Int J Earth Sciences (Geol Rundsch) (2001) 90:257–269
DOI 10.1007/s005310000129

ORIGINAL PAPER

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Ophiolite emplacement by strike-slip tectonics between the Pontide Zone and the Sakarya Zone in northwestern Anatolia, Turkey

Received: 18 August 1999 / Accepted: 10 July 2000 / Published online: 15 March 2001

Abstract Northwestern Anatolia contains three main tectonic units: (a) the Pontide Zone in the north which consists mainly of the İstanbul–Zonguldak Unit in the west and the Ballıdağ-Küre Unit in the east; (b) the Sakarya Zone (or Continent) in the south, which is juxtaposed against the Pontide Zone due to the closure of Paleo-Tethys prior to Late Jurassic time; and (c) the Armutlu–Ovacık Zone which appears to represent a tectonic mixture of both zones. These three major tectonic zones are presently bounded by the two branches of the North Anatolian Transform Fault. The two tectonic contacts follow older tectonic lineaments (the Western Pontide Fault) which formed during the development of the Armutlu–Ovacık Zone. Since the earliest Cretaceous, an overall extensional regime dominated the region. A transpressional tectonic regime of Coniacian/Santonian to Campanian age caused the welding of the İstanbul–Zonguldak Unit to the Sakarya Zone by an oblique collision. In the Late Campanian, a transtensional tectonic regime developed, forming a new basin within the amalgamated tectonic mosaic. The different tectonic regimes in the region were caused by activity of the Western Pontide Fault. Most of the ophiolites within the Armutlu–Ovacık Zone belong to the Paleo-Tethyan and/or pre-Ordovician ophiolitic core of the İstanbul–Zonguldak Unit. The Late Cretaceous ophiolites in the eastern parts of the Armutlu–Ovacık Zone were transported from Neo-Tethyan ophiolites farther east by left-lateral strike-slip faults along the Western Pontide Fault. There is insufficient evidence to indicate the presence of an ocean (Intra-Pontide Ocean) between the İstanbul–Zonguldak Unit and the Sakarya Zone during Late Cretaceous time.

Keywords Intra-Pontide Ocean · Strike-slip tectonics · Paleo-Tethys · Neo-Tethys · Northwest Anatolia

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Introduction

Two tectonostratigraphically diverse entities are distinguished in northwestern Anatolia: (a) a northern area termed the Rhodope-Pontide Continent, or the Pontide Zone; and (b) a southern area termed the Sakarya Zone (or Continent). The Pontide Zone is represented mainly by the İstanbul–Zonguldak Unit in this region (Figs. 1a,b). The area extending along the Armutlu Peninsula through Bolu to Ovacık between the Sakarya Zone and İstanbul–Zonguldak Unit is called the Armutlu–Ovacık Zone (Figs. 1b,c). According to Şengör and Yılmaz (1981), this Zone represents a suture belt of a seaway, the Intra-Pontide Ocean, which existed in Late Cretaceous time and closed by northward-directed subduction. This interpretation is based on the existence of the Arkotdağ mélange (Tokay 1973) and Abant complex (Yılmaz et al. 1981). Göncüoğlu and Erendil (1990) proposed instead that the Intra-Pontide Ocean was closed by an oblique collision; however, these complex units and their stratigraphic characteristics have not been sufficiently described, and understanding is hindered by data indicating conflicting ages and environments (Elmas et al. 1997; E. Yiğitbaş and A. Elmas, unpublished data).

The hypothetical west/east-extending Intra-Pontide Ocean thought to flank the İstanbul–Zonguldak Unit to the south as a gulf of the Vardar Ocean cannot be traced farther east (Okay et al. 1996). Furthermore, Kaya and Kozur (1987) do not accept the presence of the Intra-Pontide suture belt.

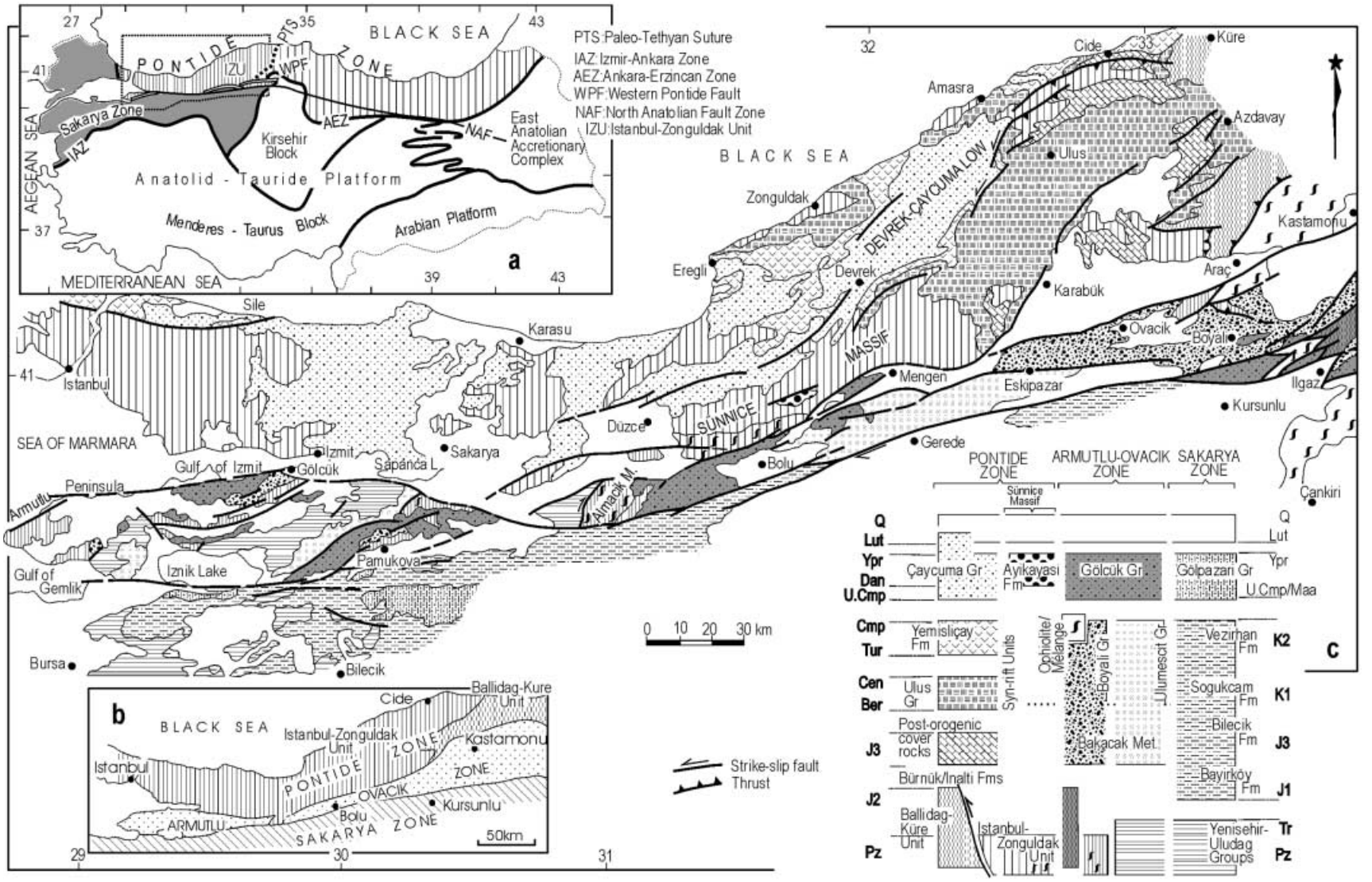


Fig. 1 **a** The major tectonic zones of Turkey separated by sutures (modified from Şengör and Yılmaz 1981; Yılmaz et al. 1997). The Pontide Zone is shown as vertical rules. The İstanbul–Zonguldak Unit in the western part of the Pontide Zone is shown as dense vertical rules. Sakarya Zone (or Continent) is shown as the shaded region. Armutlu–Ovacık Zone lies between İstanbul–Zonguldak Unit and Sakarya Zone. The *quadrangle* indicates the location of Fig. 1c; **b** major tectonic zones of the northwestern Anatolia and the units which comprise the Pontide Zone (after Yiğitbaş et al. 1999); **c** geological map of the northwestern Anatolia and generalized stratigraphy. Stratigraphic and lithological descriptions of the units are given in Fig. 2

