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Early Cretaceous closure of the Intra-Pontide Ocean in western Pontides (northwestern Turkey)

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ABSTRACT

The Intra-Pontide suture is the boundary between the İstanbul and Sakarya terranes in northwest Turkey. We provide new isotopic and stratigraphical data from the Intra-Pontide suture zone, which indicate Early Cretaceous collision between the Sakarya and İstanbul terranes. These two terranes along with the Strandja Massif make up the Pontides. Metamorphic units of the Intra-Pontide suture zone are best exposed in the Armutlu Peninsula. In the eastern part of the Armutlu Peninsula, three metamorphic units crop out forming an eastward dipping thrust stack. At the base of the thrust stack there is a metaclastic-marble sequence, which is tectonically overlain by a Cretaceous subduction-accretion complex, farther up in the thrust stack there is a high-grade metamorphic unit, which represents the Proterozoic basement of the İstanbul Zone. New clastic zircon ages from the metaclastic-marble sequence indicate that deposition of the sandstones must be later than Permian (~264 Ma) possibly during Triassic. Similar Triassic metasediments are also reported in Strandja Massif. We interpret that these metasediments were deposited during Triassic along the rift flanks leading to the opening of the Intra-Pontide Ocean, which suggest a possible Early Triassic opening for the Intra-Pontide Ocean. Our new Rb–Sr mica and Sm–Nd garnet ages dates the regional metamorphism between Late Jurassic–Early Cretaceous (158–111 Ma) along the Intra-Pontide suture zone, similar ages are also reported in the Strandja Massif. The metamorphic rocks of the Intra-Pontide suture are unconformably overlain by Campanian–Ypresian clastics. The collision between the İstanbul and Sakarya–Strandja terranes has occurred during Early Cretaceous and the Proterozoic basement of İstanbul terrane was reheated during this collision.

1. Introduction

Turkey consists of several continental blocks, which were once separated by oceans (Fig. 1, Şengör and Yılmaz, 1981; Okay and Tüysüz, 1999). Three of these continental blocks, İstanbul, Sakarya and Strandja terranes, make up the Pontides. The ocean separating the İstanbul and Sakarya terranes is known as the Intra-Pontide Ocean (Şengör and Yılmaz, 1981). There are different views on the age of opening and closing of the Intra-Pontide Ocean (cf. Robertson and Ustaömer, 2004 and references therein). Even the existence of this oceanic realm was questioned (e.g., Kaya, 1977; Kaya and Kozur, 1987; Elmas and Yiğitbaş, 2001). The Intra-Pontide suture zone is exposed in the Armutlu Peninsula bounded by strands of the North Anatolian Fault (Şengör, 1979; Barka, 1992). The Kocaeli Peninsula, located north of the Armutlu Peninsula, exposes Paleozoic–Mesozoic sequences of the İstanbul terrane, whereas the region south of the Armutlu Peninsula comprises rocks typical of the Sakarya terrane. The Armutlu Peninsula comprises a variety of metamorphic sequences, whose affinities are controversial (Robertson and Ustaömer, 2004; Elmas and Yiğitbaş, 2005). A major reason for this is the lack of geochronological data (Göncüoğlu et al., 1987, 1992; Bozcu, 1992; Yılmaz et al., 1995; Robertson and Ustaömer, 2004; Okay et al., 2008). In this paper we provide a new geological map as well as structural and geochronological data on the Intra-Pontide suture zone. We suggest that some of these rocks form the eastward continuation of the Strandja Massif.

2. Tectonic framework

The İstanbul, Sakarya and Strandja terranes show different geological histories as reflected in their stratigraphic record (Fig. 2, cf. Okay et al., 2008). The geological features of the İstanbul, Sakarya and Strandja terranes are summarized below.

2.1. The İstanbul terrane

The İstanbul terrane is a 400 km long and 55 km wide continental fragment on the southwestern margin of the Black Sea

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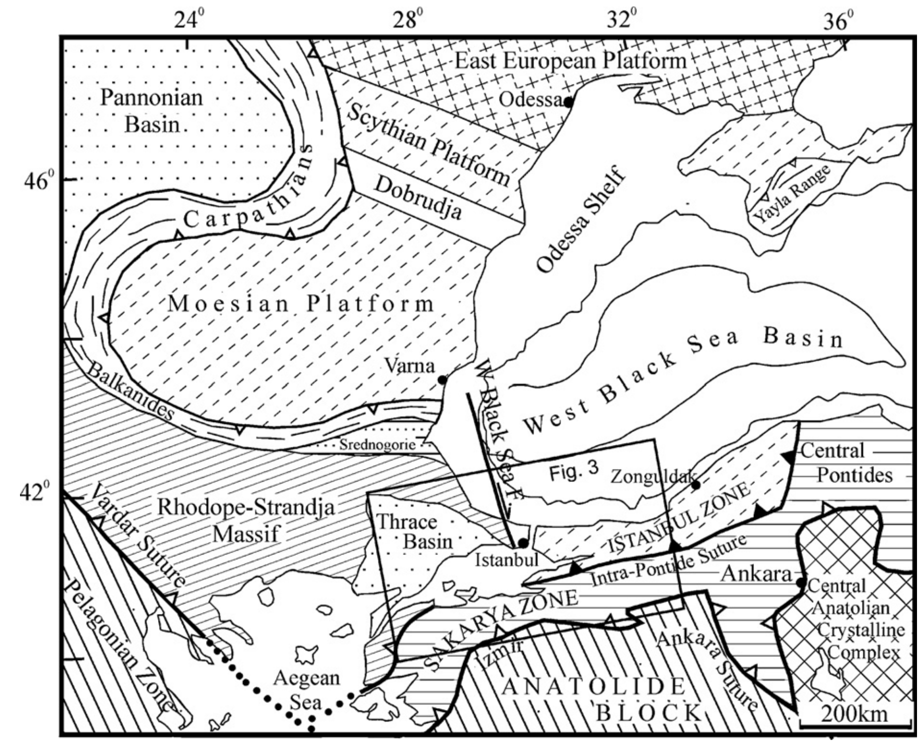

Fig. 1. Tectonic map of the northern Aegean and the Balkans showing the major terranes and the bounding sutures (Okay and Tüysüz, 1999). The filled triangles indicate the Intra-Pontide suture and polarity of the subduction whereas empty triangles indicate other sutures. Rectangle box shows location of Fig. 3.

(Okay et al., 1994). Its characteristic feature is a continuous and well-developed Paleozoic sedimentary succession, ranging in age from Ordovician to Carboniferous (e.g., Haas, 1968; Görür et al., 1997; Dean et al., 2000) deposited on a Neoproterozoic metamorphic basement (Ustaömer and Rogers, 1999; Chen et al., 2002). The basement is composed mainly of gneiss and amphibolite, intruded by voluminous Late Proterozoic–Cambrian granitoids (Yiğitbaş et al., 2004; Ustaömer et al., 2005).

Deformation of the Palaeozoic sequence of the İstanbul terrane was interpreted as related to north to northeast vergence during the Carboniferous (Zapcı et al., 2003). Paleozoic rocks of the İstanbul terrane were intruded by a latest Permian (255 Ma) granitoid (Yılmaz-Şahin et al., 2009) and unconformably overlain by the Lower Triassic red sandstones and conglomerates (Yurttaş-Özdemir, 1971; Gedik, 1975). Lower Triassic transgression was accompanied by basaltic lava flows and followed by shallow to deep marine limestone deposition (Altınlı et al., 1970). Upper Triassic deep sea flysch marks the end of this sedimentation episode.

In the western part of the İstanbul terrane, the Jurassic and Lower Cretaceous sequence is absent, and the Paleozoic and Triassic rocks are unconformably overlain by Upper Cretaceous–Paleocene clastic, carbonate and andesitic volcanic rocks (Dizer and Meriç, 1983; Tansel, 1989; Özcan et al., 2012). In contrast, in the eastern part of the İstanbul terrane there is a thick Upper Jurassic to Eocene succession separated by small unconformities (Akyol et al., 1974). Senonian andesitic lavas, dykes and small acidic intrusions are widespread in the northern part of the İstanbul terrane.

2.2. The Sakarya terrane

The Sakarya terrane forms an elongate crustal ribbon extending from the Biga Peninsula in the west to the Eastern Pontides in the east (Fig. 1). The basement of Sakarya terrane is commonly considered in three pieces. (1) A high-grade metamorphic sequence of gneiss, amphibolite and marble. The high-grade metamorphism is dated to the Carboniferous (330–310 Ma; Topuz et al., 2004, 2007; Okay et al., 2006a,b; Ustaömer et al., 2012). (2) Palaeozoic granitoids that are scattered throughout the Sakarya terrane, with Devonian, Carboniferous, Early Permian crystallization ages (Delaloye and Bingöl, 2000; Okay et al., 2002, 2006a,b; Topuz et al., 2007; Aysal et al., 2012). (3) The Karakaya Complex is interpreted as a Permo-Triassic subduction-accretion complex. It is divided into two units. The Lower Karakaya Complex consists of greenschist facies metabasites with lesser amounts of marble and phyllite (Okay and Göncüoğlu, 2004). It also includes tectonic slices of Late Triassic blueschists and eclogites (Okay et al., 2002). It is tectonically overlain by the Upper Karakaya Complex, which is made up of thick series of strongly deformed arkosic sandstones, greywacke with exotic blocks of Carboniferous and Permian limestone and radiolarian chert, basalts, olistostromes, and grain flows with Upper Permian limestone clasts and dark shales (cf. Okay and Göncüoğlu, 2004).

All these basement units are unconformably overlain by a Mesozoic sedimentary series strating with Lower to Middle Jurassic continental to shallow marine clastic rocks with ammonitico rosso horizons (Fig. 2, Altıner et al., 1991). By Late Cretaceous (between Campanian and Maastrichtian), a deep sea flysch deposited in the Sakarya terrane marks the onset of the Alpide orogeny (Gölpazarı Formation of Saner, 1978 and Yenipazar Formation of Yücel and Soner, 1991).

