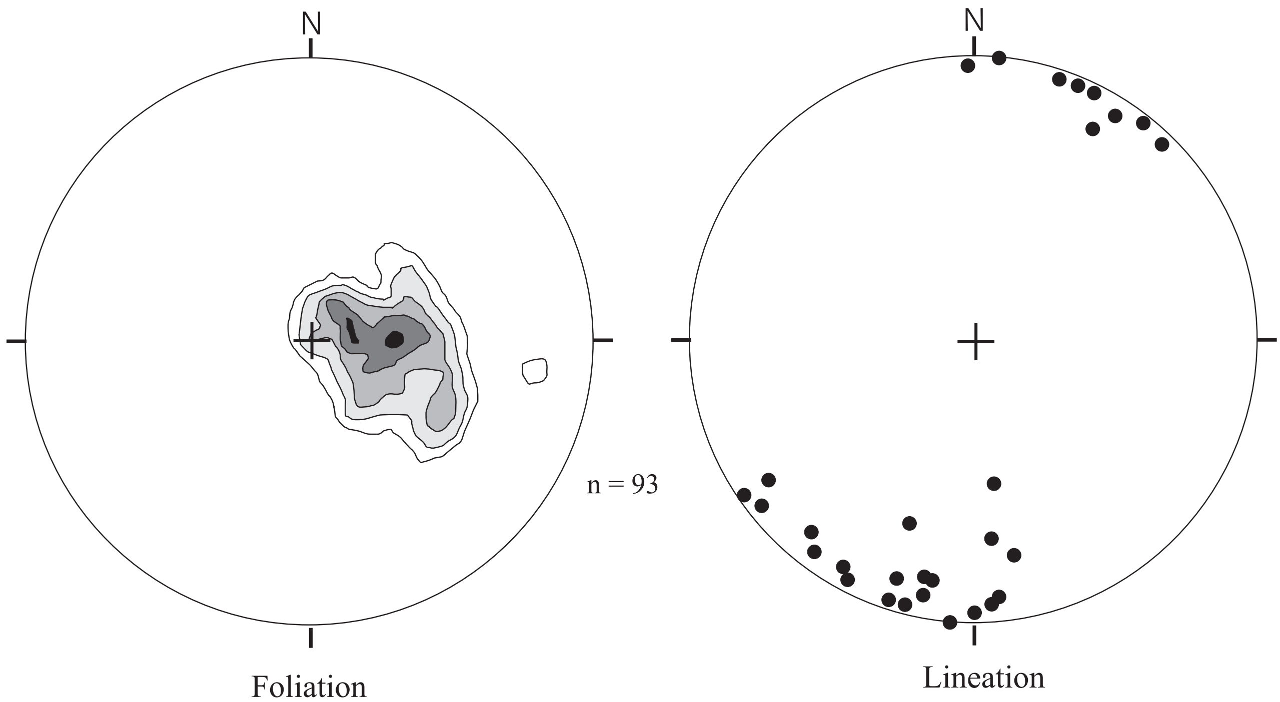

Figure 4. Stereographic projections of the foliation and lineation in the Çamlıca metamorphics. In the contoured stereonet, the contours are at 3, 5, 7, 9 and 11%

Eclogites in the Çamlıca metamorphics

Thin bands of amphibolites are found sporadically throughout the Çamlıca metamorphics. However, the main outcrops of metabasic rocks are about 1.5 km west of the village of Çamlıca. In this locality around Dedetepe, garnet-bearing metabasic rocks form several large massive outcrops and show textures typical of retrograded eclogites. However, petrographic study of over 20 samples from this region has shown that in most metabasites, garnets are the only relics from eclogite-facies metamorphism. Glaucophane is found in only a few specimens and omphacite in only one sample.

Garnet in the metabasic rocks forms strongly poikilitic porphyroblasts, up to 1 cm across, set in a groundmass of fine-grained intergrowths of green calcic amphibole, epidote/clinozoisite, albite, white mica, carbonate, rutile and opaque minerals. Calcic amphibole, epidote/clinozoisite, rutile and ilmenite, as well as sodic amphibole occur as inclusions in garnet. In many metabasite samples, the pale blue sodic amphibole inclusions in garnet are the only evidence of an early high-pressure metamorphism. However, a few samples contain large pale blue sodic amphibole crystals in the matrix, which are partially replaced by fine intergrowths of green calcic amphibole and albite. In one sample, pale apple-green omphacite is preserved in the pressure shadows of garnet porphyroblasts illustrating an early eclogite-facies metamorphism. The initial eclogite-facies assemblage appears to have been garnet + omphacite + glaucophane + rutile ± paragonite ± carbonate. The subsequent greenschist-facies overprint resulted in the replacement of omphacite and glaucophane by calcic amphibole and albite, and rutile by ilmenite. Garnet porphyroblasts have also been partially replaced by chlorite, albite and calcic amphibole.