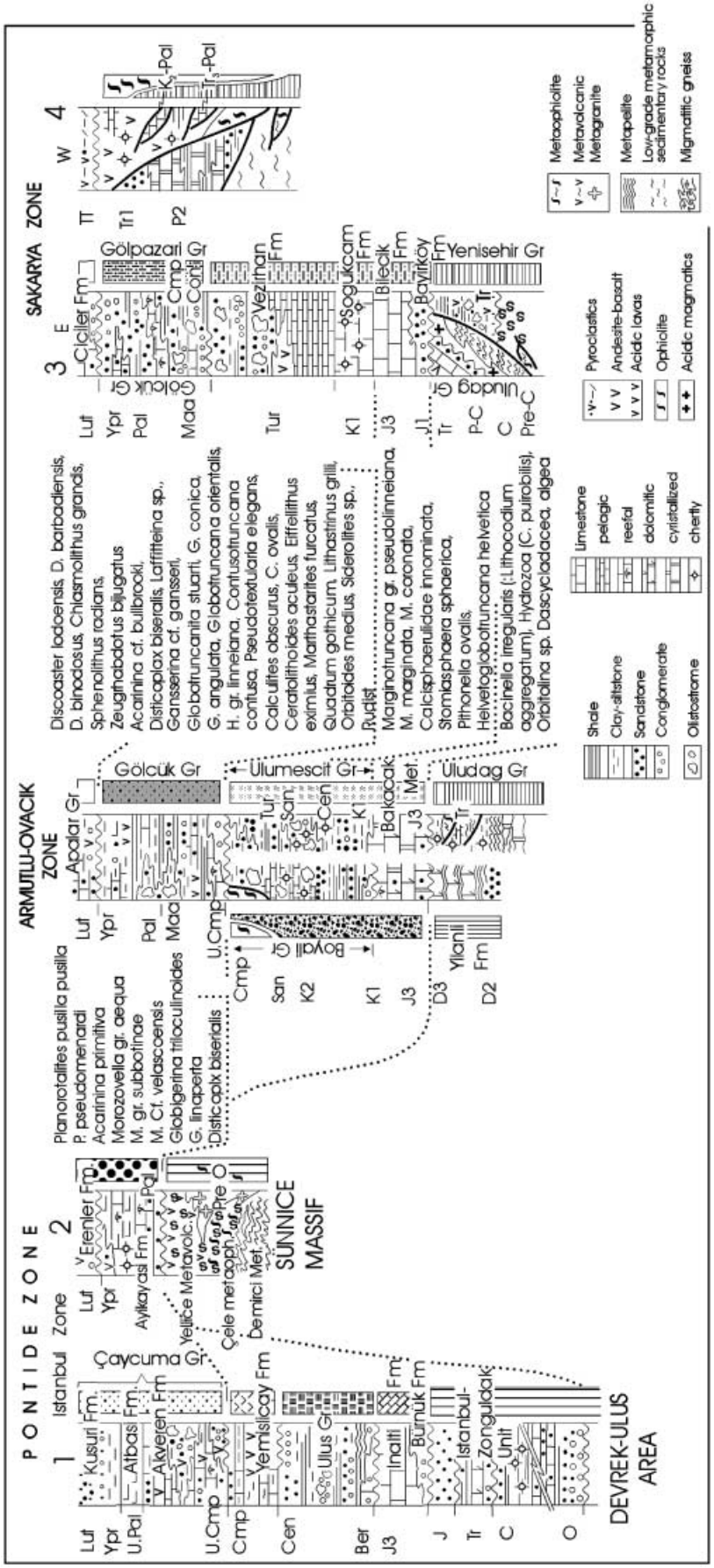


Fig. 2 Stratigraphic correlation of the tectonic units in Northwestern Anatolia. *Numbers* indicate the location of the stratigraphic sections in Fig. 3. The narrow columns beside the stratigraphic sections show the map pattern of the rock units in the Fig. 1c

The purpose of this paper is to contribute to the arguments concerning the nature of the Intra-Pontide Ocean on the basis of our recent field data from the Armutlu–Ovacık Zone.

The Pontide Zone

The western part of the Pontide Zone is represented by the İstanbul–Zonguldak Unit. This tectonic subunit of the Pontide Zone is bounded by the Black Sea to the north, the Istranca massif that is hidden under Middle–Upper Eocene clastics to the west, and the Armutlu–Ovacık Zone to the south. Its eastern contact is a thrust carrying the İstanbul–Zonguldak Unit southward over the pre-Late Jurassic units comprising the eastern Pontides (Ballıdağ-Küre Unit; Yiğitbaş et al. 1999) which consist of an ophiolite-mélange association and related sediments. The Ballıdağ-Küre Unit represents a remnant of Paleo-Tethys.

The lower parts of the İstanbul–Zonguldak Unit stratigraphic succession are represented by a high-grade metamorphic assemblage exposed in the Sünnice massif and Almacık Mountain (Figs. 1c, 2). They consist of three different rock units: (a) granitic-migmatitic rocks (Demirci metamorphic association); (b) an ordered ophiolitic assemblage (Çele metaophiolite); and (c) a volcanic-volcaniclastic succession (Yellice metavolcanic association; Yiğitbaş et al. 1999).

The three different metamorphic associations are collectively overlain by a thick sedimentary succession ranging in age from Early Ordovician to Carboniferous (Packelmann 1938; Görür et al. 1997; W.T. Dean et al., unpublished data). The Paleozoic sequence is overlain by Triassic continental to shallow marine clastics and limestones (Çakraz Formation) that are unconformably overlain by the Middle Jurassic clastics (Himmetpaşa Formation; Derman et al. 1995). These units are commonly termed the İstanbul–Zonguldak Unit sensu stricto.

Continental-fluvial clastics (Bürnük Formation) and shallow marine carbonates (İnaltı Formation), ranging in age from Callovian to Berriasian (Derman 1990), are the common cover units of the İstanbul–Zonguldak Unit and Ballıdağ-Küre Unit (Şengör and Yılmaz 1981; Yiğitbaş et al. 1999). The eastern parts of the western Pontides are unconformably covered by a Lower to Upper Cretaceous flysch–wildflysch sequence, the Ulus Group, which is succeeded by pelagic limestones with chert interbeds. The Ulus Group is conformably overlain by a pelagic volcanic-volcaniclastic sequence known as the Yemişliçay Formation, which is of Turonian-Campanian age (Aydın et al. 1986; E. Yiğitbaş and A. Elmas, unpublished data).