2.3. The Strandja Massif

The Strandja Massif is a large crystalline terrane in the southeastern Balkans. It has a Variscan quartzofeldspatic gneissic basement intruded by Late Carboniferous–Early Permian granitoids (e.g., 257 ± 6 Ma; Okay et al., 2001; Sunal et al., 2006). The basement lithologies extend some 200 km, from Bulgaria to the

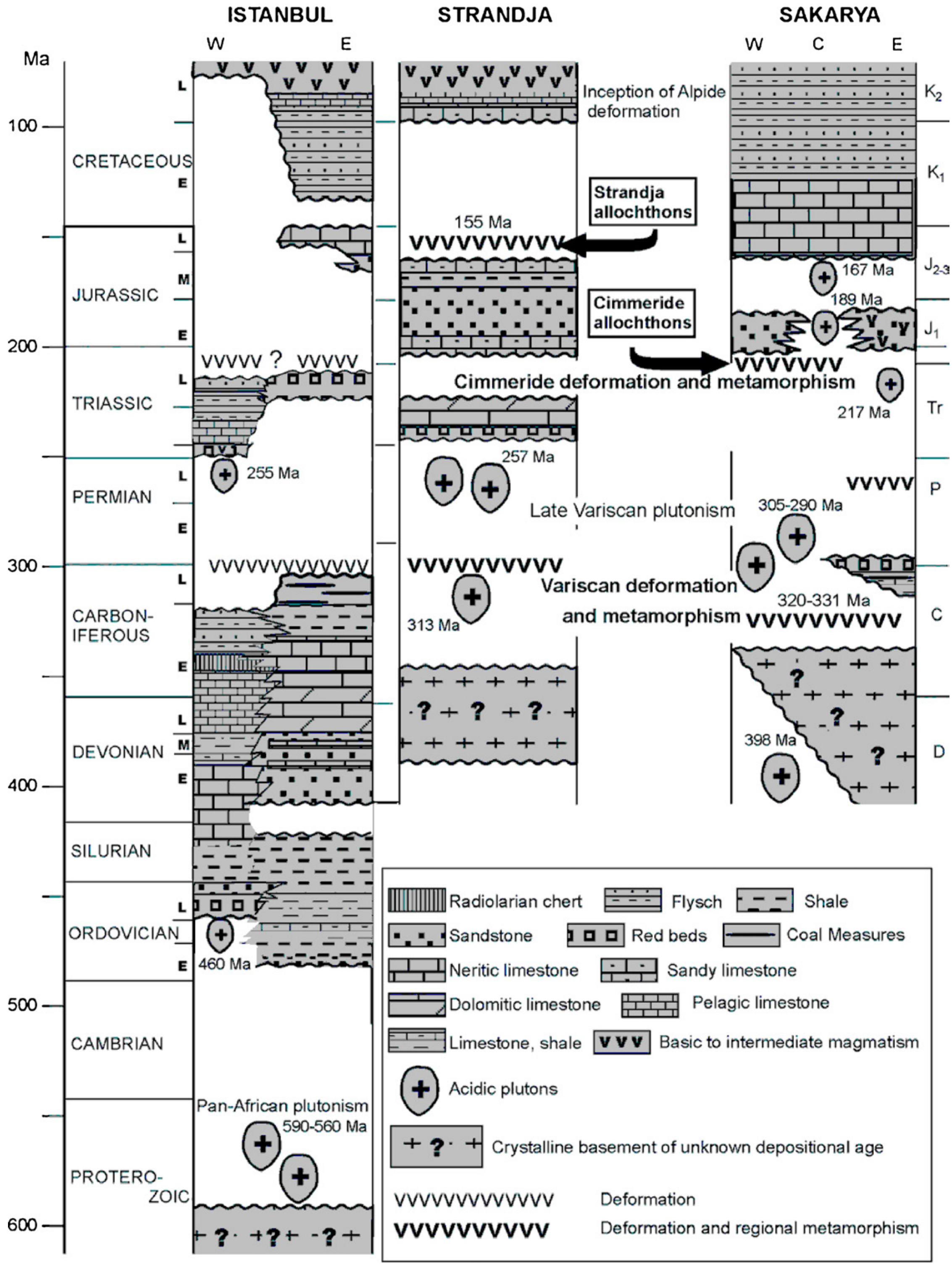

Fig. 2. Stratigraphic columns of the İstanbul, Sakarya and Strandja terranes showing the major plutonic and metamorphic events. From Okay et al. (2006a,b).

Çatalca region of İstanbul in a northwest-southeast direction. The basement is unconformably overlain by Triassic conglomerates and sandstones, which pass up into Middle Triassic shallow marine carbonates (Chatalov, 1988, 1991; Okay et al., 2001; Natal'in et al., 2005; Sunal et al., 2006; Hagdorn and Göncüoğlu, 2007). In Bulgaria the Mesozoic stratigraphy of the Strandja Massif continues into the Middle Jurassic (Chatalov, 1988). Late Jurassic–Early Cretaceous was the time of the deformation and regional metamorphism in the Strandja Massif (119–155 Ma; Okay et al., 2001; Elmas et al., 2011; Sunal et al., 2011). This mid-Mesozoic deformation was followed by exhumation of the metamorphic rocks, which are overlain by the Cenomanian shallow marine sandstones, which pass up into a thick sequence of volcanic and volcanogenic rocks of Late Cretaceous age (Fig. 2, Okay et al., 2001).

Table 1
Correlation table of the metamorphic units differentiated during our mapping and the previous publications. Bolded names refer to the groups, italics names refer to the formations; main rock types of each unit written with normal letters. The published uncertain ages (without radiogenic or paleontological data) shown in the parentheses with question mark. Bolded Late Triassic age of the third column refer to the conodont age from the limestones northeast of Iznik Lake (Önder and Göncüoğlu, 1989).

This paper	Akartuna (1968)	Göncüoğlu et al. (1987, 1992)	Bozcu (1992)	Yılmaz et al. (1995)	Robertson and Ustaömer (2004)
Pamukova Complex	**Crystalline Schists (Pre-Permian?–Permo-Carboniferous?)** -Gneiss, mica-schist, amphibole schist, marble (Permo-Carboniferous?). -Granite, granodiorite (Pre-Permian?).	**Pamukova Metamorphics (Pre-Cambrian?–Early Paleozoic?)** -Metagranite, amphibolite, quartzite, marble and overlying metaclastics, recrystallized limestone, metasiltstone, shale. -Dunite, harzburgite, pyroxenite, metagabbro.	**Geyve Metaophiolite (Late Cretaceous?)** -*İkramiye Serpantinite*: Serpentinized peridodites [only some of the outcrop area of İkramiye Serpantinite of Bozcu (1992) map]. -*Doğançay Metagabbro-Amphibolite (Late Cretaceous?)*: Gabbro-amphibolite and crosscutting aplite, pegmatites.	**Geyve Metaophiolite (Late Cretaceous?)** -Some of the serpentinized peridodites of the Geyve Metaophiolite. -Gabbro-amphibolite unit. -Granite.	**Armutlu Metamorphics (Precambrian?–Paleozoic?)** Gneiss–amphibolite, meta-conglomerate, meta-arcosic sandstone, marble, metagranite, metabasite.
			Pamukova Metamorphic Association -*Gökgöz Metagranite (Paleozoic?)*: Granite, tonalite, alaskite. -*Karapınar Amphibolite (Pre-Permian?)*: Amphibole schist and crosscutting aplite, pegmatites. -*Kirazlı Quartzite (Jurassic?)*: Slightly metamorphic quartzite and shale intercalations -*Yörüktepe Marble (Jurassic?)*: Oolitic–silisic marble, dolomite, marble breccia.	**İznik Metamorphics (Lower Paleozoic?)** -Phyllite, slate, quartzofeldspatic schist outcrops of İznik Metamorphics near Pamukova and in the Geyve Gorge.	
Maşukiye Group	**Crystalline Schists (Permo-Carboniferous?)** Clay-schist, greywacke, sericite-schist, chlorite-schist, serpantine-schist, quartzite, sericite-schist, marble.	**Lower part of İznik Metamorphics (Triassic?–Middle Jurassic?)** -*Schist-marble unit (Triassic?–**Late Triassic**)*: Metabasite, greenschist metasiltstone, metasandstone, metapyroclastite (felsic), recrystallized limestone, dolomite. -*Alıçyayla Limestone (Upper Triassic?–Middle Jurassic?)*: Metabasite, greenschist metasiltstone, metasandstone, metapyroclastite (felsic), recrystallized limestone, dolomite.	**Lower part of İznik Metamorphics (Pre-Triassic?–Triassic?)** -*Keltepe Marble (Triassic?)*: Recrystallized limestone. -*Taşlık Mermeri (Pre-Triassic?)*: Marble, dolomite. -*Orhaniye Formation (Pre-Triassic?)*: Phyllite-slate, quartzofeldspatic schist.	**Lower and middle parts of İznik Metamorphics** -Recrystallized limestone (Early Cretaceous?). -Marble, dolomite (Pre-Triassic?). -Phyllite, slate, quartzofeldspatic schist (Early Paleozoic?).	**Lower part of İznik Metamorphics** -Meta-carbonate platform (Mid-Triassic?–Jurassic?). -Meta-volcanoclastics, tuffs, terrigenous sediments (Pre-Mid Triassic?).
Sapanca Complex	**Crystalline Schists (Permo-Carboniferous?)** Clay-schist, greywacke, sericite-schist, chlorite-schist, serpantine-schist, quartzite, greywacke, sericite-schist, marble.	**Upper part of İznik Metamorphics (Upper Jurassic?–Lower Cretaceous?)** -*Metaolistostrome unit (Late Jurassic?–Early Cretaceous?)*: Serpantinised ultramafics, metagreywacke, shale and blocks of marble, chert, radiolarite, greenschist -*Metavolcanic unit (Early Cretaceous?)*: Metabasalt, metapyroclastic.	**Upper part of İznik Metamorphics (Late Cretaceous?)** -*Adliye Formation*: Slightly metamorphosed basaltic lava, pelagic limestone, chert, siltstone, shale. -*Akçay Formation*: metaflysch with exotic blocks.	**Upper part of İznik Metamorphics** -Slightly metamorphosed basaltic lava, and metaflysch with exotic blocks (Late Cretaceous?)	**Gemlik Melange (Late Cretaceous?)** -Phyllite-psammite, limestone, lava, volcanoclastic, conglomerate, serpantinite.
			Geyve Metaophiolite (Late Cretaceous?) -*Kocadağ Metabasite*: Metamorphic basalt. -*İkramiye Serpantinite*: Serpentinized peridodites [most of the outcrop area of İkramiye Serpantinite of Bozcu (1992) maps].	**Geyve Metaophiolite (Late Cretaceous?)** -Metamorphosed basaltic lava and some of the serpentinized peridodite outcrops.	**Upper part of İznik Metamorphics (Triassic?–Late Cretaceous?)** -Phyllite, cherts, metalliferous sediments.

3. Stratigraphy of the Armutlu Peninsula

The Armutlu Peninsula lies along the contact between the İstanbul and Sakarya terranes (Fig. 3). Since much of the Armutlu Peninsula is heavily forested and has a complicated geology, there are widely differing views on the nomenclature, age and extend of the geological units and their evolution (Akartuna, 1968; Göncüoğlu et al., 1987, 1992; Kaya and Kozur, 1987; Yılmaz et al., 1995; Elmas and Yiğitbaş, 2001, 2005; Robertson and Ustaömer, 2004; Ustaömer and Robertson, 2005). This is particularly the case for the metamorphic units, which have a wide distribution in the Armutlu Peninsula (Fig. 3). These metamorphic units have been named variously as the Armutlu Metamorphics, İznik Metamorphics, Geyve Metaophiolite and Pamukova Metamorphics (Göncüoğlu et al., 1987, 1992; Bozcu, 1992; Yılmaz et al., 1995; Elmas and Yiğitbaş, 2001, 2005; Robertson and Ustaömer, 2004; Ustaömer and Robertson, 2005). In our study we have mapped in detail the geology of the eastern part of the Armutlu Peninsula, south of the Sapanca Lake. The metamorphic units that we have differentiated do not correspond to those of the previous publications, as can be seen through a comparison of the geological map in Fig. 4 with those of the same region published earlier (Table 1, Akartuna, 1968; Bozcu, 1992; Yılmaz et al., 1995; Göncüoğlu et al., 1987, 1992; Robertson and Ustaömer, 2004). Therefore, not to cause further confusion, we used a new lithostratigraphic nomenclature for the metamorphic rocks.

Three metamorphic units crop out south of the Sapanca Lake, separated by thrust contacts (Figs. 4–6a). These are from base upward: (a) *Maşukiye Group*: a metaclastic-marble sequence, (b) *Sapanca Complex*: greenschist facies metabasites and phyllites with serpentinite lenses interpreted as a Lower Cretaceous subduction-accretion complex, (c) *Pamukova Complex*: a high-grade metamorphic unit, which probably represents the basement of the İstanbul terrane (Okay et al., 2008). This basement is also imbricated with a tectonic mélange, called *Gemlik Mélange* (Figs. 4 and 6b and c; Kaya, 1977; Kaya and Kozur, 1987). Upper Cretaceous and Lower Eocene sediments unconformably lie over all the older units (Akartuna, 1968; Göncüoğlu et al., 1987, 1992; Yılmaz et al., 1995; Özcan et al., 2012).

