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ARAL I. OKAY & OKAN TÜYSÜZ

İTÜ Eurasian Institute of Earth Sciences and Maden Fakültesi, Jeoloji Bölümü, Ayazağa, 80626, İstanbul, Turkey (e-mail: okay@itu.edu.tr)

Abstract: The two main Tethyan sutures of Turkey, the İzmir–Ankara–Erzincan and the Intra-Pontide sutures, are reviewed through several well-studied transects crossing the suture regions. Both sutures have formed during the Early Tertiary continental collisions following northward subduction of Tethyan oceanic lithosphere. The İzmir–Ankara–Erzincan suture is represented along most of its *c*. 2000 km length by Paleocene and younger thrust, which emplace the upper crustal rocks of the northern continent over that of the southern continent with an intervening tectonic layer of Cretaceous subduction-accretion complexes. These thrusts constitutes a profound stratigraphic, structural, magmatic and metamorphic break, of at least Carboniferous to Palaeocene age and form the main boundary between Laurasia and Gondwana in the Turkish transect. Voluminous subduction–accretion complexes of Triassic and Cretaceous ages occur respectively to the north and south of the suture giving the antithetic subduction polarities during these two periods. This, and evidence for a major accretionary orogeny of Late Triassic age north of the İzmir–Ankara–Erzincan suture suggest that two separate oceanic lithospheres, of Carboniferous to Triassic (Palaeo-Tethys) and of Triassic to Cretaceous ages (Neo-Tethys) respectively have been consumed along the suture. The final continental collision along the İzmir–Ankara–Erzincan suture was slightly diachronous and occurred in the earliest Palaeocene to the west and in the Late Palaeocene to the east. The *c*. 800 km long Intra-Pontide suture is younger in age and have formed during the Early Eocene and younger continental collisions linked to the opening of the Western Black Sea Basin as an oceanic back-arc basin. At present the North Anatolian Fault, which came into existence in the Late Miocene, follows the course of the older Intra-Pontide suture.

Sutures represent the boundaries of former lithospheric plates. In an idealized case of collision of two continental plates, the suture will be manifested as a major fault or fault zone in the brittle seismogenic part of the crust and by a shear zone in the ductile lower crust and lithospheric mantle. The sutures will form profound stratigraphic, palaeogeographic, structural, magmatic and metamorphic breaks and as such will be easy to recognize and distinguish from other major intraplate faults or fault zones. Here, the term 'suture' is used if the former plate boundary can be defined as a single fault or fault zone less than one kilometre in width, suture zone refers to a belt more than one kilometre in thickness, occupied by former oceanic crustal rocks. In the case of the suture zone, the former boundary between two plates cannot be shown as a single fault line on a map of 1:500 000 scale or smaller. The structures that represent sutures frequently show major along-strike variation in type and age, and most are probably post-collisional. For example, the suture in the Western Alps is represented from west to east, by the Late Cretaceous thrusts between the Sesia Zone and the Penninic units (e.g., Compagnoni 1977), by the segment of the post-collisional dextral strike-slip fault (the Insubric line) between the Sesia Zone and the Eastern Alps (e.g., Schmid *et al.* 1989), and by the Late Cretaceous thrusts between the Austra–Alpine and Penninic nappes along the Arosa Schuppen Zone (e.g., Ring *et al.* 1988). The only common link between these three different structures is that they are believed to separate rocks deposited on different margins of an ocean. The delineation of a suture in the field is, hence, partly subjective, as the decision which stratigraphic units belong to which former plate can be controversial especially in metamorphic areas (e.g., see Michard *et al.* 1996, for a recent discussion on the problems associated with the delineation of the Alpine suture).

Here, we describe some of the Tethyan sutures and neighbouring former continental margins in Turkey. The description is aimed in answering some of the problems associated with sutures, such as can the boundaries of former plates be described by single major faults, or by areally extensive suture zones. To what extent do the former continental margins fit into a simple Wilsonian cycle of rifting, passive margin sedimentation, subduction and collision? How can variation of deformation, metamorphism and magmatism along the sutures be explained?

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Major continental blocks of Turkey

The Tethyan Ocean, which existed between Laurasia and Gondwana as a westward narrowing embayment since the Carboniferous, was not a single continuous oceanic plate during its long evolution (Şengör 1987; Ricou 1994; Stampfli 1996). Throughout its history, small continental fragments were rifted off from either side of the Tethyan Ocean and moved towards the other side, creating new oceanic lithosphere in their wakes, and eventually colliding with the opposite continental margin. Therefore in most regions, the former plate boundary between the two megacontinents, Laurasia and Gondwana, cannot be represented by a single suture. This is most obvious in Turkey, where several sutures isolate drifting continental fragments between Laurasia and Gondwana (Şengör & Yılmaz 1981). The final amalgamation of these fragments into a single continental mass occurred in Turkey as late as Late Tertiary, when the Arabian plate collided with the Anatolian plate.