During the Late Campanian, a new tectonic regime marked by a sedimentary transgression was initiated in the region. Central and western parts of the western Pontides were almost covered by the Akveren Formation and its equivalent units. This was followed by accumulation of clastic deposits (Atbaşı Formation; Paleocene) and flysch (Kusuri Formation; Lower Eocene); thus, the deposition continued in many parts of the western Pontides until the end of Early Eocene time (Fig. 2).

The Sakarya Zone

The Sakarya Zone, situated to the south of the İstanbul–Zonguldak Unit, is bounded on its southside by the İzmir–Ankara suture (Fig. 1a). The basement of the Sakarya Zone consists of two different metamorphic associations (Fig. 2; Yılmaz et al. 1981). One is Uludağ Group that is composed of high-grade schists, gneisses, amphibolites and migmatites intruded by a granitic pluton of Carboniferous age (Yılmaz et al. 1997); these are unconformably overlain by arkoses (Cambazkaya Formation), shallow-marine Permian limestones (Derbent Limestone; Altınlı 1973) and shallow to deep marine Triassic carbonates and clastics (Karakaya Formation; Bingöl et al. 1973) which are also imbricated with ophiolitic rocks (Tekeli 1981). The second unit is the Yenişehir Group which is composed of a metaophiolite and a metamorphosed volcanic-sedimentary unit. These underwent glaucophane-bearing greenschist facies metamorphism during Late Triassic time (Yılmaz 1977; Genç 1993).

The two metamorphic associations are collectively overlain by a transgressive Liassic to Turonian sequence. This sequence is composed of Liassic fluvial deposits (Bayırköy Formation), and shallow-marine carbonates of Middle to Upper Jurassic age (Bilecik Formation), Lower Cretaceous cherty limestones (Soğukçam Formation) and radiolarian cherts and pelagic limestones of Cenomanian–Turonian age (Vezirhan Formation).

Shallow-marine limestones of Late Jurassic to Turonian age grade northward to pelagic and olistostromal units. A flysch sequence represented by proximal and intermediate turbidites and comprising the Gölpazarı Group conformably overlies the shallow water deposits and ranges in age from Coniacian through Campanian. In contrast, it overlies the pelagic and olistostromal deposits unconformably, and yields Campanian–Maastrichtian fossils. This contrast is an indication of significant tectonic activity and erosion during Coniacian–Santonian time prior to flysch sedimentation (Yılmaz et al. 1994). The flysch sequence passes upward into shallow-marine sandstone and limestones. Beginning in Middle Eocene time, shallow marine carbonate and clastics were deposited, the products of a new regional transgression on the Sakarya Zone (Yılmaz et al. 1994).

The sequence in the western part of Sakarya Continent (in Biga peninsula)

The basement of the Biga peninsula between Edremit Bay and the Sea of Marmara (Fig. 3) is represented by a quartz-micaschist unit. This unit contains calcschist, marble, metaquartzite, albite–chlorite schist levels, and serpentinite slices parallel to foliation. An Upper Permian–Lower Triassic unit in tectonic contact with this basement sequence is represented by metashale–phyllite, quartzite and calcschist at the base. The upper parts of the sequence consist of recrystallized limestone-shale alternations, shallow-marine limestones, and metamorphosed flysch (Okay et al. 1990). The entire sequence is the equivalent of the pre-Liassic basement in other parts of the Sakarya Zone. These rocks are overlain by an ophiolitic mélange containing slices of garnet-micaschist and shallow-marine to pelagic limestones ranging in age from Late Triassic to Middle Paleocene. $^{40}Ar/^{39}Ar$ isotopic ages were obtained from amphiboles at the base of peridotite slices overlying the Permian carbonates at a locality north of Ezine, and these indicate that imbrication of the ocean floor began in Aptian time (118 Ma; Okay et al. 1996). Tertiary volcanic-volcaniclastic deposits overlie all these units (Fig. 2).

The Armutlu–Ovacık Zone

The west/east-trending Armutlu–Ovacık Zone is ~20–50 km wide, and lies between the Pontide Zone and the Sakarya Zone (Figs. 1b, 3). The contacts with both these zones are marked by faults.

The area between the gulfs of Gemlik and İzmit

The basement between Gemlik and İzmit gulfs (Figs. 1, 3) consists of metagabbro-amphibolite, metabasite, acidic metalava, metavolcaniclastic, and metasedimentary rocks which are cut by migmatitic granites (Y. Yılmaz et al., unpublished data; Yiğitbaş et al. 1999). They are unconformably overlain by a sequence consisting of quartzite–quartzitic conglomerate in the lower part and gray–black–purple colored recrystallized limestone–phyllite alternations in the upper part. These rocks are the lithological equivalent of parts of Ordovician–Carboniferous component of the İstanbul–Zonguldak Unit in areas farther north (Kaya 1977). North of the Gulf of Gemlik, this sequence is unconformably overlain by low-grade metamorphosed conglomerate and sandstone containing granite, amphibolite, and marble pebbles (Fig. 3a). The unit passes upward into a sequence composed of gray–green sandstones and recrystallized limestones intercalated with black mudstone and shale (Göncüoğlu and Erendil 1990). Maastrichtian shallow marine deposits and Lutetian volcaniclastic units rest unconformably on the top.

The area between the Gulf of Gemlik-İznik Lake and Sapanca Lake

The basement of this area (Figs. 1c, 3) consists of metalava, graphite-schist, and metaclastics interbedded with recrystallized limestones (Göncüoğlu and Erendil 1990). These are unconformably overlain by a Permo-Triassic marble sequence (Orhangazi marble; Kaya and Kozur 1987). A unit consisting of basic volcanic rocks, volcaniclastics and olistostromes unconformably rests on the marble sequence. Conodonts obtained from lime mudstones in the upper parts of the unit indicate a Late Triassic age (Önder and Göncüoğlu 1989). The greenschist facies metamorphic unit is the equivalent of the Triassic Karakaya Formation (Yılmaz et al. 1994) which is widely exposed in the Sakarya Zone. This unit passes upward into white, recrystallized, cherty limestones (Göncüoğlu and Erendil 1990). Also, in the area between the Gulf of Gemlik and İznik Lake, these limestones unconformably lie on the metavolcanics and metaclastics-marble of the Karakaya Formation (Fig. 3b). The presence of gastropods, pelecypods, and algae in the limestone (Kaya 1977) indicate a shallow-marine shelf environment. The unit passes upward into a sequence composed of low-grade metamorphic basic volcanics and cherty pelagic lime mudstones which are interbedded with mudstone–shale–turbiditic sandstone. The sequence also contains serpentinite and recrystallized limestone blocks. Kaya and Kozur (1987) obtained fossils of Jurassic to Turonian age from the cherty levels in this unit. All these units are unconformably overlain by the Upper Campanian–Ypresian reefal limestone-shallow marine clastics and Lutetian deposits (Fig. 3b). In addition, cataclastic ophiolitic units are observed to the south of Sapanca Lake (Fig. 1c). Hovewer, the relation of the ophiolitic units with the other units in the area cannot be observed except with the Upper Campanian–Maastrichtian Unit which overlies them.