In order to constrain the pressure-temperature conditions of metamorphism, two retrograded eclogites and one calc-schist were analysed by electron microprobe in Bochum, Germany using an SX-50 Cameca electron microprobe with wavelength dispersive spectrometers. Additionally, white micas from two isotopically dated quartz-micaschists were analysed by electron microprobe in Tübingen, Germany. Operating conditions were generally a 15-kV accelerating voltage, a 15-nA beam current and a 10 micromillimetre beam size. The mineral modes of the analysed samples and representative mineral compositions are given in Tables 1 and 2,

Table 1. Estimated modal amounts of the analysed specimens.

	Calc-schist	Retrograded Eclogite	
	232A	237	5218
Garnet	9	37	24
Omphacite	-	3	-
Glaucophane	-	7	2
Epidote/clinozoisite	18	2	17
Calcic and s-c amphibole	19	31	28
Quartz	17	-	-
Albite	2	7	9
Chlorite	2	5	5
Phengite	15	1	-
Paragonite	-	-	5
Carbonate	17cc	-	4an
Rutile	-	2	1
Ilmenite	-	2	5
Magnetite	1	3	-

cc: calcite; an: ankerite; s-c: sodic-calcic.

respectively. The ferric iron in sodic amphibole and omphacite were calculated on the basis of 15 cations and 23 oxygens, and 4 cation structural formula, respectively. Garnet from the retrograded eclogites and calc-schist is dominantly in the grossular-almandine solid solution with minor amounts of the pyrope (3-9 mole %) and spessartine (0.2-1.8 mole %) end-members. They exhibit growth zoning involving a slight increase in pyrope and a decrease in spessartine content toward the rims (Table 2). Omphacite from eclogite sample 237 has a maximum of 46 mole % jadeite. Sodic amphiboles from the same sample plot in the glaucophane field. Green to bluish-green amphiboles, which formed subsequent to the eclogite-facies metamorphism, have variable chemistries ranging from actinolite through hornblende to barroisite. White micas from the quartz-micaschists are phengites

Table 2. Representative mineral compositions from the eclogites, calc-schist and quartz-mica schists

	Garnet					Glaucophane	Omphacite	Phengite			Paragonite	Epidote	
	237 core	237 rim	5218	232A core	232A rim	237	237	1A	1B	232A	5218	237	5218
SiO_2	36.83	36.97	37.48	36.77	36.76	55.74	54.33	53.49	54.55	51.57	47.96	36.97	39.33
TiO_2	0.06	0.14	0.02	0.23	0.15	0.00	0.02	0.11	0.08	0.17	0.00	0.04	0.03
Al_2O_3	21.03	20.97	21.63	20.71	21.21	9.20	8.28	27.20	24.71	28.05	39.71	23.81	29.03
Cr_2O_3	0.02	0.04	0.02	0.16	0.18	0.00	0.00	-	-	0.31	0.00	0.00	0.00
FeO	28.64	30.11	29.13	28.37	27.54	14.65	8.32	2.51	3.54	1.83	0.72	11.56	6.61
MgO	1.33	2.15	2.38	1.33	2.42	8.35	7.26	3.33	3.50	3.23	0.55	0.00	0.05
MnO	0.68	0.13	1.40	2.18	1.00	0.00	0.04	0.00	0.02	0.00	0.00	0.24	0.01
CaO	11.04	9.06	8.60	10.46	10.93	1.00	13.20	0.04	0.05	0.04	0.13	23.42	23.51
Na_2O	0.03	0.05	0.05	0.01	0.02	6.22	6.70	0.13	0.05	0.21	7.27	0.00	0.01
K_2O	0.03	0.02	0.00	0.00	0.00	0.03	0.00	9.12	8.86	9.77	0.73	0.00	0.00
Total	99.69	99.64	100.71	100.22	100.21	95.19	98.15	95.93	95.36	95.18	97.07	96.04	98.58
Mineral formula on the basis of	12 oxygens					23 O and 15 cations	4 cations	11 oxygens				8 cations	
Si	2.95	2.96	2.97	2.95	2.93	8.01	1.99	3.50	3.60	3.42	3.01	2.96	3.01
Al^{IV}	0.05	0.04	0.03	0.05	0.07	-	0.01	0.50	0.40	0.58	0.00	0.04	
Al^{VI}	1.94	1.94	1.99	1.91	1.92	1.56	0.35	1.60	1.52	1.61	2.94	2.20	2.62
Ti	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.01	0.01	0.00	0.00			0.02	0.00	0.00	0.00
Fe^{3+}	0.06	0.05	0.01	0.07	0.05	0.17	0.12					0.77	0.42
Fe^{2+}	1.86	1.97	1.92	1.84	1.78	1.59	0.14	0.14	0.20	0.10	0.04		
Mg	0.16	0.26	0.28	0.16	0.29	1.79	0.40	0.32	0.34	0.32	0.05	0.00	0.01
Mn	0.05	0.01	0.09	0.15	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00
Ca	0.95	0.78	0.73	0.90	0.93	0.15	0.52	0.00	0.00	0.00	0.01	2.01	1.94
Na	0.00	0.01	0.01	0.00	0.00	1.73	0.48	0.02	0.01	0.03	0.89	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.76	0.75	0.83	0.06	0.00	0.00
Total	8.02	8.03	8.03	8.05	8.06	15.00	4.01	6.85	6.82	6.92	7.00	8.00	8.00
alm	61.6	65.2	63.6	60.3	58.0	jd	35.0						
pyr	5.3	8.6	9.3	5.3	9.4	aeg	12.0						
gross	31.5	25.8	24.2	29.5	30.3	au	53.0						
spess	1.6	0.3	3.0	4.9	2.3								