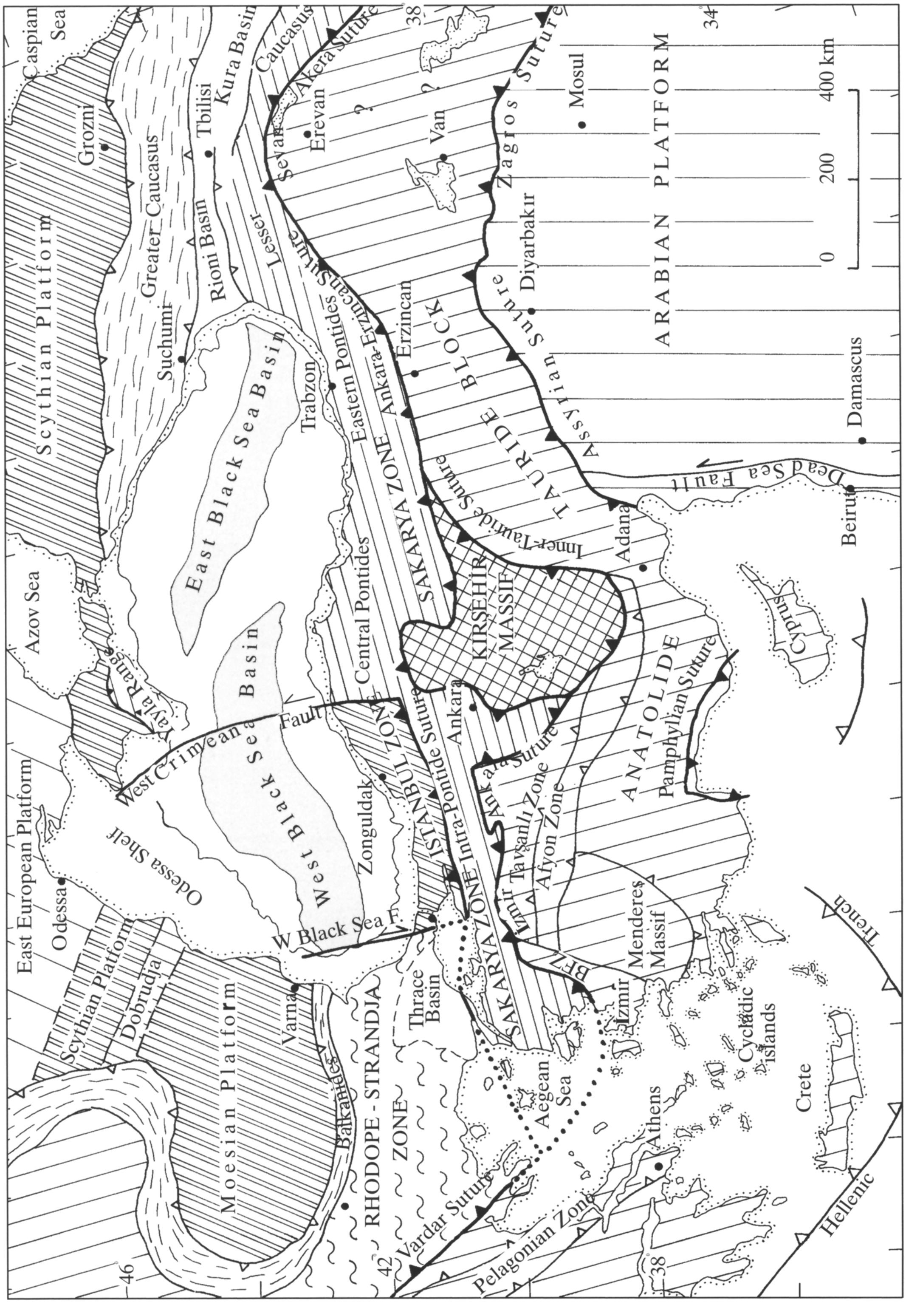
Figure 1 shows the sutures and major continental fragments in Turkey and the surrounding regions. There are six major lithospheric fragments in Turkey: the Strandja, the İstanbul and the Sakarya Zones, the Anatolide–Tauride Block, the Kırşehir Massif and the Arabian Platform (Fig. 1, Şengör & Yılmaz 1981; Şengör *et al.* 1982; Okay 1989*a*; Okay *et al.* 1994). The first three zones, which show Laurasian affinities, are classically referred to as the Pontides. They are separated by the İzmir–Ankara–Erzincan suture from the Kırşehir Massif and the Anatolide–Tauride Block, the latter is in contact with the Arabian Platform along the Assyrian–Zagros suture (Fig. 1). Although separated by the Assyrian suture, the Anatolide–Tauride Block shows a similar Palaeozoic stratigraphy to that of the Arabian Platform, and hence to the northern margin of Gondwana. The Kırşehir Massif, which consists mainly of metamorphic and granitic rocks with Cretaceous isotopic ages, is in contact along the controversial Inner Tauride suture with the Anatolide–Tauride Block, while the Intra-Pontide suture constitutes the former plate boundary between the Sakarya and İstanbul zones. Here, we describe two of the major sutures of northern Turkey, large sections of which we have mapped or seen in the field. These are the İzmir–Ankara–Erzincan suture, which extends for *c.* 2000 km from the Aegean Sea to Georgia, and the *c.* 800 km long Intra-Pontide suture. First we briefly give the relevant geological features of the continental blocks, which are separated by these sutures.

The İstanbul Zone

The İstanbul Zone is a small continental fragment, about 400 km long and 70 km wide, located in the southwestern margin of the Black Sea (Fig. 1). It is made up of a Precambrian crystalline basement overlain by a continuous, well-developed transgressive sedimentary sequence extending from Ordovician to Carboniferous, which was deformed during the Carboniferous Hercynian Orogeny (Aydın *et al.* 1986; Dean *et al.* 1997; Görür *et al.* 1997). The stratigraphy of the İstanbul Zone is shown in Fig. 2 on two sections, one from the western part near İstanbul, and the other from the eastern part around Zonguldak (Fig. 1). These sections illustrate the notable facies differences along the length of the İstanbul Zone, especially marked during the Carboniferous. In the İstanbul region the Carboniferous deposits consists of Viséan pelagic limestones and radiolarian cherts, which pass up into thick turbidites probable of Namurian age, while in the east, around Zonguldak, Visean is represented by shallow marine carbonates overlain by Namurian to Westphalian paralic coal series (Dill 1976; Kerey *et al.* 1986). Westphalian megafloras show close affinities to those of western Europe and Donetz basins (Charles 1933). The Upper Carboniferous siliciclastic rocks in the Zonguldak area were derived from the north (Kerey *et al.* 1986) and were deposited in a large deltaic basin located on the southern margin of the Laurasian plate. These features, as well as palaeomagnetic results from the Palaeozoic rocks of the İstanbul Zone (Evans *et al.* 1991) underscore its Laurasian affinity.