The northern areas of Pamukova

Similar to the area between the gulfs of Gemlik and İzmit, the basement north of Pamukova (Fig. 1c) is composed of metaophiolite, amphibolite, as well as metavolcanic and metaclastic rocks (Fig. 3c). These units are cut by gneissic granitoids (Göncüoğlu and Erendil 1990; Y. Yılmaz et al., unpublished data). They are overlain by a sequence which consists of purple-colored quartzitic sandstone at the base, followed by phyllite, and brecciated dolomitic marbles at the top. The entire sequence is equivalent to the Early Ordovician–Carboniferous sequence and underlying pre-Ordovician metamorphic basement of the İstan-

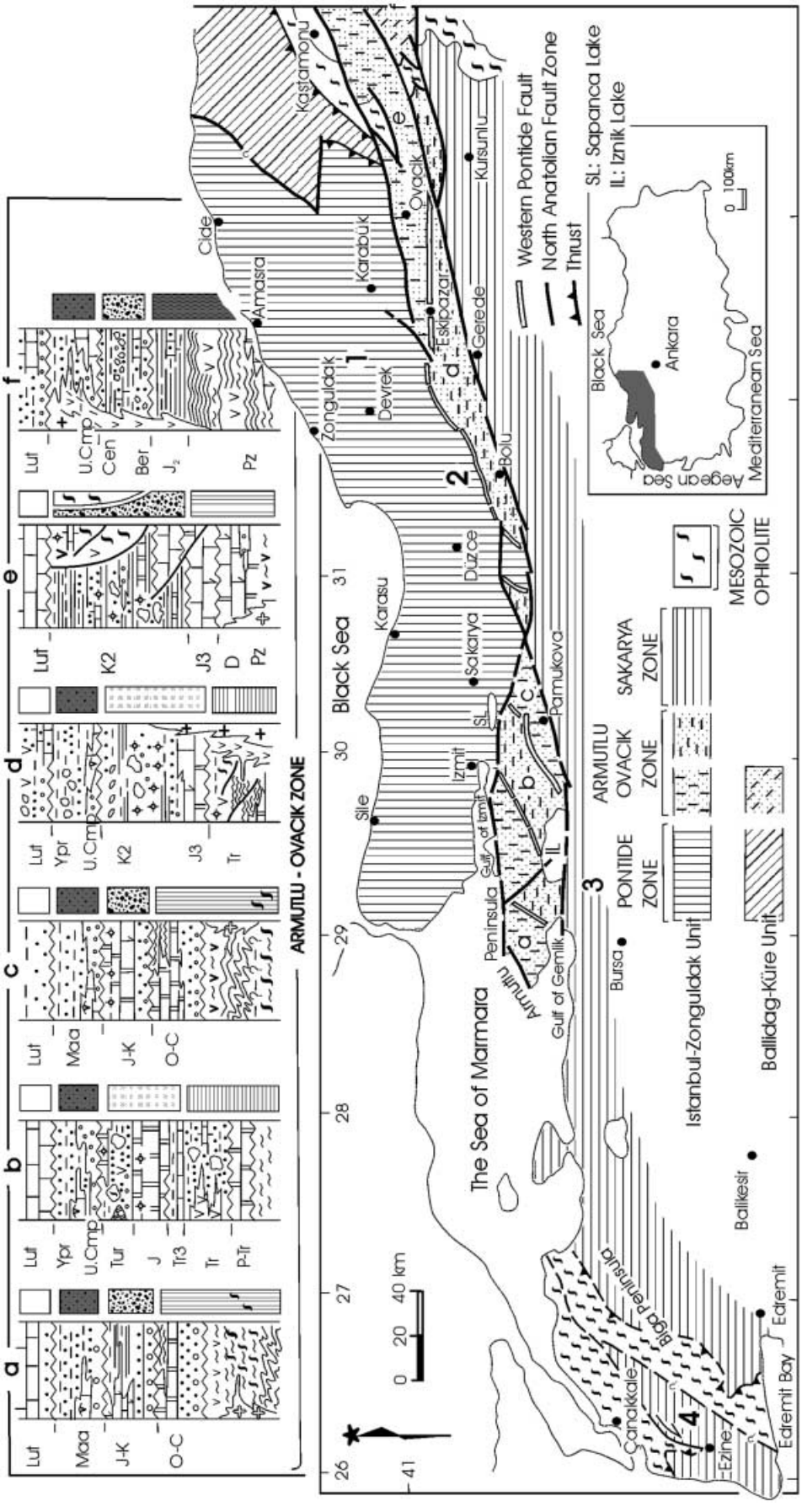


Fig. 3 Representative stratigraphic sections and their locations from the different parts of the Armutlu–Ovacık Zone. *Letters* indicate the locations of the stratigraphic sections. See Fig. 2 for lithological description. *Numbers* indicate the locations of the stratigraphic sections in Fig. 2. The narrow columns beside the stratigraphic sections show the map pattern of the rock units in the Fig. 1c

bul–Zonguldak Unit in the north (Fig. 2) and to the rocks in the area between the gulfs of Gemlik and İzmit to the west (Fig. 3a). The metamorphic units are unconformably overlain by clastic rocks that pass upward into dolomite and recrystallized limestone with chert interbeds (Göncüoğlu and Erendil 1990). All these units are overlain by Maastrichtian reefal limestones and succeeding turbiditic deposits (Fig. 3c).

The area between Bolu and Eskipazar

The basement in this area is represented by greenschist metamorphic rocks (Fig. 3d). They consist of metabasite, slate-phyllite, calcschist, gneiss, metachert, felsic metalava, metaophiolite, and metagranite (the Ağalar metamorphic association; E. Yiğitbaş and A. Elmas, unpublished data). The sequence was intensely affected by polyphase deformation and tectonic imbrication, and metamorphic foliation and crenulation cleavage are well developed; however, the stratigraphic characteristics within each thrust slice are recognizable. Similar to the area between the Gulf of Gemlik-İznik Lake and Sapanca Lake, the origin and type of these rocks differ from the metamorphic association in the Sünnice massif (Fig. 1c) where the basement units of the İstanbul–Zonguldak Unit are exposed.

This metamorphic association is overlain by a thick marble sequence of Late Jurassic–Early Cretaceous age (Bakacak metamorphics), the metamorphic equivalent of the Bilecik Formation in the Sakarya Zone (E. Yiğitbaş and A. Elmas, unpublished data). The marble sequence passes upward into low-grade metasediments of Cretaceous age (Ulumescit Group; E. Yiğitbaş and A. Elmas, unpublished data) which contain a weakly developed foliation without significant neo-mineralization. These metamorphic features decrease upwards. The lower parts of the unit consist of red-colored flyschoid clastics which pass rapidly upward into pelagic deposits which consist of thin-bedded chert, mafic lavas and red mudstone–limestone with blocks which belong to Mesozoic units from the Sakarya Zone and their metamorphic equivalents in the Armutlu–Ovacık Zone. Ophiolite blocks become more abundant east of Eskipazar. The features of lower and middle parts of the Ulumescit Group indicate a deepening marine depositional environment. The upper part of the sequence is composed of plant-bearing turbiditic sandstone–submarine channel to fluvial deposits.