3.1. The Pamukova Complex; Late Proterozoic–Ordovician basement

The Pamukova Complex is an epidote-amphibolite facies metamorphic unit consisting of metadunite, metapyroxenite, amphibolite, gneiss, metagranite, marble, metaquartzite and calc-schist. This unit was interpreted as a metamorphosed Cretaceous ordered ophiolite suit and was named as Geyve Metaophiolite (Bozcu, 1992; Yılmaz et al., 1995). However, recent zircon dating in the Armutlu Peninsula showed that this unit is Neoproterozoic–Ordovician in age (Okay et al., 2008) and our observations do not confirm the presence of an ordered ophiolitic suit. For this high-grade metamorphic unit we used the name of Pamukova Complex, as suggested by Göncüoğlu et al. (1987). There are four subunits in the Pamukova Complex (Figs. 4–6): (1) A metamorphosed banded ultramafic–mafic unit with a structural thickness of 1400 m. This unit consists of metadunite (~40% of all outcrops), metapyroxenite (~40%), metagabbros (~20%), all banded in cm scale. These rocktypes and their banded nature suggest a probable mantle cumulate origin. (2) A banded gneiss–amphibolite unit, which structurally underlies the banded peridodite. The contact between the banded ultramafic–mafic unit and amphibolite–gneiss unit was probably a thrust fault before the metamorphism because the overlying metaultramafics must have been formed in the deeper parts of lithosphere comparing with the underlying gneiss and amphibolites (Figs. 4 and 6). This second subunit is mainly made up of quartzofeldspatic gneiss (~40% of all outcrops) and amphibolites (~40%), which usually make up 2–10 cm thick bands. In some places pegmatite, aplite dykes and sills cut the amphibolite–gneiss bands (15%), minor amounts of mica-schists are also found (~5%) in this subunit. "Hornblende + plagioclase + albite + epidote" mineral parageneses in the amphibolites is typical for the epidote-amphibolite facies metamorphism (Spear, 1993; Miyashiro, 1994). (3) The third subunit of the Pamukova Complex is a leucocratic, medium to coarse-grained metagranite, which cuts the amphibolite–gneiss unit. Metagranite has undergone weak metamorphism and cataclasis; quartz has recrystallized into subgrains, whereas plagioclase largely retains its magmatic crystal outlines. Xenoliths of amphibolite, mica-schist, gneiss and marble are observed in this metagranite. (4) Fourth unit of the Pamukova Complex is a metasedimentary unit mainly made up of tectonic intercalation of marble (70–75% of the outcrops), metaquartzite (25–30%) and calc-schist (3–5%). This unit forms east-west trending, north dipping tectonic slices up to 10 km long and 1.5 km thick (Fig. 4) and it is probably the source of the marble xenoliths in the metagranite. Even though stratigraphic contacts of these metasediments and the metamagmatic (mafics and ultramafics) rocks of the Pamukova Complex cannot be observed, we speculate that the contact may have been depositional, probably an unconformity (Fig. 5).

The metamagmatic rocks of the Pamukova Complex were previously interpreted either as a Cretaceous ophiolite (Bozcu, 1992; Yılmaz et al., 1995) or a Neoproterozoic ophiolite and related arc associations (Yiğitbaş et al., 2001, 2004). Most of the outcrops of the Pamukova Complex in the Armutlu Peninsula comprise banded gneiss, amphibolites and metagranites (total ~70 of all outcrop areas), which are not common rock types in the ophiolite successions, furthermore no regular ophiolitic series is observed in the Pamukova Complex.

3.1.1. Zircon geochronology of the Pamukova Complex

Up to now, the only available isotopic age data from the basement in the Armutlu Peninsula were Neoproterozoic–Ordovician zircon ages (Okay et al., 2008). A similar basement has also been described from the Almacık Mountains, ~50 km farther east (Yiğitbaş et al., 2004), in the Sünnice, Bolu Massif (Yiğitbaş et al., 1999, 2004; Ustaömer et al., 2005) and in the Karadere (Chen et al., 2002). In the Bolu Massif and in the Karadere Neoproterozoic (560–590 Ma) zircon U–Pb ages are reported from the basement (Ustaömer et al., 2005; Chen et al., 2002). Rb–Sr geochronology also indicates latest Precambrian cooling (548–545 Ma) for the basement in the Karadere area (Chen et al., 2002). During the present study two gneiss samples from the Pamukova Complex were dated using TIMS U–Pb conventional technique. All of the isotopic measurements have been done with Thermal Ionization Mass Spectrometer (Finnigan MAT 262) in the Tübingen University. The TIMS U–Pb conventional technique is described in Siebel et al. (2005).

Sample 3902 was collected at ~110 km west of the mapping area, north of Gemlik (Fig. 3) and sample 3282 was collected from south of the Sapanca Lake (Fig. 4). The detailed petrographical descriptions of the dated samples are given in Appendix A. Five different zircon populations were used to date sample 3282 and three zircon populations were used to date the sample 3902. While some of the zircons have inner cores, most of them show very good growth zoning, typical for igneous zircons, which shows that they were not affected by the later metamorphism (Fig. 7). U–Pb zircon results from the sample 3282 are Latest Proterozoic (591.9 ± 5.1 Ma, Table 2 and Fig. 8a), while those from the sample 3902 are older but again Late Proterozoic (685 ± 24 Ma, Table 2, Fig. 8b). These data are consistent with the reported Late Proterozoic (~561 Ma) zircon ages from the gneisses of the gneiss–amphibolite subunit and

Table 2
U–Pb zircon data of the zircons from Pamukova Complex (samples 3902, 3282) and Maşukiye Group (samples 2032, 3859).

Sample number	Weight [mg]	U [ppm]	Pb [ppm]	$^{206}Pb/^{204}Pb$	Isotopic ratios				$^{207}Pb/^{206}Pb$	Rho[b]	Apparent age [Ma]		
					$^{206}Pb/^{238}U$	2σ [%]	$^{207}Pb/^{235}U$	2σ [%]			$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
U/Pb data from the gneisses of Pamukova Complex													
3902[a]													
Z1(3)	0.035	78.0	15.4	92.57	0.10820	0.59	0.9277	0.86	0.06218	0.7163	662.27	666.41	680.45
Z2(2)	0.024	40.0	17.3	40.11	0.11340	0.70	1.2378	4.01	0.07916	0.4389	692.47	817.88	1176.20
Z3(4)	0.048	44.1	9.6	58.65	0.08560	0.54	0.7396	0.85	0.06267	0.6744	529.45	562.19	696.99
Z4(3)	0.025	126.1	19.7	88.58	0.08345	0.53	0.7154	0.64	0.06218	0.8459	516.66	547.94	680.20
Z5(2)	0.013	157.2	54.0	49.87	0.11590	0.54	1.0695	0.89	0.06693	0.6605	706.92	738.51	835.52
3282													
Z1(1)	0.023	89.7	9.8	611.61	0.09753	0.66	0.8060	1.05	0.05994	0.6565	599.90	600.19	601.27
Z2(1)	0.020	88.1	13.8	124.02	0.09714	0.62	0.8041	1.32	0.06003	0.4984	597.64	599.13	604.78
Z3(3)	0.020	232.3	21.9	1893.12	0.09136	0.57	0.7520	0.60	0.05969	0.9466	563.59	569.36	592.49
Z4(1)	0.055	79.7	7.5	828.52	0.08784	0.60	0.7201	1.01	0.05945	0.6352	542.76	550.72	583.77
Z5(1)	0.014	287.0	27.4	318.51	0.07937	0.54	0.6552	0.64	0.05988	0.8563	492.34	511.70	599.14
U/Pb clastic zircon data from Maşukiye Group													
2032													
Z1(3)	0.02	469.3	32.6	1491.37	0.068843	0.58	0.644203	0.99	0.67868	0.6319	429.18	504.90	864.52
Z2(3)	0.03	726.0	37.4	1650.83	0.050370	0.53	0.369404	0.54	0.05319	0.9809	316.79	319.21	336.91
Z3(2)	0.02	997.5	74.2	1722.48	0.071610	0.57	0.561637	0.63	0.05688	0.9210	445.85	452.59	486.99
Z4(4)	0.02	663.4	42.7	458.93	0.058656	0.54	0.448028	0.75	0.05540	0.7372	367.44	375.90	428.32
Z5(2)	0.01	257.2	19.6	586.10	0.069937	0.60	0.592044	0.82	0.06140	0.7476	435.78	472.17	653.16
3859													
Z1(1)	9.00	698.2	217.3	707.46	0.262166	0.52	5.465150	0.53	0.15119	0.9800	1500.90	1895.10	2359.40
Z2(1)	17.60	377.8	27.7	99.05	0.042275	0.70	0.320057	6.20	0.05490	0.6300	266.92	281.95	408.51
Z3(2)	2.00	121.6	6.3	251.41	0.041840	0.54	0.303267	0.68	0.05257	0.8100	264.23	268.95	310.29
Z4(2)	0.50	33.3	2.0	258.12	0.046764	0.53	0.331809	0.57	0.05146	0.9400	294.62	290.95	261.54
Z5(1)	7.00	670.6	69.8	140.41	0.066537	0.55	0.543874	0.76	0.05928	0.7600	415.26	440.98	577.53

[a] Bracketed numbers indicate number of grains in fraction.
[b] Correlation coefficient of ($^{206}Pb/^{238}U$)/($^{207}Pb/^{235}U$).