with Si per formula unit (p.f.u.) ranging from 3.44 to 3.66. It is notable (?) that, despite the strong greenschist overprint, all the analysed white micas from the quartz-micaschists are phengitic (Figure 5).

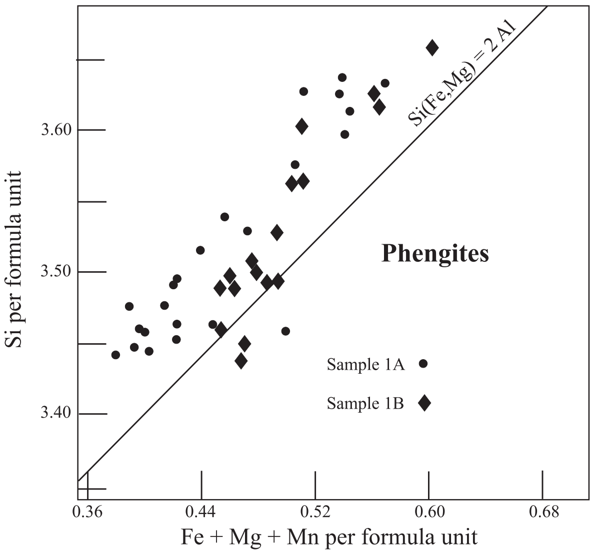

Figure 5. Phengite compositions from two dated quartz-mica schists shown in terms of Si and (Fe + Mg + Mn) per formula unit (p.f.u.). The ideal celadonite-muscovite substitution line is also shown.

The temperatures of the eclogite-facies metamorphism were estimated using the garnet-clinopyroxene Fe-Mg geothermometre of Ellis and Green (1979). An average omphacite composition and a range of garnet rim compositions from eclogite sample 237 were used in the calculations. The estimated metamorphic temperature using the garnet-clinopyroxene Fe-Mg geothermometre is 510 ± 50 °C at a pressure of 11 kbar. Minimum pressures can be estimated from the maximum jadeite content of the omphacite on the basis of the equilibrium albite = jadeite + quartz. The maximum jadeite content in the omphacite is 46 mole %, which gives a minimum pressure of 11 kbar at 510°C using the Holland (1990) calibration.

An important question is whether the eclogites represent exotic tectonic blocks or the Çamlıca metamorphics have undergone an *in situ* early eclogite-facies metamorphism. The phengitic chemistry of the white micas from the quartz-micaschists (Table 2), which constitute the bulk of the Çamlıca metamorphics, indicates that they have also undergone eclogite-facies metamorphism. Around the village of Çamlıca, the quartz-micaschists are intimately interlayered with garnet-amphibolites with amphibole + albite textures, suggestive of retrogression from glaucophane formation. Therefore, it is strongly likely that the whole of the Çamlıca metamorphics have underwent an initial eclogite-facies metamorphism strongly overprinted by greenschist-facies metamorphism.