Upper Cretaceous and older units of the Armutlu–Ovacık Zone are generally overlain with an angular unconformity by an Upper Campanian–Ypresian sedimentary sequence (Fig. 2; Gölcük Group; A. Elmas and E. Yiğitbaş, unpublished data). Between Bolu and Eskipazar, this sequence begins with debris flows that are likely slope deposits and continue upward into Upper Campanian reefal limestone–sandstone units (Fig. 3d). The sequence deepens rapidly in the upper part and passes into turbiditic flysch that contains some blocks in its upper part where it takes on a regressive aspect. The nanoplankton assemblage obtained from the matrix of this unit indicates an Upper Maastrichtian–Paleocene age (A. Elmas and E. Yiğitbaş, unpublished data). The uppermost part of the sequence is composed of plant-bearing sandstones. The abrupt lateral and vertical transitions within Cretaceous–Lower Eocene rocks are ascribed to intensive tectonism.

East of Ovacık

The basement in the eastern parts of the Armutlu–Ovacık Zone (Figs. 1c, 3) consists of gneiss, amphibolite, slate-phyllite, quartzite and brecciated Devonian dolomite-calcschist which is intruded by granite. Upper Jurassic limestone covers the İstanbul–Zonguldak Paleozoic sequence (Fig. 3e) and is overlain unconformably by a sequence which consists of interbedded dark-gray lime mudstone–marl–sandstone-shale. The sequence contains wave ripples, burrows and cut-and-fill structures and passes upward into an Upper Cretaceous pelagic sequence composed of block-bearing radiolarite, chert, red lime mudstone with manganese nodules and mafic lavas. The blocks are derived from non-metamorphic Cretaceous ophiolite and units of the İstanbul–Zonguldak Unit. The cataclastically altered units adjacent to the tectonic lineaments are overturned toward the south–southwest. All lithological characteristics indicate that the unit is equivalent of Ulumescit Group to the west. The Jurassic–Upper Cretaceous units in the Armutlu–Ovacık Zone are underlain by units belonging to either İstanbul–Zonguldak Unit or Sakarya Zone (named Boyalı and Ulumescit Groups, respectively; Fig. 2). Northeast of Kurşunlu, the equivalents of the Upper Cretaceous pelagic sequence overlie Lower Cretaceous cherty limestones (Soğukçam Limestone) of the Sakarya Zone.

To the east of Ovacık, the units of Armutlu–Ovacık Zone are tectonically bounded by parts of an ophiolitic suite (Figs. 1c, 3e). South–southwest verging thrust faults that extend WNW to ESE are common in the ophiolitic units. Each tectonic slice is composed of ultrabasite, serpentinite and gabbro at the bottom, and basic lava, pelagic limestone–mudstone, argillaceous lime mudstone intercalated with quartzitic–volcaniclastic sandstone at the top. A nanoplankton assemblage from lime mudstone levels indicates a Late Cretaceous age (A. Elmas and E. Yiğitbaş, unpublished data); these are unconformably overlain by Lutetian clastics.

Ilgaz area

The equivalents of the Ballıdağ-Küre Unit of the eastern Pontide Zone are also present in the eastern part of Armutlu–Ovacık Zone (northeast of Ilgaz; Figs. 1c, 3). This sequence, which consists of metalava, marble-dolomite and slate-phyllite, is unconformably overlain by Lower Cretaceous shallow marine clastics which are equivalents of the basal part of the Boyalı Group to the east of the Armutlu–Ovacık Zone. All the units are unconformably overlain by Upper Campanian shallow marine deposits and volcaniclastics which are intruded by felsic-intermediate rocks (Fig. 3f).

Discussion and evolution

Pre-Late Cretaceous evolution of the northwestern Anatolia

In light of the foregoing data, it is clear that the pre-Jurassic basement of the İstanbul–Zonguldak Unit and Sakarya Zone are different from each other. The pre-Ordovician basement of the İstanbul–Zonguldak Unit, metamorphosed to amphibolite grade facies, is covered by an Ordovician–Carboniferous transgressive sequence and cut by metagranites. With the Paleozoic units of the İstanbul–Zonguldak Unit bounded by a right-lateral strike slip fault (the Western Black Sea Fault; Okay et al. 1994) of pre-Eocene age which juxtaposed it against the Istranca Zone to the west, these Paleozoic rocks do not belong to other parts of northwestern Turkey; instead, they are similar to units of the Laurasian margin and thus represent south-facing passive continental margin deposits (Hass 1968). The origin and the initial tectonic positions of the major zones of the Pontides are compatible with the Late Paleozoic paleogeographic reconstructions that show a large oceanic realm, Paleo-Tethys, in this region (Şengör 1987; Scotese et al. 1979; Smith et al. 1981). This ocean closed before the Malm in the Pontides (Şengör et al. 1980; Şengör and Yılmaz 1981; Tüysüz 1990).

By contrast, the Sakarya Zone to the south has a low-grade metamorphic upper Paleozoic basement, the Ordovician–Carboniferous sequence is not present, and there is a sequence of Triassic rocks (Karakaya Formation; Bingöl et al. 1973) which is not present in the İstanbul–Zonguldak Unit (Şengör et al. 1984). The Karakaya Formation consists of increasingly deeper marine deposits and ocean-floor assemblages (Yılmaz 1981). The basin was short lived and closed during the latest Triassic (Bingöl et al. 1973).

The Armutlu–Ovacık Zone, bounded tectonically by the İstanbul–Zonguldak Unit and the Sakarya Zone, appears to represent a tectonic mixture of both zones. Each area within the Armutlu–Ovacık Zone contains basement units and the metamorphic-cataclastic equivalents of the Upper Jurassic–Upper Cretaceous units from the other two zones. In the Armutlu–Ovacık Zone the equivalents of the basement of İstanbul–Zonguldak Unit, derived from Laurasia (Kerey 1984; Şengör 1987), are present between the gulfs of Gemlik and İzmit, north of Pamukova, and east of Ovacık (Figs. 3a,c,e). Pieces of the Gondwanan basement of Sakarya Zone are present between the Gulf of Gemlik, İznik lake and Sapanca lake, and around Bolu-Eskipazar in the Armutlu–Ovacık Zone (Fig. 3b,d).