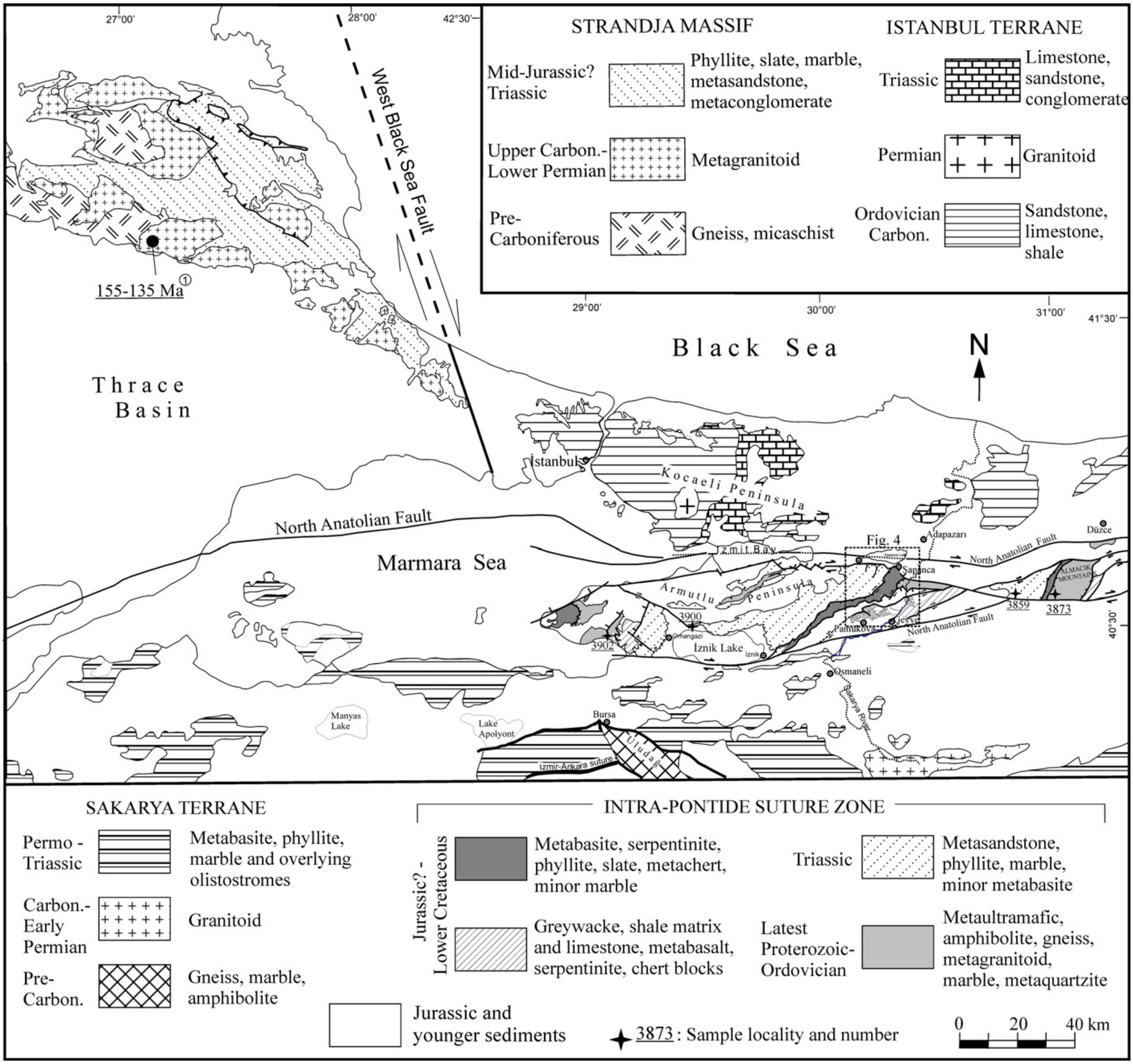

Fig. 3. Geological map of Intra-Pontide suture and surrounding terranes (compilation of Akartuna, 1968; Chatalov, 1988; Okay et al., 2001; Göncüoğlu et al., 1987, 1992; Eisenlohr, 1995; Türkecan and Yurtsever, 2002; Aksay et al., 2002; Özcan et al., 2012 and our observations). Dashed rectangle box shows location of Fig. 4. Location numbers with stars are the numbers of the dated samples outside the mapping area ([1]: the age of metamorphism in Strandja Massif from Okay et al., 2001 and Sunal et al., 2011).

the cross-cutting metagranites at different outcrops in the Armutlu Peninsula (Okay et al., 2008). It is noteworthy that Okay et al. (2008) also reported some Ordovician (~460 Ma) Pb–Pb evaporation ages from this unit.

3.1.2. Metamorphic ages of the Pamukova Complex; Rb–Sr mica and Sm–Nd garnet data

During the present study, biotites and muscovites from seven samples, including four gneisses (samples 3282, 3252, 3873, 3902), two metagranites (samples 3479 and 3483) and one calc-schist marble (sample 3263) were dated using TIMS Rb–Sr mica technique (Figs. 3 and 4). The detailed petrographical descriptions of the dated samples are given in Appendix A. The closure temperatures of muscovite and biotite for Sr are 500 ± 50 °C and 300 ± 50 °C, respectively (e.g., Jäger et al., 1967; Cliff, 1985). The analytical technique was the same as described in Okay et al. (2006a,b). One sample was collected from the eastern part of the Almacık Mountains (Fig. 3, sample 3873), one sample was collected from north of Gemlik (Fig. 3, sample 3902) and five of the samples were collected from south of Sapanca Lake (Fig. 4). The new Rb–Sr mica ages of the samples from Pamukova Complex are generally between 111 and 158 Ma, only one metagranite gave an older age of 179.3 ± 1.8 Ma (Table 3). Two different types of garnet separates from a metagranite (sample 3479) gave also similar Sm–Nd ages of 156 ± 12 Ma and 157 ± 18 Ma (Table 4) compatible with the ca. 159 Ma Rb–Sr result from the same sample (Table 3).

The Rb–Sr and Sm–Nd data indicate that the Neoproterozoic basement of the İstanbul Zone and the cross-cutting Ordovician granitoids in the Armutlu Peninsula were reheated during Late Jurassic–Early Cretaceous interval.

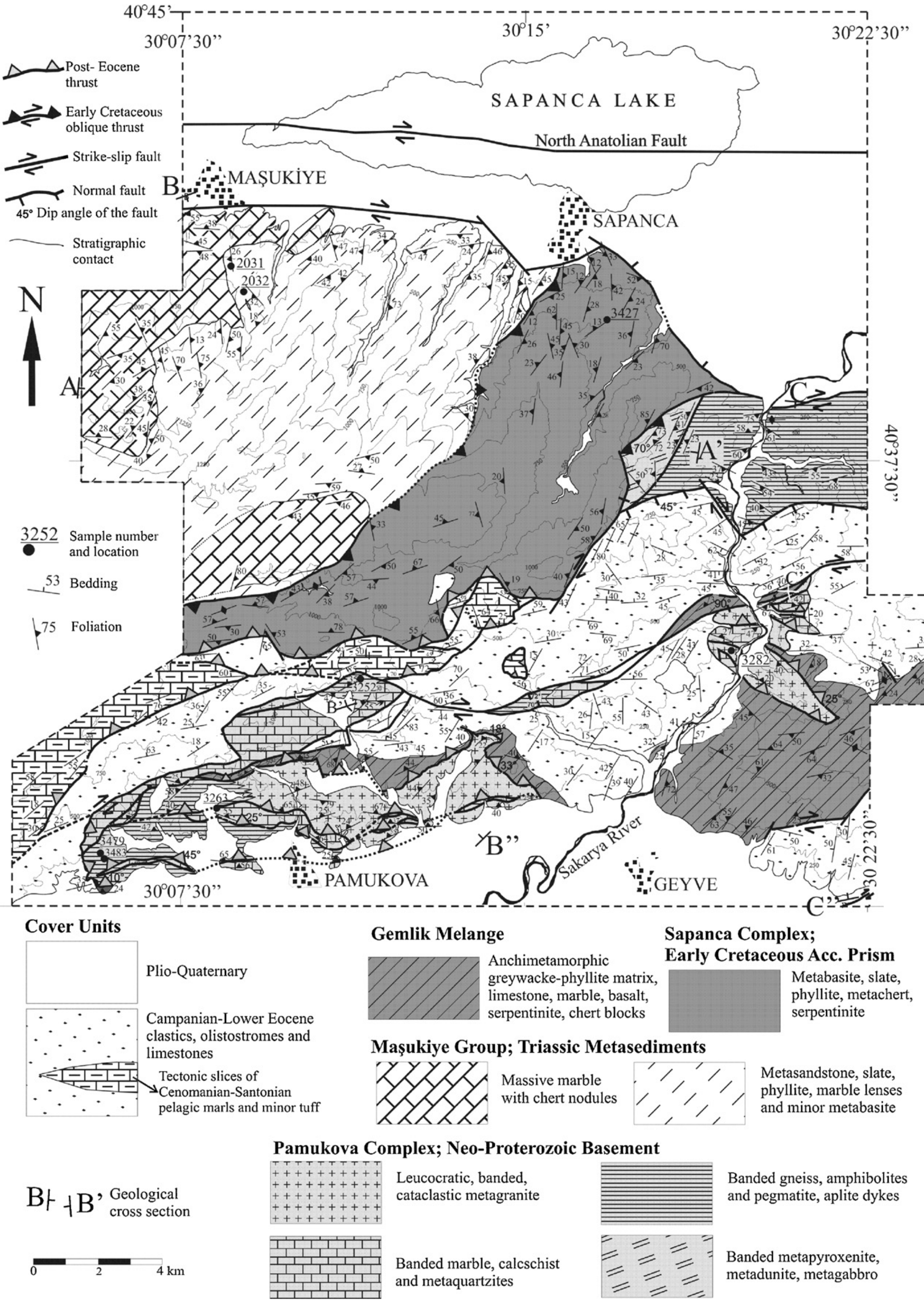

Fig. 4. Geological map of south of the Sapanca Lake (simplified from Akbayram, 2011). Location numbers are the numbers of the dated samples.

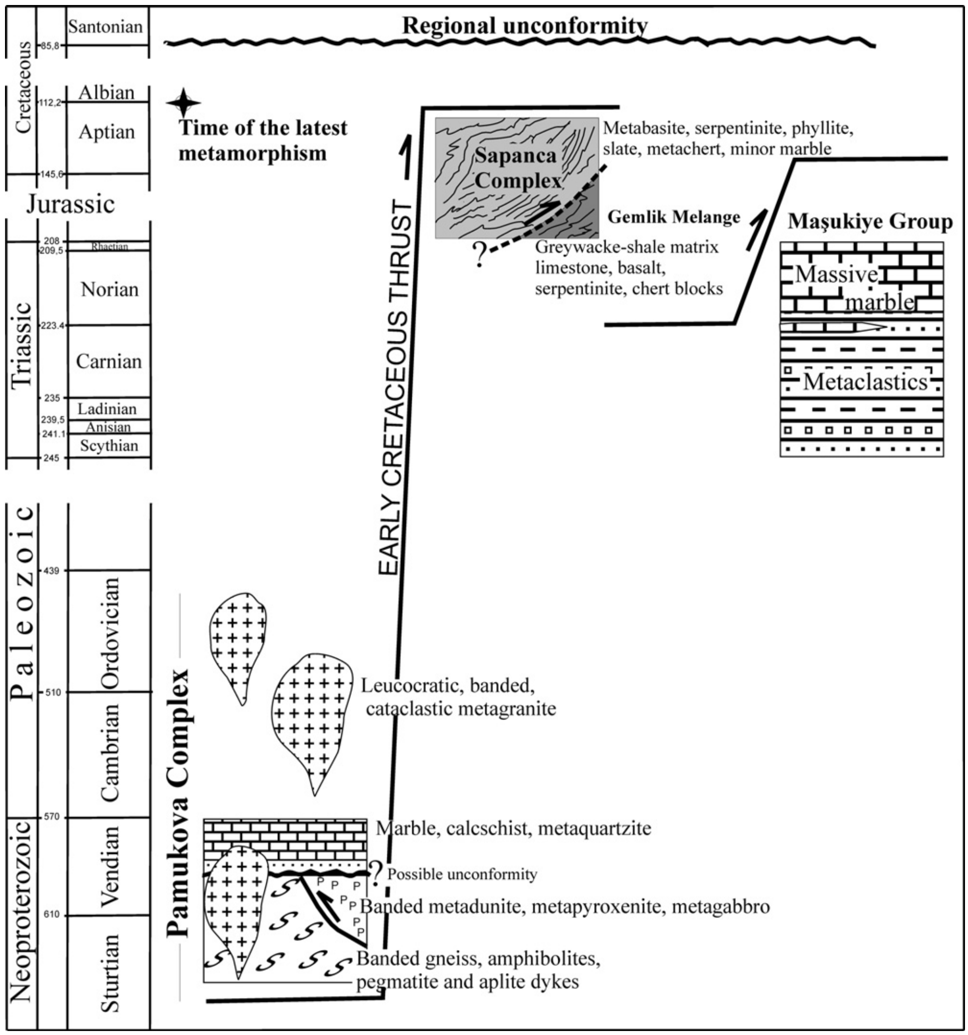

Fig. 5. Generalized stratigraphic column of the area south of Sapanca Lake.