In the İstanbul Zone Hercynian deformation started earlier and is stronger to the west (Mid-Carboniferous) than to the east (latest Carboniferous). In the İstanbul region it is characterized by minor folds, relatively rare and discontinuous

Fig. 1. Tectonic map of northeastern Mediterranean region showing the major sutures and continental blocks. Sutures are shown by heavy lines with the polarity of former subduction zones indicated by filled triangles. Heavy lines with open triangles represent active subduction zones. The Late Cretaceous oceanic crust in the Black Sea is shown by grey tones. Small open triangles indicate the vergence of the major fold and thrust belts. BFZ denotes the Bornova Flysch Zone. Modified after Şengör (1984), Okay (1989*a*), and Okay *et al.* (1994, 1996).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Caspian Sea
Scythian Platform
Grozni
Greater Caucasus
Tbilisi
Kura Basin
Caucasus
Akera Suture
Sevan
Erevan
Lesser
Rioni Basin
Suchumi
East Black Sea Basin
Trabzon
Eastern Pontides
Ankara-Erzincan Suture
Erzincan
Van
Mosul
Zagros Suture
Diyarbakır
Assyrian Suture
ARABIAN PLATFORM
0
200
400 km
Damascus
Dead Sea Fault
Beirut
TAURIDE BLOCK
Inner-Tauride Suture
Adana
KIRŞEHİR MASSIF
SAKARYA ZONE
Central Pontides
Azov Sea
Yayla Range
West Black Sea Basin
West Crimean Fault
Ankara
ANATOLIDE
Pamphylian Suture
Cyprus
East European Platform
Odessa
Odessa Shelf
Zonguldak
İSTANBUL ZONE
Intra-Pontide Suture
Ankara Suture
Tavşanlı Zone
Afyon Zone
İzmir
Menderes Massif
BFZ
W Black Sea F.
Scythian Platform
Dobrudja
Moesian Platform
Varna
Thrace Basin
SAKARYA ZONE
İzmir
Trench
Balkanides
RHODOPE - STRANDJA ZONE
Aegean Sea
Cycladic islands
Crete
Athens
Vardar Suture
Pelagonian Zone
Hellenic