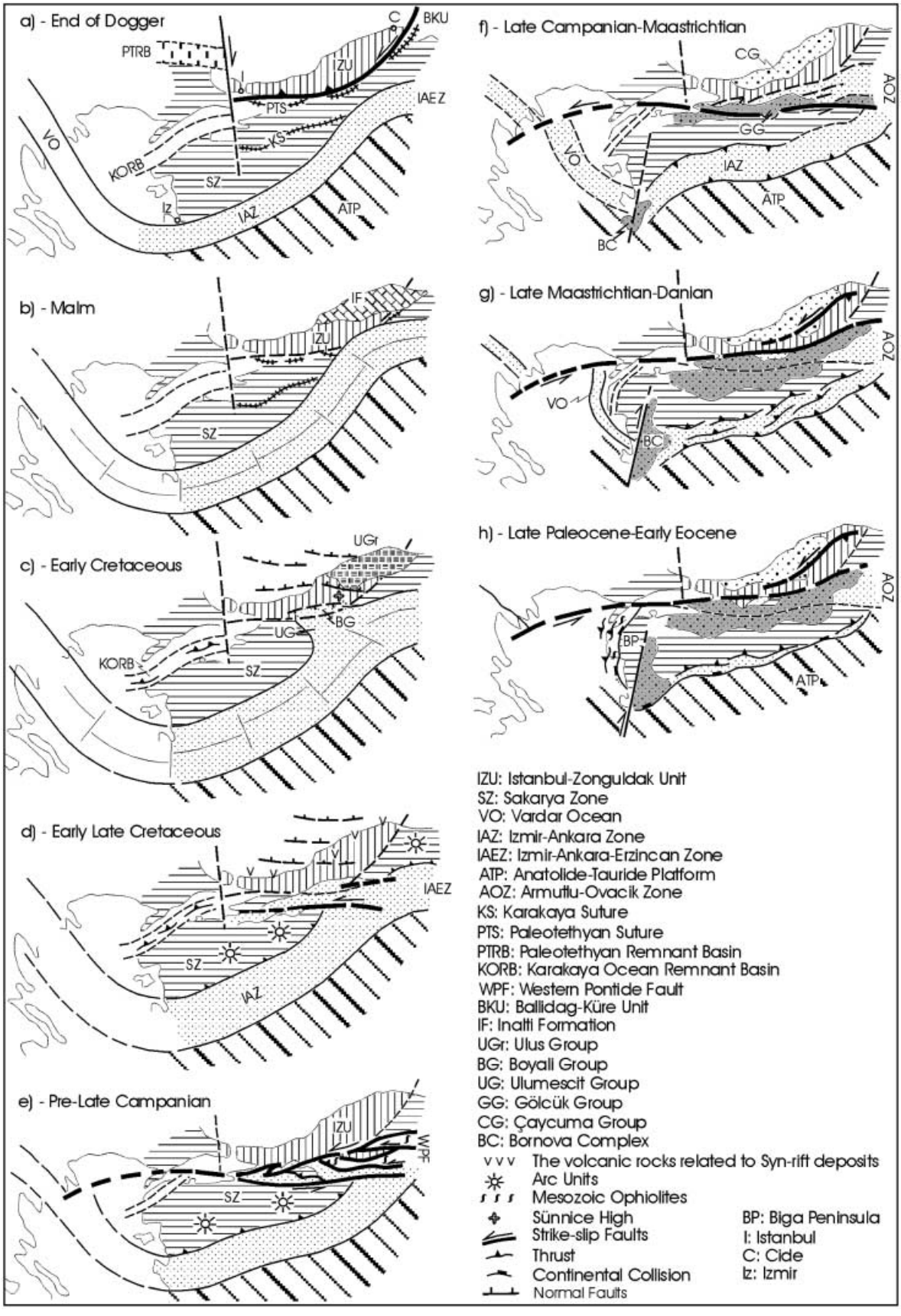
Fig. 4a–h Paleotectonic maps depict the tectonic evolution of northwestern Anatolia and surroundings from the Dogger to the Eocene

The Upper Jurassic carbonates and clastics (Kayalı and Cihatlı limestones, Kaya and Kozur 1987; Bakacak metamorphics, E Yiğitbaş and A. Elmas, unpublished data) are the first cover strata common to all the different basement rocks in the Armutlu–Ovacık Zone. The equivalents of the Upper Jurassic units of the Armutlu–Ovacık Zone are known in the Pontides as the Bürnük and İnaltı formations and in the Sakarya Zone the Bilecik Formation. This indicates that the İstanbul–Zonguldak Unit and the Sakarya Zone were juxtaposed prior to Late Jurassic time (Fig. 4a) by a closing of this part of Paleo-Tethys. With this conclusion, the Intra-Pontide suture is regarded as a remnant of the Paleo-Tethyan ocean floor. In the western areas of the İstanbul–Zonguldak Unit, which are bounded by the West Black Sea Fault on the west (Okay et al. 1994), the Paleotethyan Ocean might have survived later.

To the south, the Karakaya Ocean did not close in Late Jurassic–Early Cretaceous time (Figs. 4b,c), because the initial intra-ocean ophiolite obduction did not occur until the end of Early Cretaceous time (Okay et al. 1996). Likewise, Altıner and Koçyiğit (1992) suggested that the terrigeneous clastics in the Edremit-Balya region (west of the Biga Peninsula) of the Sakarya Zone were continuously deposited during Triassic–Jurassic time. In addition, they proposed the presence of a basin, a remnant probably from the Karakaya orogenesis, and the presence of a transgressive sequence developed in Middle Hettangian time that lay above the remains of Karakaya orogen.

The Jurassic units were overlain by the Lower Cretaceous–Campanian sequence, known as the Ulus Group and Yemişliçay Formation in the Pontides and the Soğukçam and Vezirhan formations in the Sakarya Zone. The Cretaceous units are represented by the Ulumescit and Boyalı groups in the Armutlu–Ovacık Zone.

It is known that a Neo-Tethyan suture zone lies between the Sakarya Zone and the Menderes-Taurus Block comprising southern Turkey (Şengör and Yılmaz 1981; Fig. 4). On the other hand, Şengör and Yılmaz (1981) and Yılmaz et al. (1994) suggested that the ophiolite slices in the Intra-Pontide suture


a) - End of Dogger
PTRB
C
BKU
IZU
PTS
IAEZ
VO
KS
KORB
SZ
Iz
IAZ
ATP
b) - Malm
IF
IZU
SZ
c) - Early Cretaceous
UGr
BG
UG
KORB
SZ
d) - Early Late Cretaceous
IAEZ
SZ
IAZ
e) - Pre-Late Campanian
IZU
WPF
SZ
f) - Late Campanian-Maastrichtian
CG
AOZ
GG
VO
IAZ
ATP
BC
g) - Late Maastrichtian-Danian
AOZ
VO
BC
h) - Late Paleocene-Early Eocene
AOZ
BP
ATP
IZU: Istanbul-Zonguldak Unit
SZ: Sakarya Zone
VO: Vardar Ocean
IAZ: Izmir-Ankara Zone
IAEZ: Izmir-Ankara-Erzincan Zone
ATP: Anatolide-Tauride Platform
AOZ: Armutlu-Ovacik Zone
KS: Karakaya Suture
PTS: Paleotethyan Suture
PTRB: Paleotethyan Remnant Basin
KORB: Karakaya Ocean Remnant Basin
WPF: Western Pontide Fault
BKU: Ballidag-Küre Unit
IF: Inalti Formation
UGr: Ulus Group
BG: Boyali Group
UG: Ulumescit Group
GG: Gölcük Group
CG: Çaycuma Group
BC: Bornova Complex
The volcanic rocks related to Syn-rift deposits
Arc Units
Mesozoic Ophiolites
Sünnice High
Strike-slip Faults
Thrust
Continental Collision
Normal Faults
BP: Biga Peninsula
I: Istanbul
C: Cide
Iz: Izmir

between the collided Sakarya Zone and Rhodope-Pontide fragment (also including the İstanbul–Zonguldak Unit) represent a Late Cretaceous suture belt. We regard them as also equivalent to the Armutlu–Ovacık Zone; however, ophiolitic units in the Armutlu–Ovacık Zone are exposed only east of Ovacık, north of Pamukova, and Almacık Mountain. The ophiolitic units in both Almacık and Pamukova areas were regionally deformed under epidote/amphibolite-grade metamorphism (Bozcu 1992; Y. Yılmaz et al., unpublished data). In addition, metaophiolites are observed together with high-grade schist, gneiss, and migmatite of the İstanbul–Zonguldak Unit. Therefore, metaophiolites of Pamukova and Almacık Mountain must be derived from either the Paleo-Tethyan or the pre-Ordovician metaophiolites exposed in the Sunnice massif. However, ordered and unmetamorphosed ophiolitic units which were observed together with Upper Cretaceous pelagic units are situated only in the easternmost part of the Armutlu–Ovacık Zone (east of Ovacık) and in the northwest part of Sakarya Zone (in the western areas of Biga peninsula). The presence of these ophiolitic units in the Armutlu–Ovacık Zone is recognized on the basis of blocks and slivers in Turonian–Lower Campanian strata (Ulumescit and Boyalı groups) in the western areas of Ovacık.