3.2. The Sapanca Complex; Early Cretaceous Accretionary Prism

The Sapanca Complex consists of strongly deformed metabasite (~55–60% of all outcrops), slate-phyllite (~20–25%), serpentinite (~15%), metachert (~5–10%) and minor marble. It lies tectonically under the Neoproterozoic basement (Figs. 4 and 6a). This contact is well preserved as a 50 m thick fault zone at the northern part of the mapping area, west of the Geyve Gorge. The fault zone dips 70° toward the southeast separating banded ultramafic rocks of the Pamukova Complex from the underlying metabasites, serpantinites of the Sapanca Complex. Despite the strong deformation, some primary features of the metabasites such as relict pillow lavas, are locally observed. Mineral paragenesis of the metabasites is "actinolite + chlorite + albite + epidote + stilpnomelane + calcite", typical for the greenschist facies metamorphism (e.g., Laird, 1982; Maruyama et al., 1983). There are no data on the protolith ages of the unit. Samples rich in mica are rare in the Sapanca Complex and only one phyllite sample was dated (sample 3427, for location see Fig. 4). Mineral paragenesis of the sample is muscovite + quartz + albite. The Rb–Sr muscovite age of this phyllite is 110.8 ± 3.4 Ma (Table 3).

Based on its lithological features, especially the presence of serpentinite lenses and abundance of metabasites, we interpreted the Sapanca Complex as an Early Cretaceous subduction-accretion complex of the Intra-Pontide suture zone.

3.3. The Maşukiye Group; Triassic metasediments

The Maşukiye Group consists of ~1750 m thick arkosic metasandstones (60% of all outcrops), black phyllites (~35%), marble (5%) and rare metabasite lenses, which are overlain by thickly bedded to massive marbles, ca. 1050 m thick. The Maşukiye Group is tectonically overlain by the Sapanca Complex but the contact does not crop out well. We interpret this contact as a thrust because the metabasite bands of the Sapanca Complex dipping to the east are overlying the metasandstones, marbles of the Maşukiye Group and this contact is almost parallel to the thrust between the Pamukova Complex and the Sapanca Complex (Figs. 3 and 4). The arkosic character of the metasandstones of the Maşukiye Group shows a continental source. The marbles show laminations typical for the shallow marine linestones. Önder and Göncüoğlu (1989) reported from northeast of Iznik Lake Late Triassic conodonts from limestones, which may be correlated with the Maşukiye Group. Metasedimentary rocks lithologically similar to the Maşukiye Group have also been described from the Almacık Mountains (Abdülselamoğlu, 1959; Yılmaz et al., 1982). Yılmaz et al. (1982) assumed a Paleozoic age for this unit and interpreted it as the metamorphic equivalent of the İstanbul Paleozoic sequence.

In order to constrain the sedimentation age of the Maşukiye Group, we have dated clastic zircons from the metasandstones. Zircons from one sample from the Almacık Mountains (Fig. 3, sample

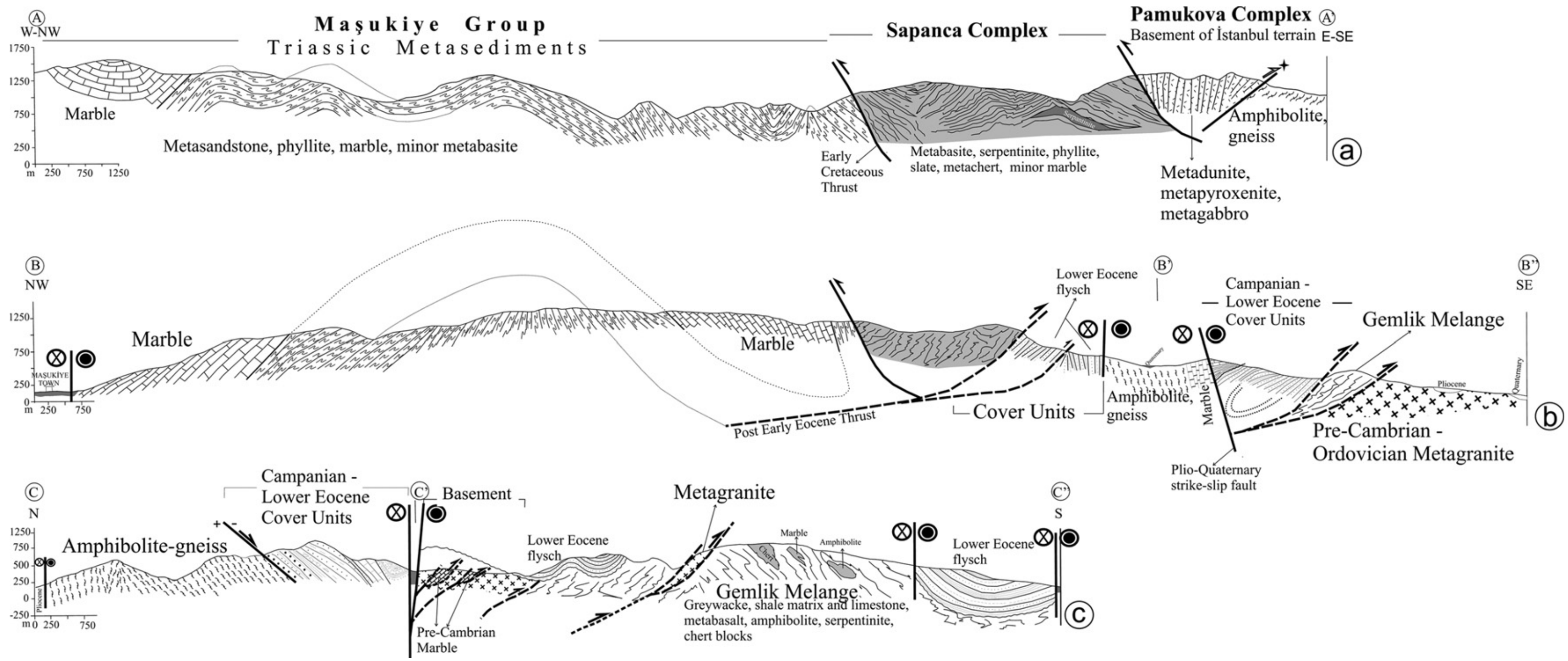

Fig. 6. Geological cross sections across the mapping area. For location of cross-sections see Fig. 4.

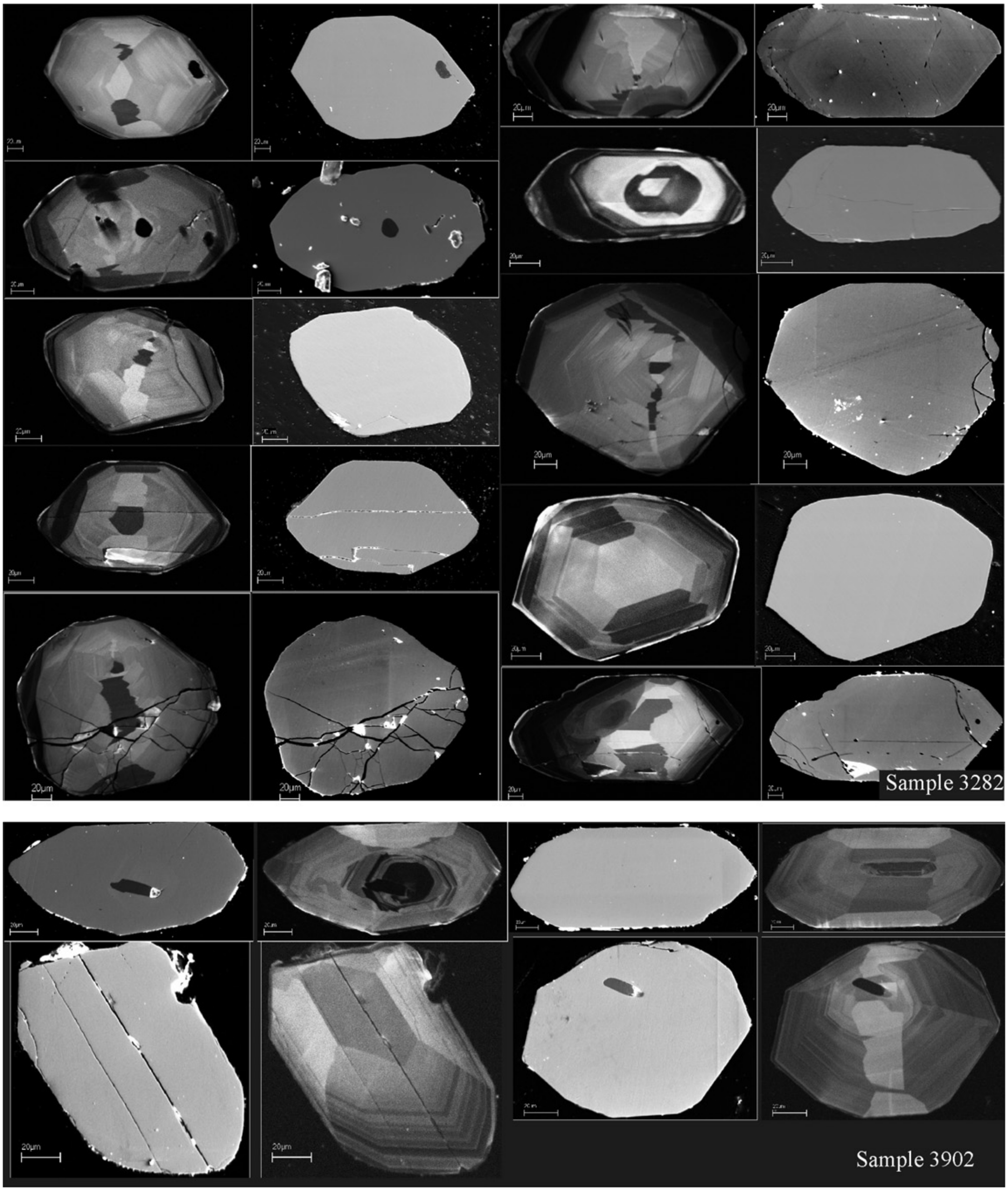

Fig. 7. Cathodoluminescence and secondary-electron images of selected grains of samples 3282 and 3902.

3859) and two samples from south of Sapanca Lake (Fig. 4, samples 2031 and 2032) were dated using both conventional TIMS U–Pb and TIMS Pb–Pb single-zircon stepwise evaporation technique of Kober (1986, 1987). The single zircon TIMS Pb–Pb evaporation technique is very advantageous especially for the clastic zircon dating. Only one small zircon grain is needed during measurement, no wet chemistry is involved therefore there is no blank contamination and one knows precisely which grain is being dated. It has given results that agree with the TIMS U–Pb dating technique (e.g., Cocherie et al., 1992). The TIMS Pb–Pb evaporation analytical technique was the same as described in Kober (1986, 1987).

3.3.1. *Clastic zircon geochronology of the Maşukiye Group*

Zircons from the sample 3859 (from Almacık Mountains, Fig. 3) are mostly pale pink and prismatic, with no or very few inclusions. Some yellow prismatic and reddish hypidiomorphic zircons also exist. Some of the zircons have inner cores, most of them show very good growth zoning (Fig. 9). Five zircon populations were dated using conventional U–Pb technique from the sample 3859 (Fig. 10). ^{207}Pb/^{235}U ages of these five fractions are between 268 and 1895 Ma, three fractions give relatively precise Permian age (268–291 Ma; Table 2).