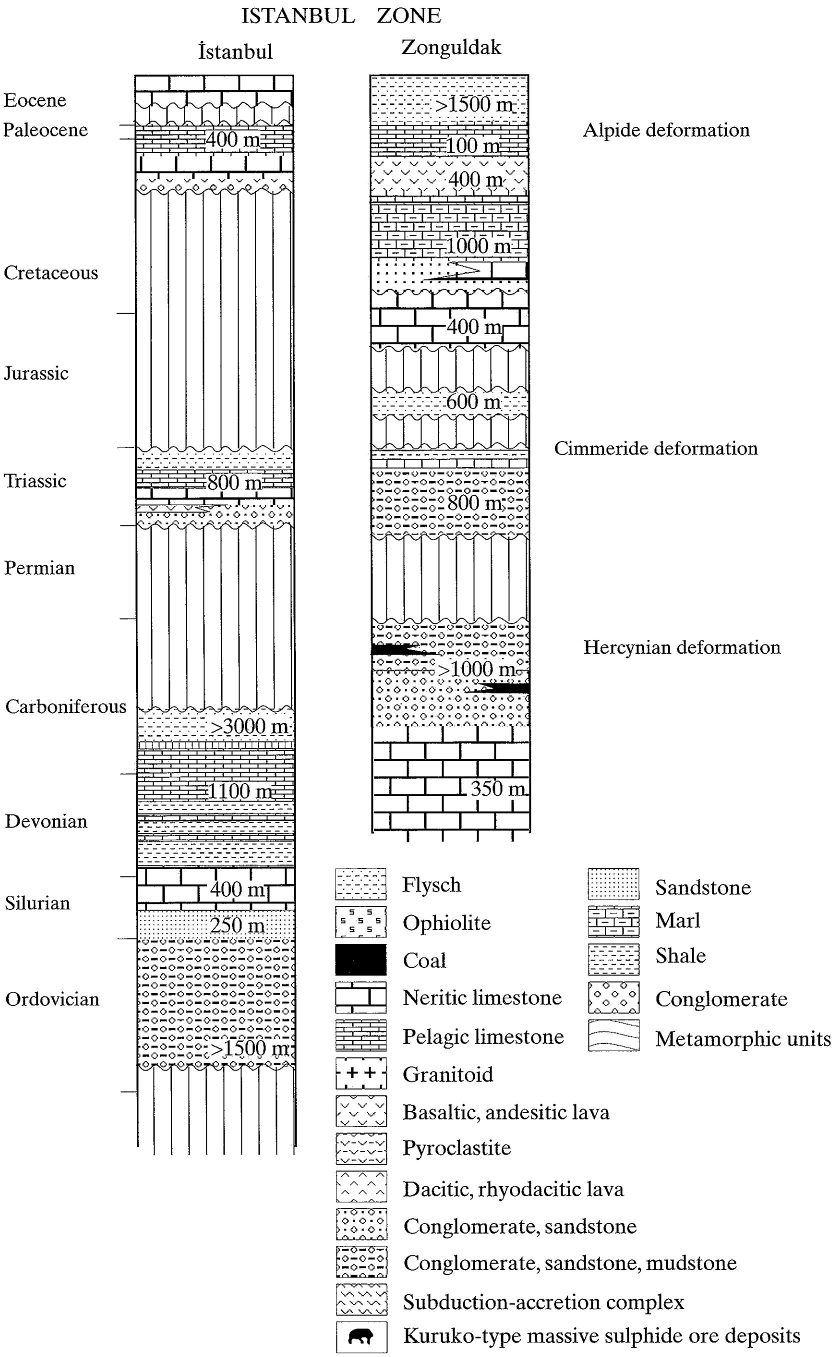

Fig. 2. Synthetic stratigraphic sections of the İstanbul Zone from the İstanbul and Zonguldak regions based on Yurttaş-Özdemir (1973), Dean *et al.* (1996) and Görür *et al.* (1997).

thrust faults, and minor but widespread strike-slip faults and shear zones. The deformed Palaeozoic sequence is unconformably overlain by the earliest Triassic sedimentary rocks (Fig. 2).

The Triassic sequence is well developed in the İstanbul region and comprises an approximately 800 m thick transgressive sequence of earliest Scythian to Norian age (Fig. 2, Assereto 1972; Yurttaş-Özdemir 1973; Gedik 1975). It ends with a flysch-like sequence of sandstone and shale with *Halobia* sp. marking the onset of Late Triassic Cimmeride deformation, which is particularly strong in the Sakarya Zone to the south. In marked contrast with the İstanbul region, Triassic sequence in the eastern part of the İstanbul Zone is represented by terrigenous, variegated sandstones and conglomerates with a total thickness of 800 m (Fig. 2). The upper parts of these continental deposits locally comprise lacustrine marls and limestones, which yield latest Triassic ages (Akyol *et al.* 1974; Alişan & Derman 1995). The palaeomagnetic results from the Triassic rocks of the İstanbul Zone indicate its continued affinity with Laurasia (Sarıbudak *et al.* 1989; Theveniaut 1993).

In the western part of the İstanbul Zone, the Jurassic and Lower Cretaceous sequence is absent, and the Palaeozoic and Triassic rocks are unconformably overlain by Upper Cretaceous–Palaeocene clastic, carbonate and andesitic volcanic rocks (Dizer & Meriç 1983; Tansel 1989). In contrast, in the eastern part of the İstanbul Zone there is a thick Middle Jurassic to Eocene succession marked by small unconformities (Fig. 2, Akyol *et al.* 1974). Senonian andesitic lavas, dykes and small acidic intrusions, which are widespread in the northern part of the İstanbul Zone, were produced during the northward subduction of the Intra-Pontide Ocean.

The İstanbul Zone shows a similar Palaeozoic–Mesozoic stratigraphy to that of Moesian Platform, and prior to the late Cretaceous opening of the West Black Sea Basin it was situated south of the Odessa shelf (Fig. 1, Okay *et al.* 1994). Together with very similar Palaeozoic sequences farther west, including the Montagne Noire in France, Carnic Alps in Austria, Krajstides in Bulgaria, the İstanbul Zone and its continuation in the Scythian platform formed part of the passive continental margin of Laurasia. With the inception of back-arc spreading, the İstanbul Zone was rifted off from the Odessa shelf and was translated southward, bounded by two transform faults, the West Black Sea fault in the west and the West Crimean fault in the east (Fig. 1, Okay *et al.* 1994). Both of these transform faults are mapped in the offshore seismic sections (Finetti *et al.* 1988). The southward translation of the İstanbul Zone led to the gradual closure of the Intra-Pontide Ocean by north-dipping subduction. During the Early Eocene the İstanbul Zone collided with the Sakarya Zone leading to the formation of the eastern part of the Intra-Pontide suture.

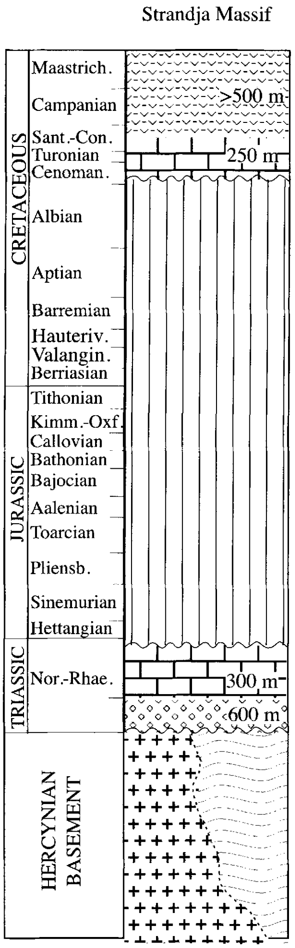

Fig. 3. Synthetic stratigraphic section of the Strandja Zone based on Aydın (1974). Symbols as in Fig. 2.

The Strandja Zone

The Strandja Zone constitutes the easternmost part of the little understood crystalline region of the Rhodope–Strandja Massif in northeastern Greece, southern Bulgaria and Turkish Thrace (Fig. 1). The stratigraphy of the Strandja Zone is strikingly different from that of the İstanbul-Zone. In the Turkish Thrace it consists of a basement of metamorphic rocks intruded by Permian granites (244 Ma, Aydın 1974), which are unconformably overlain by a Triassic sedimentary sequence (Fig. 3; Aydın 1974). The Triassic sequence shows a development similar to the Germanic Triassic facies and has clear Laurasian affinity. In the Bulgarian part of the Strandja Zone the Mesozoic sequence extends up to the mid-Jurassic (Chatalov 1988). The Triassic to Middle Jurassic sequence as well as the crystalline basement was folded, thrust-faulted and regionally metamorphosed during the mid-Jurassic, and were unconformably overlain by Cenomanian conglomerates and shallow marine limestones (Fig. 3). These pass up to Senonian andesitic volcanic and volcanoclastic rocks and associated granodiorites (Moore *et al.* 1980), formed during the northward subduction of the Intra-Pontide Ocean (Boccaletti *et al.* 1974; Şengör & Yılmaz 1981).