The existence of unmetamorphosed Late Cretaceous ophiolitic units only in the eastern parts of the Armutlu–Ovacık Zone, vs the deformed ophiolitic units in the other parts of this zone belonging to the pre-Ordovician basement of İstanbul–Zonguldak Unit, indicate that Late Cretaceous ophiolites are foreign to the region. They must have been transported westward from the İzmir–Ankara–Erzincan Zone.

The Mesozoic sequence in the northern region of the Sakarya Zone is represented by transgressive units (Bilecik, Soğukçam, Vezirhan and Gölpazarı sequences). The Ulumescit and Boyalı groups in the Armutlu–Ovacık Zone are the equivalents of the pelagic upper parts of this sequence. The Boyalı Group which is underlain by the İstanbul–Zonguldak units and their Upper Jurassic cover units, which is composed of the equivalents of the Ulus Group and Yemişliçay Formation in the İstanbul–Zonguldak Unit; however, the Ulumescit Group, which is underlain by the equivalents of the basement of Sakarya Zone and their Upper Jurassic cover units, is composed of the equivalents of the Soğukçam and Vezirhan formations in the Sakarya Zone (Fig. 2).

The Late Cretaceous–Early Eocene tectonism and its significance

Initially shallow marine in aspect, the rapid deepening during the deposition of the Ulumescit and Boyalı groups in Coniacian–Santonian time was due to dramatic tectonic down-warping; thus, the Late Cretaceous tectonism which caused the transfer of Upper Cretaceous ophiolitic units from east to west also influenced sedimentation of Upper Cretaceous strata in the Armutlu–Ovacık Zone.

The Boyalı Group contains blocks derived from the Sakarya Zone as well as blocks of non-metamorphosed ophiolite which become more common east of Eskipazar. This suggests that a significant uplift of the Sakarya Continent took place during the Turonian–Campanian (Fig. 4d,e; E. Yiğitbaş and A. Elmas, unpublished data), and ophiolite blocks were derived from ophiolitic units within the İzmir–Ankara–Erzincan Zone to the east (Fig. 4e).

The Upper Campanian sedimentary sequence was deposited without interruption on the Jurassic–Cretaceous sequences in southern areas of the Armutlu–Ovacık Zone also, whereas it overlies unconformably the older units in the northern parts of Sakarya Zone. This rapid change between the continuous and discontinuous units indicates that some parts of the region were uplifted and eroded before flysch deposition (probably in the Coniacian–Santonian; Yılmaz et al. 1994). Furthermore, the low greenschist metamorphism in the Armutlu–Ovacık Zone developed during Coniacian–Santonian time (pre-Late Campanian; Yılmaz et al. 1994) prior to the deposition of the non-metamorphosed Late Campanian sedimentary cover. On the other hand, in the Armutlu–Ovacık Zone, the Upper Campanian deposits covered different basement units (Fig. 1c).

These major differences in the stratigraphic relations of the Upper Campanian strata and the low degree of metamorphism did not affect the inner parts of the Sakarya Zone, because it was separated by a tectonic lineament (Western Pontide Fault) from its northern margin. These two regions were deformed independently until Campanian time (Yılmaz et al. 1994).

The pre-Late Campanian (during the Coniacian–Santonian time) tectonism caused the welding of İstanbul–Zonguldak Unit and Sakarya Zone by an oblique collision (Fig. 4e), because, the İstanbul–Zonguldak Unit, Sakarya Zone, and Upper Jurassic to Lower Campanian cover units in the Armutlu–Ovacık Zone are oriented end-to-end rather than overlapping each other. The map pattern of the Armutlu–Ovacık Zone, which shows triangular or rhombohedral-shaped fault-bounded sectors, argues that the different blocks in the zones amalgamated with each other by strike-slip tectonics, rather than thrusting. Göncüoğlu and Erendil (1990) suggested that the exposure of Pamukova metamorphic unit (equivalent to the basement units of the İstanbul–Zonguldak Unit) as two belts in the western and eastern parts of the Armutlu Peninsula is indicative of significant strike-slip deformation in the Armutlu-Pamukova area. The strike-slip faults bordering the İstanbul–Zonguldak Unit to south must have been left-lateral.

Moreover, the oceanic rocks in the İzmir–Ankara Zone were subducted northward beneath the Sakarya

Zone beginning in the Turonian (Fig. 4d). Arc volcanism on the Sakarya Zone was active in Turonian–Campanian time (Yılmaz 1981). Considering the extent of ocean in the region and the direction of subduction and compression, the fault at northern side of the Sakarya Zone must have been a left-lateral strike-slip fault. Thus, the left-lateral strike slip fault system that was active in the region during Late Cretaceous time before the Late Campanian (Elmas et al. 1997) caused the İstanbul–Zonguldak Unit to be juxtaposed against the Sakarya Zone in the west. In addition, the oceanic units in the eastern area were transported from east to west due to this tectonism (Fig. 4d,e). This caused compression and nappe formation in western parts of triangle-shaped area in the Armutlu–Ovacık Zone (Fig. 4e).

Calc-alkaline arc magmatism in Late Cretaceous time is reported from middle and eastern parts of the Pontides (Gedik et al. 1992) and Sakarya Zone (Yılmaz 1981) north of İzmir–Ankara–Erzincan Zone (Fig. 4d,e). Magmatic arc activity continued into the Paleocene in some parts of the eastern Pontides (Terlemez and Yılmaz 1980). The Turonian–Campanian arc volcanism and its deposits (Yemişliçay Group) which are observed in the east part of the İstanbul–Zonguldak Unit coincides with the deposition of the Boyalı Group and the upper parts of the Ulumescit Group in the Armutlu–Ovacık Zone to the south. In the Pontide Zone, the volcanic products of the island-arc must not have extended from the eastern areas to the west because the Upper Cretaceous volcanic rocks in the western areas westward from Cide are developed as a natural continuation from the underlying Ulus Group (E. Yiğitbaş and A. Elmas, unpublished data) which is a product of the Black Sea basin formed under extensional regime (Figs. 4c,d).

The Upper Campanian–Maastrichtian flysch (the Gölcük Group) extends from the Sakarya Zone to the Pontide Zone as the common sedimentary cover for all three zones. The existence of debris-flow units at the base and the sedimentary cover and the characteristics of the sequence as a whole (Fig. 2) indicate the development of a new basin which was controlled by an active tectonism. The sequence began with a transgression at the base and ended with a regression following the development of wildflysch in its central parts. Blocks in the Late Campanian–Maastrichtian Gölcük Group were derived from the Sakarya Zone, and indicate that the fault at the northern margin of the Sakarya Zone was active also during this period (Fig. 4f). The deepening of the sequence continued with the development of Late Maastrichtian–Danian wildflysch deposits which include blocks belonging to the İstanbul–Zonguldak Unit. The shallowing of the sequence following the development of the wildflysch deposits indicate that the Gölcük Group was influenced by a new compressional tectonic regime, created by reactivation of the fault on the south side of the İstanbul–Zonguldak Unit (Fig. 4g).