Zircons from two samples (from south of Sapanca Lake, samples 2031, 2032) are mostly brown, prismatic, with no or very few inclusions. Some reddish brown and yellow zircons also exist. While some of the zircons have inner cores, most of them show very good growth zoning, typical for igneous zircons (Fig. 9). Six zircon populations were dated using conventional U–Pb technique from the sample 2032 (Fig. 10). U–Pb results of detrital zircons from sample 2032 give ^{207}Pb/^{235}U ages between 320 and 505 Ma (Table 2, Fig. 10). Twelve zircon grains were dated using Pb–Pb single zircon evaporation technique from the samples 2031 and

Table 3
Rb–Sr mica age data from Pamukova Complex, Maşukiye Group and Sapanca Complex.

Sample	Rock Type	Mineral	Rb [ppm]	Sr [ppm]	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Age [Ma, 2σ]
Pamukova Complex							
3282	Gneiss	Rock	74.625	658.399	0.3280	0.709987	111.3 ± 1.1
		Biotite	131.583	0.867	471.3454	1.455214	
3252	Gneiss	Rock	72.268	134.471	1.5568	0.720473	151.0 ± 3.4
		Muscovite	181.607	59.642	8.8342	0.736096	
3305	Gneiss	Rock	38.337	686.829	0.1614	0.704795	172 ± 30
		Biotite	23.934	81.104	0.8537	0.706484	
3902	Gneiss	Rock	6.291	35.104	0.5186	0.708679	154.6 ± 2.7
		Biotite	44.489	12.965	9.9491	0.729410	
3263	Calc-schist marble	Rock	167.433	435.389	1.1131	0.712461	135.5 ± 2.2
		Biotite	626.695	132.916	13.6802	0.736660	
3483	Metagranite	Rock	37.650	40.230	0.7229	0.722908	179.3 ± 1.8
		Muscovite	477.134	0.680	4116.8974	11.211705	
3479	Metagranite	Rock	235.209	82.798	8.2391	0.732729	158.8 ± 1.6
		Muscovite	4.817	1022.171	710.6117	2.318385	
3873	Grt-biotite schist	Rock	69.074	132.738	1.5100	0.739915	127 ± 0.03
		Biotite	306.015	10.476	86.0480	0.889950	
Maşukiye Group							
2032	Metasandstone	Rock	72.430	216.600	0.9679	0.711583	138 ± 1.5
		Muscovite	276.238	17.198	46.8979	0.801687	
2663	Metasandstone	Rock	21.260	11.273	5.4730	0.739009	256.4 ± 9.5
		Muscovite	102.553	32.774	9.0926	0.752211	
Sapanca Complex							
3428	Phyllite	Rock	132.893	317.819	1.2102	0.711643	110.8 ± 3.4
		Muscovite	108.009	39.704	7.8816	0.722153	

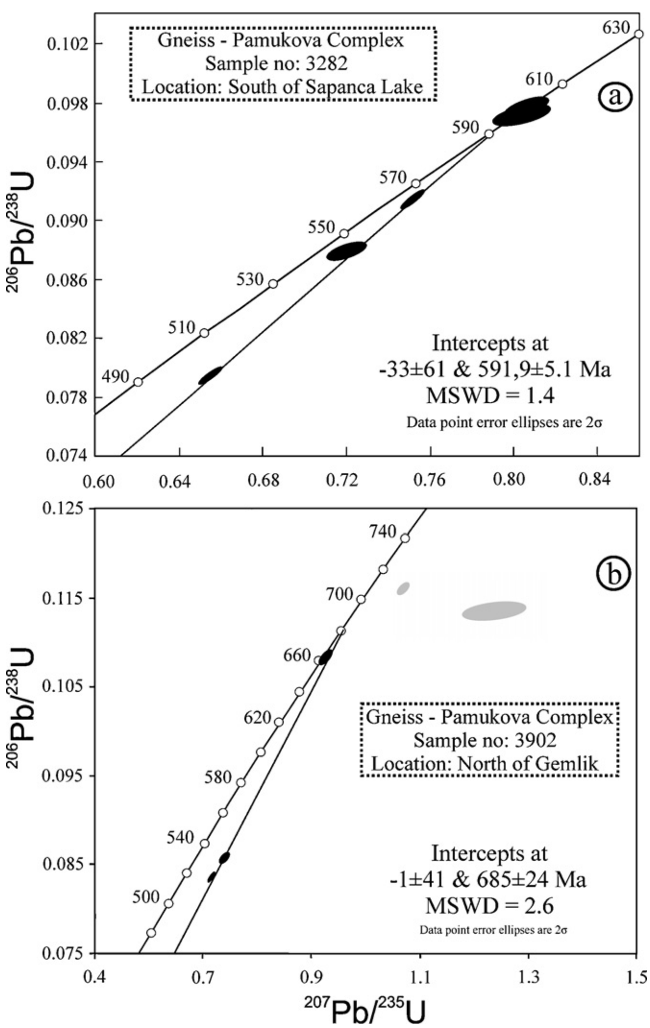

Fig. 8. U–Pb concordia diagrams and the age of zircons from Pamukova Complex (see Figs. 3 and 4 for locations).

2032. Eight zircon ages at 14 heating steps have been obtained from sample 2031 and four zircons ages at 10 heating steps have been obtained from sample 2032 (Table 4). Detrital Pb–Pb single zircon evaporation results of these two samples are between 283 and 557 Ma (Table 5). Three main age groups are defined as follow (Fig. 11a and b). First age group is the youngest, between 283 and 316.5 Ma. The most abundant second age group is between 339 and 376 Ma. The third and the last age group give older ages between 407 and 464 Ma. The oldest, solitary Neoproterozoic age (557 Ma) obtained from the first temperature step of the second grain of sample 2032. This age is probably unreliable because it shows a large difference with the result of second temperature step (Table 5).

If we consider all the clastic zircon ages from three samples three major age populations are apparent (Fig. 11). Youngest overall ages are between 269 Ma and 319 Ma (Age group 1 in Fig. 11). The second age group is between 339 Ma and 376 Ma and the third age group is between 406 Ma and 472 Ma (Age groups 2 and 3 in Fig. 11). It is noteworthy that U–Pb measurements give only one Paleo-Proterozoic age (1895 Ma, Table 2). In summary, despite the scatter there is concentration of ages of Devonian–Permian, and Ordovician–Silurian. The clastic zircon data indicate that the depositional age of the metaclastic unit must be younger than Middle Permian (268 Ma). This deposition age is compatible with the Late Triassic conodont age from the marbles, in the upper part of the metasedimentary succession (Önder and Göncüoğlu, 1989) and suggests a Late Permian–Triassic depositional age. This shows that the Maşukiye Group cannot be the equivalent of the İstanbul Paleozoic sequence, as suggested by Yılmaz et al. (1982).

Recent review of Sunal et al. (2008) on the zircon ages of the pre-Mesozoic basements of Eastern Mediterranean shows that while the Cyclades and the Strandja Massif have Ordovician zircons, Ordovician ages are absent in the nearby tectonic units such as Menderes, Pelagonia and Kırşehir massifs (Keay and Lister, 2002). The Ordovician–Silurian zircon ages were also reported in the Sredna Gora-Balkan Zone (Titorenkova et al., 2003; Malinov et al., 2004; Peytcheva et al., 2004; von Quadt and Peytcheva, 2004; Carrigan et al., 2005), which is possibly a continuation of the Strandja massif (Natal'in et al., 2005; Natal'in, 2006). Devonian and Permian zircons could be transported from the Paleozoic

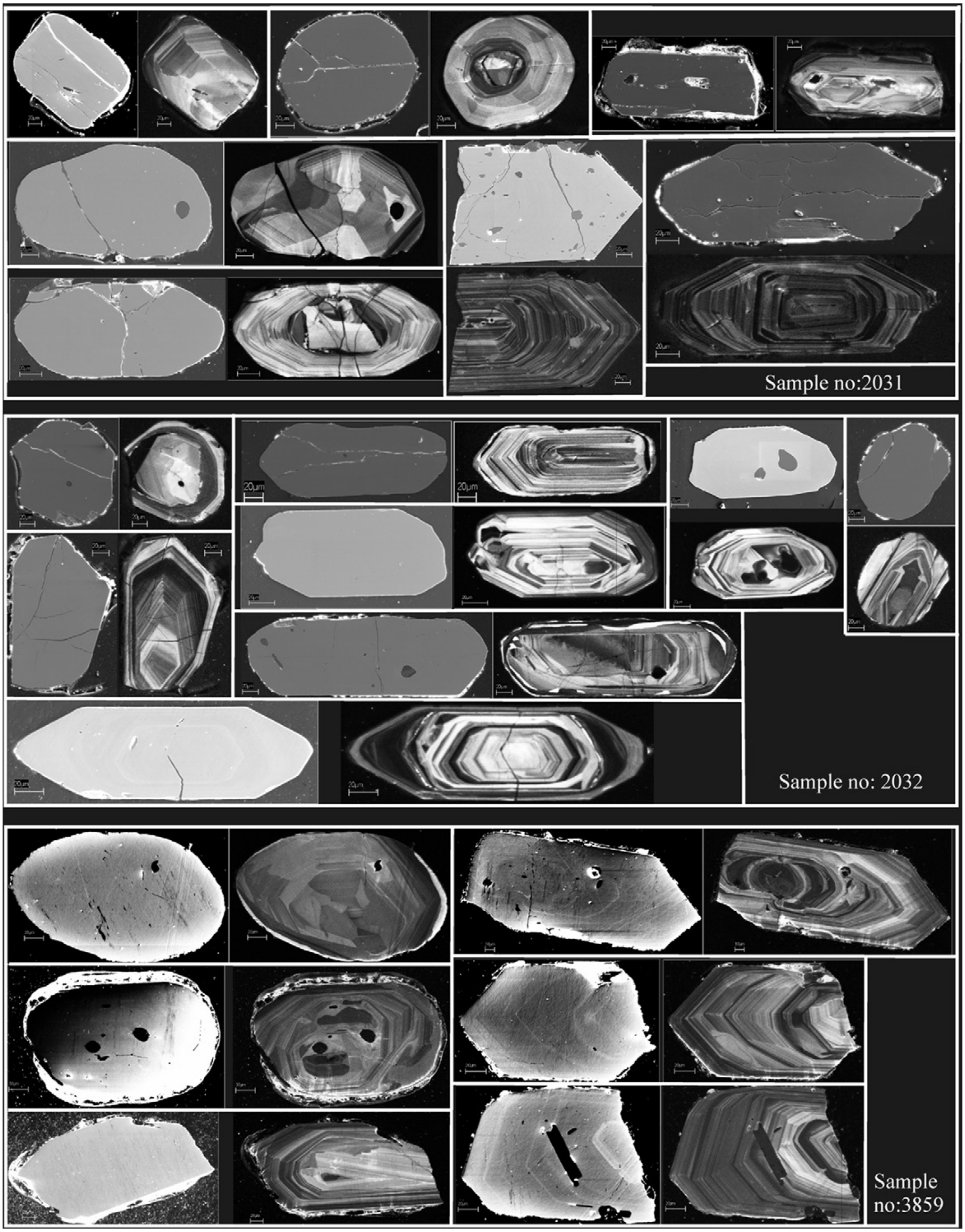

Fig. 9. Cathodoluminescence and secondary-electron images of selected grains of samples 2031, 2032 and 3859.

granitoids reported in the Pontides, from the İstanbul (Yılmaz, 1977) and Sakarya Zones (Delaloye and Bingöl, 2000; Okay et al., 2002, 2006a,b; Topuz et al., 2007; Aysal et al., 2012) or the Strandja Massif (Okay et al., 2001, 2008; Sunal et al., 2006).

3.3.2. *Metamorphic ages of the Maşukiye Group: Rb–Sr mica data*

Two metasandstone samples were dated from the metaclastic unit south of Maşukiye (Fig. 4, samples 2032 and 2663). Metasandstones typically contain quartz + albite + K-feldspar +

Table 4
Sm–Nd garnet age data from Pamukova Complex.