The Sakarya Zone

The Sakarya Zone is an east–west-oriented continental fragment, about 1500 km long and 120 km wide, between the Anatolide–Tauride Block to the south and the İstanbul and Strandja zones and the eastern Black Sea to the north (Fig. 1). It includes the Sakarya Continent of Şengör & Yılmaz (1981) as well as the Central and Eastern Pontides, which show a similar stratigraphic and tectonic development (Okay 1989*a*). The most

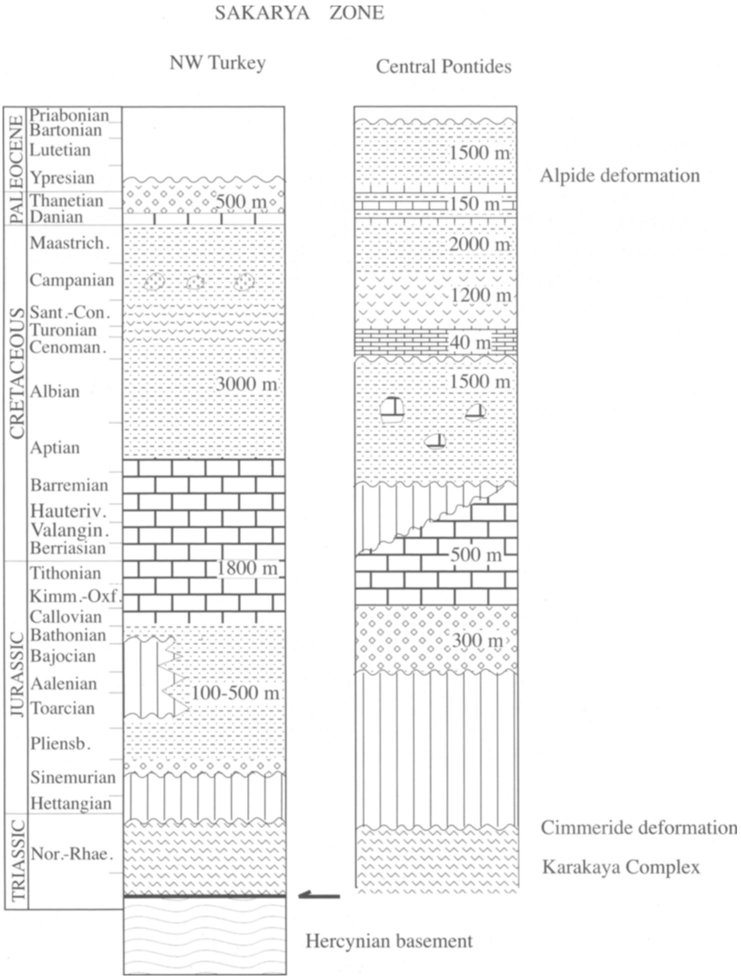

Fig. 4. Synthetic stratigraphic sections of the western and central parts of the Sakarya Zone (Saner 1978, 1980; Altıner *et al.* 1991; Tüysüz 1993). See Fig. 18 for a stratigraphic section of the eastern part of the Sakarya Zone. Symbols as in Fig. 2.

striking geological feature of the Sakarya Zone is the widespread presence of Triassic subduction–accretion complexes, rare in the rest of the Alpide–Himalayan chain, which form a strongly deformed and partly metamorphosed basement to the overlying Lower Jurassic–Eocene sequence (Fig. 4, Tekeli 1981). The Triassic subduction–accretion units, called the Karakaya Complex in the western part of the Sakarya Zone, comprise a lower section of Permo-Triassic metabasite–marble–phyllite series, over three kilometres in thickness, with exotic Triassic eclogite (Okay & Monie 1997) and blueschist lenses (Monod *et al.* 1996). This sequence, named as the Nilufer Unit, occurs throughout the Sakarya Zone. In northwest Turkey Mid-Triassic conodonts have been described from the upper parts of the Nilüfer Unit (Kaya & Mostler 1992), while the age of the regional metamorphism is latest Triassic (Monod *et al.* 1996; Okay & Monie 1997). An oceanic seamount (Pickett & Robertson 1996) or alternatively an oceanic intra-arc to fore-arc tectonic setting (Okay *et al.* 1996) have been proposed for the Nilufer Unit. The Nilufer Unit is tectonically overlain by chaotically deformed but unmetamorphosed clastic and basic volcanic rocks of Triassic age with exotic blocks of Carboniferous and Permian neritic limestone, basalt, Carboniferous and Permian radiolarian chert (Bingöl *et al.* 1975; Okay & Mostler 1994; Kozur & Kaya 1994; Leven & Okay 1996; Okay *et al.* 1996; Tüysüz 1996). Most of these clastic rocks probably represent trench deposits (Okay *et al.* 1996; Pickett & Robertson 1996). The basement of the Nilufer Unit, as observed in a few tectonic windows, consists of high-grade metamorphic rocks with Late Carboniferous zircon ages (Okay *et al.* 1996). The final phase of deformation and metamorphism of the subduction–accretion complexes occurred during the latest Triassic, and the various units of the Karakaya Complex are unconformably overlain by Jurassic terrigenous to shallow marine clastic sedimentary rocks.