Age of the regional metamorphism

The oldest units lying unconformably over the Çamlıca metamorphics are Neogene sedimentary and volcanic rocks (Figure 3, Siyako *et al.* 1989; Ercan *et al.* 1995; Karacık & Yılmaz 1998). In order to constrain the age of the regional metamorphism of the Çamlıca metamorphics, three samples of quartz-micaschist were isotopically dated using the Rb/Sr method. The analytical conditions were the same as those described in Okay & Satır (2000). All three samples consist essentially of quartz and white mica with minor opaque minerals and chlorite. Sample 236 also contains small garnet crystals, which, however, make up less than 5% of the mode. Electron microprobe analyses from two quartz-micaschists show that the white micas are phengites (Figure 5). The Rb/Sr analytical data are given in Table 3, and the sample locations are shown in Figure 3. All three samples gave comparable potassic white mica ages of 65 to 69 Ma. The closure temperature of muscovite for Sr is

Table 3. Rb/Sr isotopic data from the Çamlıca quartz-micaschists

Sample	Mineral	Rb, ppm	Sr, ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Age, Ma
236	rock	28	10	8,109	0,71865	
	white mica	277,2	57,04	14,08	0,72447	69±2
1A	rock	35	238	0,426	0,70988	
	phengite	385	16,1	69,70	0,78468	65±0.9
1B	rock	24	406	0,171	0,70894	
	phengite	409	23	51,73	0,76362	69±0.9

generally considered to be ~500°C (e.g., Jäger et al 1967; Cliff 1985). The highest temperature experienced by these rocks was ~510°C during the eclogite-facies metamorphic event. Therefore, the 65-69 Ma ages are very close to the age of the peak metamorphism and show that the eclogite-facies metamorphic event occurred during the Maastrichtian.

Discussion and Conclusions

Petrological and isotopic data presented herein indicate that a large tract of metamorphic rocks in the central Biga Peninsula were metamorphosed under eclogite-facies conditions during the Maastrichtian. The tectonic significance and tectonic affinity of these Çamlıca metamorphics are highly problematic. The Sakarya Zone in northwest Turkey does not contain evidence for Cretaceous or Tertiary regional metamorphism. Unmetamorphosed Jurassic and Lower Cretaceous sedimentary rocks are exposed in the eastern part of the Biga peninsula (Figure 2). Regional blueschists and eclogites occur widely in the Tavşanlı Zone, 175 km farther west (Figure 1; Okay & Tüysüz 1999). However, they differ markedly from the Çamlıca metamorphics in terms of lithology, tectonic setting and mineral assemblage. Furthermore, the peak of high-pressure metamorphism in the Tavşanlı Zone is ~11 my older than that in the Çamlıca metamorphics (Sherlock *et al.* 1999). Exotic eclogite blocks occur in the ophiolitic mélange north of Küçükkuyu (Okay *et al.* 1991). Although these eclogite blocks are similar in terms of mineral assemblage to those in the Çamlıca metamorphics, they have yielded ~100 Ma Rb/Sr phengite ages, 30 my older than that of the Çamlıca metamorphics (Okay & Satır 2000). Blueschists are also found north of Şarköy in southern Thrace as exotic blocks in Middle Eocene sediments. However, they represent slivers in an Upper Cretaceous-Paleocene accretionary complex, transported later into a Mid-Eocene flysch basin (Şentürk & Okay 1984; Okay & Tansel 1994), quite unlike the Çamlıca metamorphics.

The absence of any correlatives of the Çamlıca metamorphics in Anatolia suggests that its affinity must lie with the large area of crystalline rocks that constitute the Rhodope and Serbo-Macedonian massifs of Bulgaria and Greece (Figure 1). In particular, the Upper Tectonic Unit of the Rhodope Massif exhibits many similarities to the Çamlıca metamorphics (Papanikolaou & Panagopoulos 1981; Barr *et al.* 1999). It consists dominantly of quartz-micaschists and gneisses with horizons of calc-schist, marble and amphibolite. At least some of the amphibolites represent retrograded eclogites (Liati & Mposkos 1990). The Rhodope metamorphic complex appears to have undergone a complicated metamorphic evolution with an initial eclogite-facies metamorphism overprinted by granulite- to greenschist-facies events. The ages of these metamorphic and deformational events are poorly known, with isotopic ages ranging from the Early Cretaceous (Wawrzenitz & Mposkos 1997) to Eocene (Liati & Gebauer 1999).

Acknowledgements

This study was supported by TPAO and by the TÜBİTAK projects YDABÇAG 227/G and 419/G. We thank Muzaffer Siyako and Kerem Ali Bürkan for help during the field work, and Gerhard Franz and Roland Oberhänsli for constructive and helpful reviews of an earlier version of the manuscript.

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Received 25 February 2000; revised typescript accepted 27 November 2000