Sample	Rock type	Mineral	Sm [ppm]	Nd [ppm]	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	Age [Ma, 2σ]
3479	Metagranite	Rock	7.277	38.210	0.1151	0.512288	
		Garnet 1	4.182	0.702	3.6005	0.515942	156 ± 12
		Garnet2	4.742	1.137	2.5212	0.514857	157 ± 18

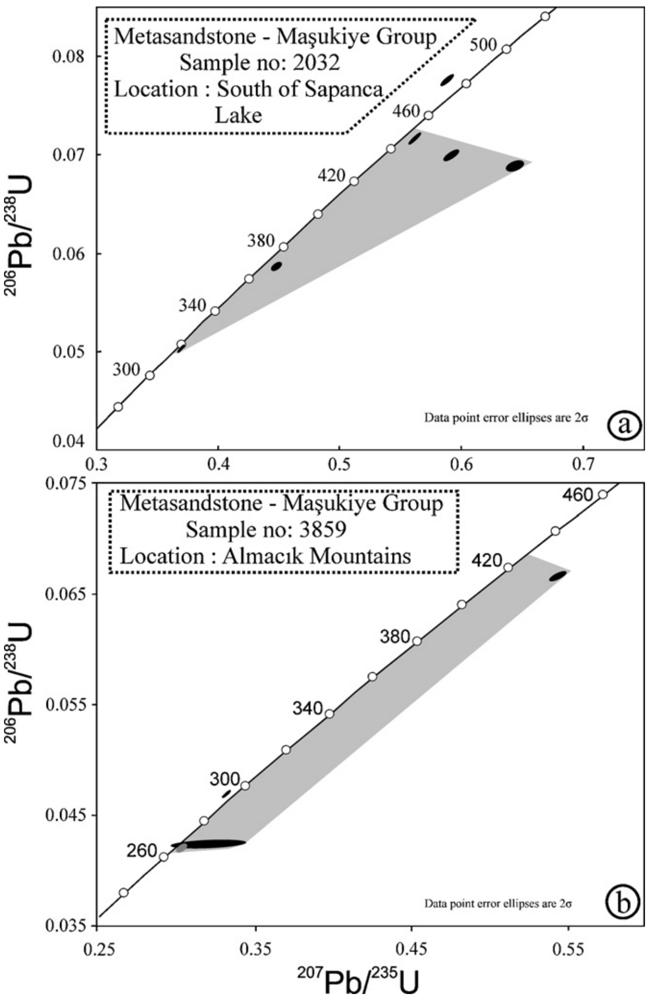

Fig. 10. U–Pb concordia diagrams of clastic zircons from south of Sapanca Lake (a) and Almacık Mountains (b) (see Figs. 3 and 4 for locations).

muscovite ± calcite assemblage. The metamorphic effects in these metasandstones are development of foliation, recrystallization of quartz into smaller polygonal grain aggregates and the formation of the muscovites along the cleavage planes. In sample 2663 secondary chlorite is also found. Metabasite lenses in the metaclastics contain"chlorite + albite + epidote + actinolite + phengite + leucoxene" mineral paragenesis, typical for the greenschist facies metamorphism (e.g., Laird, 1982; Maruyama et al., 1983). The Rb–Sr muscovite-whole rock age of sample 2032 is 138 ± 1.5 Ma and that of sample 2663 is 256 ± 9.5 Ma (Table 2). We interpret the older age as a mixed age with contamination by clastic mica. If this is the case, the sedimentation of the Maşukiye Group is younger than Late Permian (256 ± 9.5 Ma), possibly Triassic.

3.4. The Gemlik Mélange

The Neoproterozoic basement of İstanbul Zone (the Pamukova Complex) is imbricated with a tectonic mélange south of Sapanca Lake, called as the Gemlik Mélange (after Kaya and Kozur, 1987; Robertson and Ustaömer, 2004). The Gemlik Mélange crops out only in the southern part of the area mapped and it has no contacts with the other metamorphic units. Dextral strike-slip contacts, probably related the North Anatolian Fault, exist between the Gemlik Melange and the Campanian–Eocene cover units (Fig. 4). The mélange has an anchimetamorphic phyllite–metagreywacke matrix (comprise ~50% of all outcrops) with blocks of chert, marble, red pelagic limestone, mica-schist, basalt, metagabbro and minor serpentinite. In thin sections, metagreywacke-phyllite matrix shows pervasive deformation, shearing, foliation and quartz has recrystallized into subgrains, but degree of metamorphism is not strong enough to form metamorphic minerals. North of Geyve, block types are diverse as chert, marble, red pelagic limestone, mica-schist, basalt, metagabbro, and minor serpentinite, whereas north of Pamukova marble and chert blocks are common. Size of the marble blocks ranges from 2 cm to large olistoliths up to 1.1 km long 250 m wide. Kaya and Kozur (1987) described the Gemlik Mélange as an "olistostrome" north of Gemlik. The same authors

Table 5
Isotopic data from single zircon grain Pb/Pb evaporation analyses.

Zircon grains	Zircon features	Evaporation temp. (°C)	Number of ratios	$^{204}Pb/^{206}Pb$ ratio	$^{207}Pb/^{206}Pb$ ratio	$^{207}Pb/^{206}Pb$ ages and errors (Ma)
2031						
1	125–180 μm, medium, prismatic, brown	1380	187	0.000149	0.053491 ± 051	349.7 ± 2.2
		1400	93	0.000205	0.053371 ± 226	344.6 ± 9.7
		1420	35	0.000109	0.053671 ± 229	357.3 ± 9.7
2	125–180 μm, medium, prismatic, brown	1435	133	0.000359	0.053586 ± 097	353.7 ± 4.1
3	125–180 μm, medium, prismatic, brown	1420	114	0.000045	0.052374 ± 040	301.8 ± 1.7
4	63–125 μm, medium, idiomorphic, reddish brown	1380	138	0.000159	0.052712 ± 156	316.5 ± 6.8
5	63–125 μm, small, rounded and thick, light yellow	1400	127	0.000500	0.054932 ± 426	409.5 ± 17.9
6	~125 μm, big, idiomorphic, brown	1380	225	0.000197	0.053238 ± 054	339 ± 2.3
		1400	54	0.000078	0.053451 ± 097	348 ± 4.1
		1420	136	0.000077	0.053238 ± 068	359.7 ± 2.9
7	~125 μm, big, idiomorphic, brown	1380	143	0.001777	0.054867 ± 292	406.8 ± 12.2
		1400	152	0.001179	0.055398 ± 106	428.4 ± 4.3
8	~125 μm, big, idiomorphic, brown	1380	60	0.004789	0.055968 ± 106	451.1 ± 20.4
		1400	222	0.002333	0.053942 ± 111	368.6 ± 4.7
2032						
1	~125 μm, medium, idiomorphic, elongated, brown	1380	96	0.000643	0.052396 ± 253	302.8 ± 11.2
		1400	72	0.000450	0.052220 ± 228	295.1 ± 10.1
2	~125 μm, medium, idiomorphic, elongated, brown	1380	142	0.007695	0.058724 ± 320	556.9 ± 12.1
		1400	75	0.001104	0.056301 ± 096	464.3 ± 3.8
3	~125 μm, medium, idiomorphic, elongated, reddish brown, shows metallic luster	1380	66	0.000179	0.052231 ± 232	295.6 ± 10.3
		1400	184	0.000145	0.051940 ± 078	282.8 ± 3.4
		1420	96	0.000093	0.052332 ± 120	300 ± 5.3
4	~125 μm, medium, idiomorphic, elongated, brown	1380	108	0.000361	0.053998 ± 069	371 ± 2.9
		1400	111	0.000062	0.053998 ± 085	370.6 ± 3.6
		1420	176	0.000191	0.053304 ± 131	341.8 ± 5.7

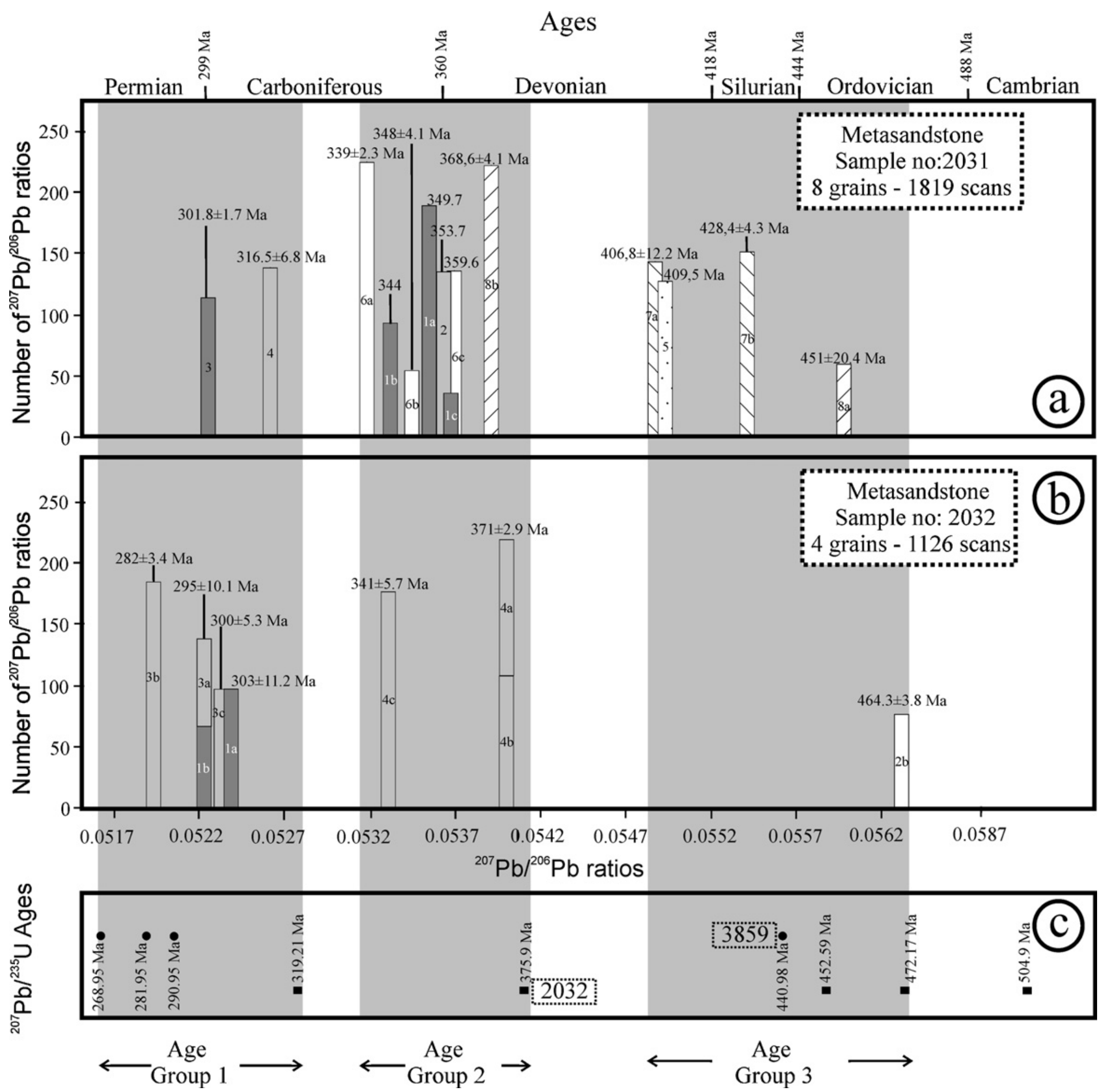

Fig. 11. (a) Histogram showing the distribution of ^{207}Pb/^{206}Pb ratios derived from the evaporation of single zircon grains of sample 2031 and (b) sample 2032. (c) U–Pb ages from the Maşukiye Group (from samples 2032 and 3859). Gray vertical columns refer to three main age groups derived from all clastic zircon analyses.

also reported a Late Jurassic–Early Cretaceous? radiolarian fauna from the cherts of the Gemlik Mélange. Göncüoğlu and Erendil (1990) and Robertson and Ustaömer (2004) also described the unit as a tectonic mélange.