The Jurassic–Eocene stratigraphy of the Sakarya Zone is summarized in Fig. 4 in two sections from the western and central part of the Sakarya Zone. The succession to the west consists of Lower to Middle Jurassic continental to shallow marine clastic rocks with ammonitico rosso horizons, Upper Jurassic–Lower Cretaceous carbonates, Upper Cretaceous–Palaeocene volcanic and sedimentary rocks (Fig. 4). The Senonian andesitic volcanism observed in the northern parts of the Sakarya Zone is related to the northward subduction of the İzmir–Ankara–Erzincan Ocean. Palaeomagnetic data from the Sakarya Zone indicate that it was close to the Laurasian margin during the Liassic and Late Cretaceous time (Channel *et al.* 1996).

The Anatolide–Tauride Block

The Anatolide–Tauride Block forms the bulk of the southern Turkey and in contrast to the Pontide continental fragments shows a similar Palaeozoic stratigraphy to the Arabian Platform, and hence to that of Gondwana. During the obduction, subduction and continental collision episodes in the Late Cretaceous–Palaeocene, the Anatolide–Tauride Block was in the footwall position and therefore underwent much stronger Alpide deformation and regional metamorphism than that observed in the Pontide zones. During the Senonian a massive body of ophiolite and accretionary complex was emplaced over the Anatolide–Tauride Block. The northern margin of the Anatolide–Tauride Block underwent HP–LT (high pressure–low temperature) metamorphism at depths of over 50 km under this oceanic thrust sheet. Erosional remnants of this thrust sheet of ophiolite and accretionary complex occur throughout the Anatolide–Tauride Block. In the Turkish geological literature the accretionary complex is often referred to as ophiolitic melange; however, it generally lacks a matrix and is structurally more similar to an imbricate thrust stack. With the inception of continental collision in the Palaeocene the Anatolide–Tauride Block was internally sliced and formed a south to southeast-vergent thrust pile. The compression continued until the Early to Mid-Miocene in the western Turkey and is still continuing in the eastern Anatolia. The lower parts of the thrust pile to the north were regionally metamorphosed, while the upper parts to the south form large cover nappes. This leads to subdivision of the Anatolide–Tauride Block into zones with different metamorphic and structural features, in a similar manner to the subdivision of the Western Alps into Helvetics and Penninics albeit with a different polarity. There are three main regional metamorphic complexes: a Cretaceous blueschist belt, the Tavşanlı Zone, to the north and two Barrovian-type metamorphic belts, the Afyon Zone of Palaeocene age and the Menderes massif of Eocene age farther south (Fig. 1). To the northwest of Menderes Massif there is a belt of chaotically deformed uppermost Cretaceous–Paleocene flysch with Triassic to Cretaceous limestone blocks. This Bornova Flysch Zone has an anomalous position between the İzmir–Ankara suture and the Menderes Massif (Fig. 1). The Taurides, which lie south of the metamorphic regions, consist of a stack of thrust sheets of Palaeozoic and Mesozoic sedimentary rocks (e.g., Gutnic *et al.* 1979; Özgül

1984). Although the Anatolide–Tauride Block shows a variety of metamorphic, structural and stratigraphic features, there are some elements of stratigraphy common to all of these zones and which distinguish the Anatolide–Tauride Block as a single tectonic entity. These are a Precambrian crystalline basement, a discontinuous Cambrian to Devonian succession dominated by siliciclastic rocks, a Permo-Carboniferous sequence of intercalated limestone, shale and quartzite, and a thick Upper Triassic to Upper Cretaceous carbonate sequence. On the other hand, Hercynian deformation or metamorphism, and Triassic subduction–accretion units, characteristic features of the Sakarya Zone, are not observed in the Anatolide–Tauride Block.

The Kırşehir Massif

The Kırşehir Massif is a region of metamorphic and voluminous granitic rocks with Cretaceous isotopic ages. It is generally regarded as separated by the Inner Tauride Suture from the Anatolide–Tauride Block (Fig. 1, Şengör *et al.* 1982), however, some workers consider the Kırşehir Massif as the northern metamorphosed margin of the Anatolide–Tauride Block (e.g., Poisson *et al.* 1996; Yalınız *et al.* 1996). The metamorphic rocks of the Kırşehir Massif constitute a coherent metasedimentary sequence of granulite, gneiss, micaschist, metaquarzite, marble and calcsilicate rock, which are isoclinally folded and multiply deformed (Seymen 1983). The regional metamorphism varies from greenschist to granulite facies and is of high-temperature–medium/low-pressure type. The age of regional metamorphism, although widely accepted as Cretaceous, is poorly constrained. The few K/Ar isotopic data on biotite and muscovite from the micaschists yield Late Cretaceous ages (75–80 Ma, Göncüoğlu 1986). The metamorphic rocks are tectonically overlain by an unmetamorphosed Late Cretaceous accretionary complex of basalt, radiolarian chert, pelagic limestone, sandstone and serpentinite. The accretionary complex as well as the metamorphic rocks are intruded by granitic rocks, which cover large areas in the Kırşehir Massif. They are mainly monzogranites, quartz-monzonites with a calc-alkaline character, and with a trace element geochemistry suggesting a syn- to post-collisional tectonic setting (Akıman *et al.* 1993; Erler & Göncüoğlu 1996). The K/Ar biotite and hornblende, and Rb/Sr hornblende and whole rock ages from the granitic rocks fall in the range of 110 Ma to 75 Ma (Ataman 1972; Göncüoğlu 1986; Güleç 1994). An upper age limit on the granitic magmatism as well as on regional metamorphism is provided by the Upper Maastrichtian terrigenous to shallow-marine clastic and carbonate rocks, which lie unconformably on the metamorphic as well as on the granitic rocks (Seymen 1981).