In the Armutlu–Ovacık Zone, its tectonic fragments are commonly bounded by the strike-slip faults formed during latest Cretaceous and Early Eocene time (Yiğitbaş et al. 1995). This is seen clearly along the section between Bolu and Mengen, where the faults separating the Triassic metamorphic units from the upper parts of Upper Cretaceous succession of the Ulumescit Group are transgressively overlain by the Lutetian sediments. The faults are hidden by a thick Eocene and Neogene sequence, but they likely have a large dip-slip component as well as an important strike-slip displacement (E. Yiğitbaş and A. Elmas, unpublished data).

Other evidence for left-lateral strike-slip tectonics in the region is also seen in areas to the north. Between Devrek and the Black Sea (Fig. 1c) the Devrek-Çaycuma low contains a thick Mesozoic–Tertiary sedimentary sequence (Yemişliçay, Akveren, Atbaşı and Kusuri formations). Development of the basin started from Late Campanian–Early Maastrichtian time and lasted until compressional tectonism at the end of Early Eocene time. The units in the basin were deformed and imbricated with the underlying Paleozoic rocks to the northeast of the region. Thrust faults formed during this deformation were transferred by the left-lateral strike-slip tectonics towards the southwest (Cide-Devrek virgation of Yiğitbaş and Elmas 1997; Fig. 1c). The stratigraphic features of the Turonian to Eocene sequences indicate that the tectonic activity continued intermittently from the beginning of Late Cretaceous time (Yiğitbaş and Elmas 1997).

A block-bearing complex, similar to Gölcük Group, developed in the Sakarya Zone of western Anatolia. The Bornova Complex developed adjacent to a carbonate platform in the İzmir–Ankara Zone (Fig. 4f,g,h), and contains Late Triassic–Middle Maastrichtian carbonate blocks within a pelagic matrix of Campanian–Danian age (Erdoğan et al. 1990). This indicates that the tectonic activity in the Bornova flysch zone was contemporaneous with deposition of the Gölcük Group in the Armutlu–Ovacık Zone. The tectonic complexes of the İzmir–Ankara Zone overlie the Maastrichtian units of Anatolide–Tauride platform to the south (Erdoğan and Güngör 1992). The continental collision between the Sakarya Zone and the Anatolide-Tauride platform occurred in Paleocene time (Şengör and Yılmaz 1981). The Late Cretaceous ophiolite and the Bornova Complex were thrust onto the Anatolide–Tauride platform following Late Paleocene time (Fig. 4h; Erdoğan and Güngör 1990). The fault that controlled and bounded the Bornova Complex on the west is interpreted to be a right-lateral strike-slip fault. Furthermore, this fault bordered units representing Vardar Ocean on the east and caused the transfer of oceanic units from south to north (Fig. 4f,g,h).

In the Biga Peninsula, it is known that initial intra-oceanic obduction began at the end of Early Cretaceous time (Okay et al. 1996); thus, the ophiolites and

the Upper Cretaceous–Paleocene units might be related to the Karakaya Ocean which survived until the end of Paleocene time. A further likelihood is that the Upper Cretaceous–Paleocene units were transferred to the east by the Western Pontide Fault from the Vardar Ocean in the west (Fig. 4f,g,h). In this model the Vardar Ocean forms the southern margin of the Rhodope–Pontide fragment in the Balkans (Dewey et al. 1973) without the Sakarya Zone between them (Figs. 4f,g,h). The Western Pontide Fault controlled the development of units in the Armutlu–Ovacık Zone in Late Cretaceous–Early Eocene time.

A new tectonic regime started in Anatolia because of the final collision of the Arabian and Anatolian plate (Şengör 1979). The right-lateral North Anatolian Fault which began to develop during the Late Miocene–Early Pliocene period related to this new tectonic regime (Dewey et al. 1986) further complicated the structures of this internally chaotic zone. The northern branch of North Anatolian Fault which borders the İstanbul–Zonguldak Unit on the south accelerated the transport of the units in Armutlu–Ovacık Zone towards the west.

Conclusion

Three tectonostratigraphic entities are distinguished in northwestern Anatolia. From north to south, these are: (a) the Pontide Zone, composed of the İstanbul–Zonguldak Unit in the west and the Ballıdağ–Küre Unit in the east; (b) the Armutlu–Ovacık Zone; and (c) the Sakarya Zone. The Paleozoic–Triassic sequences in the İstanbul–Zonguldak Unit and Sakarya Zone are different. The Armutlu–Ovacık Zone, bounded tectonically by the İstanbul Zonguldak Unit and the Sakarya Zone, appears to represent a tectonic mixture of both flanking zones.

Upper Jurassic deposits are the first common cover unit in the Armutlu–Ovacık Zone, İstanbul–Zonguldak Unit, and the Sakarya Zone; therefore, the İstanbul–Zonguldak Unit and the Sakarya Zone were juxtaposed prior to Late Jurassic time during closure of Paleotethyan–Karakaya oceans. However, to the west of the West Black Sea Fault which bounds the İstanbul–Zonguldak Unit on the west, the Karakaya Ocean survived until later.

The left-lateral strike-slip tectonics (the Western Pontide Fault) which were active during the Late Cretaceous prior to Late Campanian time (particularly Coniacian–Santonian) further welded the İstanbul–Zonguldak Unit and Sakarya Continent by oblique collision. This strike-slip motion and its related compression caused the last phase of metamorphism in the Armutlu–Ovacık Zone. In addition, during Late Cretaceous time (pre-Late Campanian), north-dipping subduction of Neo-Tethys (İzmir–Ankara–Erzincan Zone) occurred south and southeast of the Sakarya Zone. The left-lateral strike-slip fault zone which is oblique to the direction of subduction caused the westward transfer of Late Cretaceous ophiolite from the İzmir–Ankara–Erzincan Zone into the eastern parts of Armutlu–Ovacık Zone.

From Late Campanian time, strike-slip faults caused the development of west/east-extending basins in the region. The flyschoid deposits (Gölcük Group) were formed as a common cover unit of the three tectonic zones. The characteristics of the sedimentary sequence which ranges in age from Late Campanian to Early Eocene indicate that left-lateral strike-slip tectonics continued to the end of Early Eocene time. Also, the ophiolitic units which might have been related partially to the remnant of the Karakaya Ocean to the northwest of the Sakarya Continent were transported eastward by the Western Pontide Fault by closure of the Vardar Ocean to the west.

The right-lateral North Anatolian Fault Zone, which formed in response to the final collision of the Arabian and Anatolian plates at the end of Miocene time, contributed to the further transfer of the units to the west. This fault zone followed former tectonic lines in between the İstanbul Zone, Armutlu–Ovacık Zone, and the Sakarya Continent.

Acknowledgements This paper includes results of a decade-long field study supported by TPAO (Turkish Petroleum Co.), TUBITAK (Turkish Scientific and Technical Research Unit, project no. YDABÇAG 218-A and 199Y065) and University of İstanbul Research Fund (project no: 705/260495). We are grateful for their support. We thank Y. Yılmaz and B. Natal'in for thoughtful discussion on Pontide geology, to the journal reviewer B.C. Burchfiel and an anonymous referee for incisive and comprehensive critiques of the manuscript. Ö. Balkaş, M. Aydın, Ö. Şahintürk, and H.S. Serdar joined us in some field excursions and made valuable suggestions. B.R. Pratt and R. Kerrich (University of Saskatchewan) kindly read and corrected the manuscript.

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