3.5. Late Cretaceous–Tertiary Cover Units

South of Sapanca Lake, Upper Cretaceous and Lower Eocene sedimentary rock cover the older units unconformably (Akartuna, 1968). Göncüoğlu et al. (1987, 1992) reported that the oldest cover sediments are Cenomanian–Coniacian in age, but Bozcu (1992) and Yılmaz et al. (1995) report only Campanian–Maastrichtian ages. In our study we found the oldest unconformable unit as a Campanian–Maastrichtian thick sandstone-conglomerate-limestone sequence with *Orbitoides* sp. and *Siderolites* sp, however, the contacts between these sediments and the underlying metamorphic rocks are faulted (Figs. 3 and 4; Akbayram, 2011). There is also a Cenomanian–Santonian pelagic limestone-shale unit which has no exposed stratigraphic contacts (Fig. 3; Akbayram, 2011). A recent sedimentological study showed that first transgression over both İstanbul Zone and Sakarya Zone in the Armutlu Peninsula occurred in the Santonian (Fig. 5; Özcan et al., 2012).

4. Discussion

In the Armutlu Peninsula, geological evolution of the Intra-Pontide Ocean and the subsequent events can be evaluated in two phases. First one is the Early Triassic opening and Early Cretaceous closure of the Intra-Pontide Ocean and the second one is the post-orogenic compressional phase possibly related to the İzmir-Ankara Ocean closure farther south that ends with the uplift in the Armutlu Peninsula in the Early Eocene time (Zattin et al., 2010; Akbayram, 2011).

The Triassic metaclastics in the Armutlu Peninsula (the Maşukiye Group) were interpreted as the equivalent of the İstanbul Paleozoic sequence (Yılmaz et al., 1982) or were included in the Karakaya complex of the Sakarya Zone (Yılmaz et al., 1995; Robertson and Ustaömer, 2004). We suggest that these Triassic metasediments in the Armutlu Peninsula form the eastern continuation of metasediments exposed in the Strandja Massif. Both of these units show not only similar stratigraphies, but also similar depositional and metamorphic ages. In the Strandja Massif, the metasedimentary cover starts with continental sandstones, siltstones and conglomerates of Early Triassic age, which are overlain by Middle Triassic shallow marine carbonates

(Chatalov, 1988; Hagdorn and Göncüoğlu, 2007). This was followed by Late Jurassic–Early Cretaceous deformation and regional metamorphism (119–155 Ma; Okay et al., 2001; Elmas et al., 2011; Sunal et al., 2011). The Maşukiye Group also consists of arkosic metasandstones overlain by thickly bedded massive marbles with laminations suggesting a shallow marine origin. Zircon and clastic mica ages indicate that the arkosic metasandstones are Triassic or younger, which is in good agreement with earlier published Late Triassic conodont ages from the marbles (Önder and Göncüoğlu, 1989). The metamorphism also occurred during Late Jurassic–Early Cretaceous as shown by our Rb–Sr mica ages from all of the metamorphic units of the Armutlu Peninsula and the Almacık Mountains, similar to the metamorphic ages from the Strandja Massif (Okay et al., 2001; Elmas et al., 2011; Sunal et al., 2011). Along with these similarities, paleogeographical positions of İstanbul, Sakarya and Strandja terranes during Early Mesozoic interval also play a critical role. The Strandja Massif is located south of the Moesian platform before the Cretaceous opening of the Black Sea (Fig. 1, Okay et al., 1994). The İstanbul terrane was contiguous to Moesia and Scythian Platform, which exhibit similar stratigraphies (Fig. 1, Okay et al., 1994, 2006a,b). Therefore existence of the units of the Strandja Massif along the southern border of the İstanbul Zone is a strong possibility. Indeed in the regional map view, metasediments south of Sapanca Lake seems continuing through the Strandja Triassics (Fig. 3). An unmetamorphosed Triassic continental to shallow marine unit is also known in the İstanbul Zone (Yurttaş-Özdemir, 1971; Gedik, 1975) starting with Early Triassic conglomerates and basaltic lava flows (Kaya and Lys, 1981); these lavas probably represent the onset of rifting of the Intra-Pontide Ocean. Indeed, the Early Triassic is characterized by widespread rifting and mafic magmatism in the Eastern Mediterranean region, possibly associated with mantle plumes (e.g., Dixon and Robertson, 1999). In summary Triassic sedimentary units of the Pontides altogether probably represent the earlier passive margin sediments of the Intra-Pontide Ocean, deposited on the rift flanks of the basin. The age of the radiolarian chert blocks in the melanges of the Intra-Pontide suture showed that Intra-Pontide Ocean remained opened during the Late Jurassic (Kaya and Kozur, 1987). Late Jurassic (∼155 Ma) metamorphic ages show that the subduction of the Intra-Pontide Ocean had also been initiated during this time interval. Subduction was to the north because the basement the İstanbul Zone, which was located in the north, overlies the accretionary prism of the Intra-Pontide suture. All of the metamorphic units of the Intra-Pontide suture were metamorphosed during Early Cretaceous (between 135 and 110 Ma). The first regional transgression over İstanbul and Sakarya Zones also show that the Intra-Pontide Ocean must have been closed before Santonian (Özcan et al., 2012). This means that Early Cretaceous metamorphism was the latest metamorphic event along the Intra-Pontide suture zone that marks the collision between İstanbul and Sakarya terranes. While the basement of the İstanbul terrane was reheated during this collision, Paleozoic and Triassic rocks of the İstanbul terrane escaped this metamorphism probably because they were uplifted during Early Cretaceous.

5. Conclusion

The Intra-Pontide suture zone is the boundary between the İstanbul and the Sakarya terranes. Along this suture zone in the Armutlu Peninsula south of Sapanca Lake, three metamorphic units crop out forming an eastward dipping thrust stack. The oldest metamorphic unit is an epidote-amphibolite facies Neoproterozoic–Ordovician unit representing the basement of İstanbul terrane and cross-cutting granitoids (Yiğitbaş et al., 2001, 2004; Okay et al., 2008). The basement is thrusted over a greenschist facies Lower Cretaceous accretionary complex formed during the consumption of the Intra-Pontide Ocean. The third unit is a metaclastic-marble serie that possibly has a passive margin origin, which is tectonically overlain by the accreationary complex. Detrital zircon and mica geochronology shows that the metaclastic-marble unit was deposited after the Permian possibly during Triassic. This depositional age is confirmable with the Middle Triassic conodont ages from the marbles, overlying the clastics (Önder and Göncüoğlu, 1989). We interpret that these Triassic metasediments form the western continuation of Triassic metasediments of the Strandja Massif. All of the metamorphic units of the Intra-Pontide suture zone were metamorphosed during Late Jurassic–Early Cretaceous (158–110 Ma). Campanian and younger sediments unconformably overlie the metamorphic units of the Intra-Pontide suture zone, south of Sapanca Lake. The first regional transgression over İstanbul and Sakarya terranes show that the Intra-Pontide Ocean must be closed before Santonian (Özcan et al., 2012). Interpretation of the data indicates that the collision between the İstanbul and Sakarya–Strandja terranes occurred during Early Cretaceous and the Proterozoic basement of İstanbul terrane was reheated during this collision.

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Appendix A. Petrographic Descriptions of Dated Samples

A.1. Petrographic descriptions of samples from Pamukova Complex

Sample 3282 (Location: north of Geyve – UTM: 36 T/02°73′540″ N–44°94′805″ E) is an orthogneiss from the Neoproterozoic–Ordovician basement. The rock is made up of hornblende, plagioclase, biotite, epidote, quartz, chlorite, prehnite, pumpelliyite. The sericitization of the plagioclase and chloritization of biotite are common. Titanite and zircon are the accessory minerals. It was probably a quartzdiorite before the metamorphism.

Sample 3252 (Location: north of Pamukova – UTM: 36 T/03°61′997″ N–44°94′357″ E) is a cataclastic orthogneiss from the Neoproterozoic–Ordovician basement. The rock mainly made up of plagioclase, K-feldspar, muscovite, quartz and minor garnet. Titanite and pyrite are accessory phases. Chloritization of the muscovites and sericitization of the plagioclase are common. The rock is strongly altered. Garnets are idiomorphic and grow over the foliation.

Sample 3479 (Location: west of Pamukova – UTM: 36 T/02°54′813″ N–44°89′160″ E) is a metagranitic dyke in the Neoproterozoic–Ordovician basement. The sample is leucocratic and medium-grained. Main constituents are plagioclase, K-feldspar, muscovite, garnet and quartz. Titanite, zircon and apatite are accessory minerals. Quartz shows recrystallization textures such as subgrains whereas magmatic texture of plagioclase is preserved. Muscovite and garnet are idiomorphic and larger than the other minerals (muscovites up to 3 mm wide and garnets up to 0.5 mm thick).

Sample 3483 (Location: west of Pamukova – UTM: 36 T/02°53′739″ N–44°88′602″ E) is a metagranitic dyke in the gneiss–amphibolite unit of the Neoproterozoic basement. The petrography of the sample is very similar to sample 3479, however this sample does not comprise garnet. This sample has very large muscovite minerals (up to 7 mm wide), which were picked for dating in the field.

Sample 3263 (Location: northeast of Pamukova – UTM: 36 T/02°57′534″ N–44°92′451″ E) is a calc-schist marble from the Neoproterozoic–Ordovician basement. Calcite is the main constituent. Secondary chlorite and epidote also observed in thin section.

Sample 3873 (Location: Almacık mountains – UTM: 36 T/03°27′109″ N–44°95′920″ E) is a garnet-biotite schist from Neoproterozoic–Ordovician basement. The main constituents of this sample are idiomorphic garnet, biotite, hornblende and plagioclase. The schistose texture is very well preserved in thin section.

Sample 3902 (Location: north of Gemlik – UTM: 36 T/06°75′703″ N–44°83′404″ E) is a gneiss from Neoproterozoic basement and mainly made up of plagioclase, hornblende, biotite, quartz and feldspars. The sericitization of the plagioclases and alteration of hornblendes are common. Titanites and zircons are the accessory minerals.

A.2. Petrographic descriptions of samples from Maşukiye Group

Sample 2032 (south of Maşukiye – UTM: 36 T/02°58′849″ N–45°06′291″ E) is a white, well-foliated arkosic metasandstone from Triassic metasediments. The rock is mostly made up of quartz, plagioclase, K-feldspar, muscovite and minor calcite. Muscovites are usually lies along the cleavage planes.

Sample 2663 (south of Maşukiye – UTM 36 T/02°62′075″ N–44°94′201″ E) is also white, well-foliated arkosic metasandstone from Triassic metasediments, mostly made up of quartz, plagioclase, K-feldspar and muscovite with secondary chlorite and zircon as accessory.

A.3. Petrographic description of sample from Sapanca Complex

Sample 3428 is a fine-grained phyllite from the metabasite-phyllite unit. Mineral parageneses of the sample is muscovite + quartz + albite.

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