The İzmir–Ankara–Erzincan suture

This is the major suture in Turkey and represents the scar of the main Tethys ocean between Laurasia and Gondwana between the late Palaeozoic and Early Tertiary. The İzmir–Ankara–Erzincan suture extends from north of İzmir eastwards to the border with Georgia from where it continues as the Sevan–Akera suture in the Lesser Caucasus (Fig. 1, Khain 1975; Adamia *et al.* 1977; Knipper 1980). In the west, the İzmir–Ankara–Erzincan suture probably connects across the Aegean Sea to the Vardar suture. The various structures, which define the İzmir–Ankara–Erzincan suture in the field, form a profound stratigraphic, structural, metamorphic and magmatic break. It separates the Sakarya Zone to the north from the Kırşehir Massif and the various units of the Anatolide–Tauride Block to the south (Fig. 1). The İzmir–Ankara–Erzincan suture is not rectilinear but is strongly segmented forming several major loops along its length (Fig. 1). The suture will be described on the basis of these segments starting in the west.

The İzmir–Ankara–Erzincan suture between İzmir and Balıkesir

Along this northeast-trending, 180 km long segment of the İzmir–Ankara–Erzincan suture between the Aegean Sea and the region of Balıkesir, the Sakarya Zone is in contact with the Bornova Flysch Zone of the Anatolide–Tauride Block (Fig. 1).

The Sakarya Zone north of the suture consists of the Karakaya Complex unconformably overlain by a Jurassic to Lower Cretaceous succession (Fig. 5). In this region the Karakaya Complex is represented by the Nilüfer Unit, tectonically overlain by the Upper Triassic arkosic sandstones (Okay *et al.* 1996). The arkosic clastic rocks pass upwards and eastwards to extensive olistostromes, which form a 15 km wide and 150 km long belt immediately east of the suture (Fig. 5). The olistostromes are dominated by exotic Carboniferous and Permian neritic limestone blocks; there are also rare blocks of basalt, Carboniferous pelagic limestone and radiolarite (Okay *et al.* 1991, 1996; Okay & Mostler 1994; Leven & Okay 1996). The age of the exotic

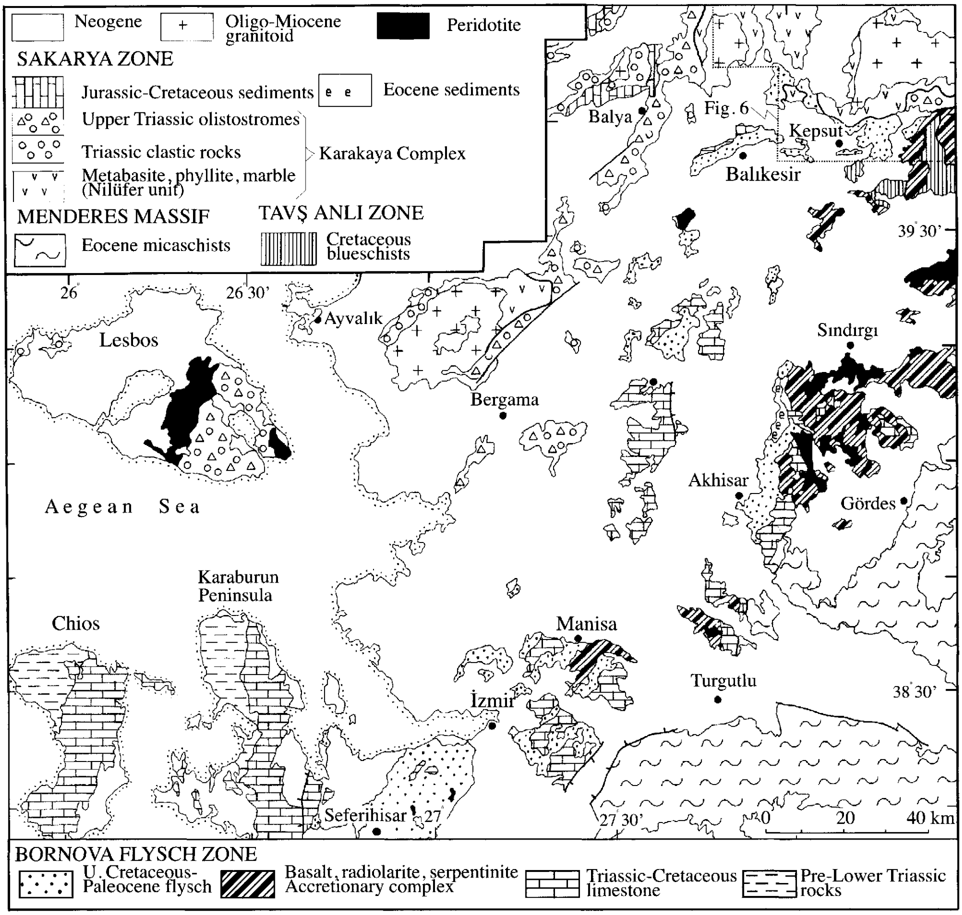

Fig. 5. Simplified geological map of the region around the İzmir–Ankara–Erzincan suture between İzmir and Balıkesir (modified from Okay & Siyako 1993; Akyüz & Okay 1996).

neritic limestone blocks ranges from Mid-Carboniferous (Bashkirian) to the latest Permian (Dorashamian) with a general trend of younging in the age of blocks eastwards towards the suture (Leven & Okay 1996). The Jurassic–Cretaceous sequence, largely eroded during the Early Tertiary, is preserved 15 km west of suture in the Balya region (Fig. 5). In this region Liassic sequence consists of continental to shallow-marine sandstones and shales, which are overlain disconformably by the Upper Jurassic–Lower Cretaceous neritic limestones, 800 m thick. These are unconformably overlain by Albian–Cenomanian pelagic limestones (Okay *et al.* 1991).

The Bornova Flysch Zone to the east of the suture consists of chaotically deformed late Maastrichtian to Palaeocene greywackes with Triassic to Cretaceous limestone and rarer peridotite, radiolarian chert, and basalt blocks (Okay & Siyako 1993). The limestone blocks, which reach a few kilometres in size, range in age from Middle Triassic to Maastrichtian (Şahinci 1976; Poisson & Şahinci 1988; Erdoğan 1990; Okay & Siyako 1993). Within the blocks the Triassic to Lower Cretaceous is represented by neritic platform carbonates, while Senonian is represented by red, pelagic, cherty limestones. Towards the east the limestone-flysch of the Bornova Flysch Zone is associated with a Cretaceous oceanic accretionary complex of radiolarian chert, basalt, pelagic shale, pelagic limestone, sandstone and serpentinite. Isolated bodies of peridotite rest on this accretionary complex (Fig. 5).

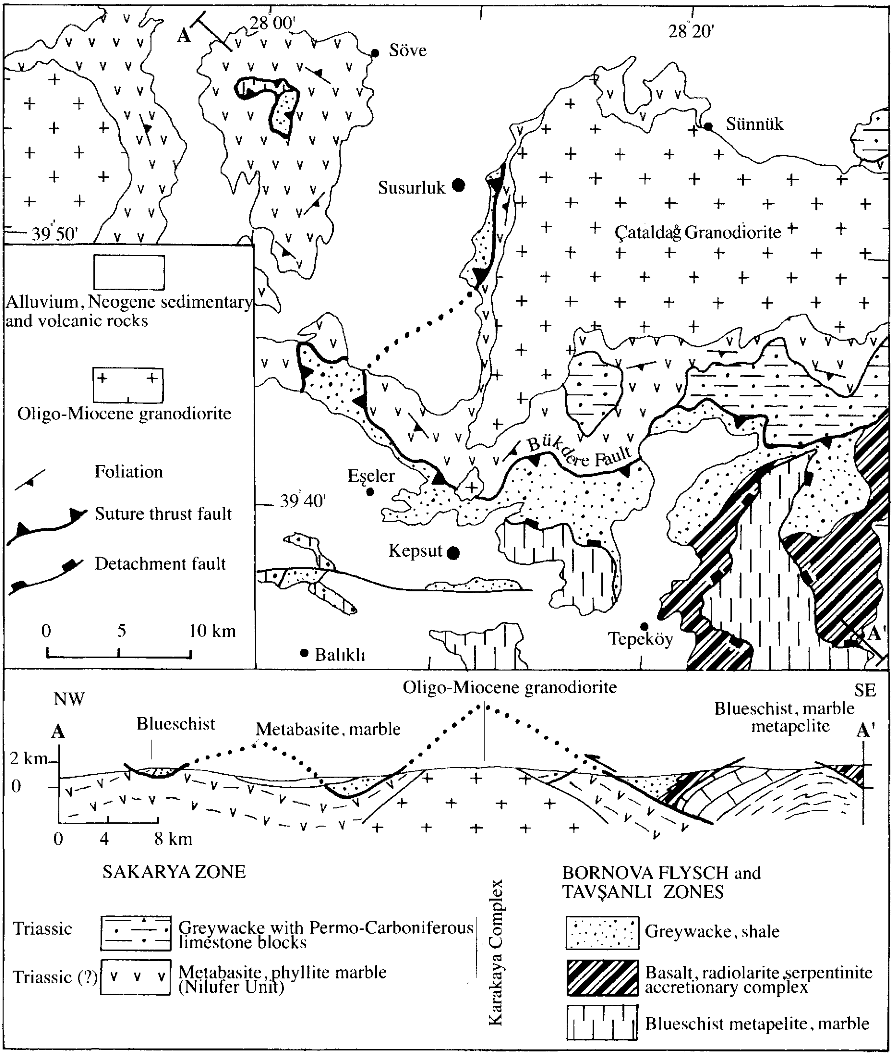

Fig. 6. Geological map and cross-section of the suture region north of Balıkesir in northwest Turkey. For location see Fig. 5 (simplified from Akyüz & Okay 1996).

The Kepsut transect The suture trace between İzmir and Balıkesir is almost completely covered by Neogene sedimentary and volcanic rocks, and only in the Kepsut region northeast of Balıkesir the pre-Neogene rocks from both sides of the suture are seen in contact (Fig. 5). A map and cross-section of this region based on Akyüz & Okay (1996) are shown in Fig. 6. This region is characterized by a dome structure centred on the Oligo-Miocene Çataldağ granodiorite, which has exposed the tectonic relation between the Sakarya and Bornova Flysch zones. The Sakarya Zone in the Kepsut region is made up of the metabasite–marble–phyllite sequence of the Nilüfer Unit tectonically overlain by Triassic greywackes with exotic Permian and Carboniferous limestone blocks (Akyüz & Okay 1996). The Bornova Flysch Zone is represented by strongly sheared turbidites with Triassic and Cretaceous limestone as well as blueschist blocks. The chaotically deformed turbidites, which in many areas form a tectonic mélange, are gradually replaced eastwards by a Cretaceous accretionary complex of basalt, radiolarian chert, pelagic limestone and shale. Blueschist-facies marbles and metapelites are exposed under the accretionary complex

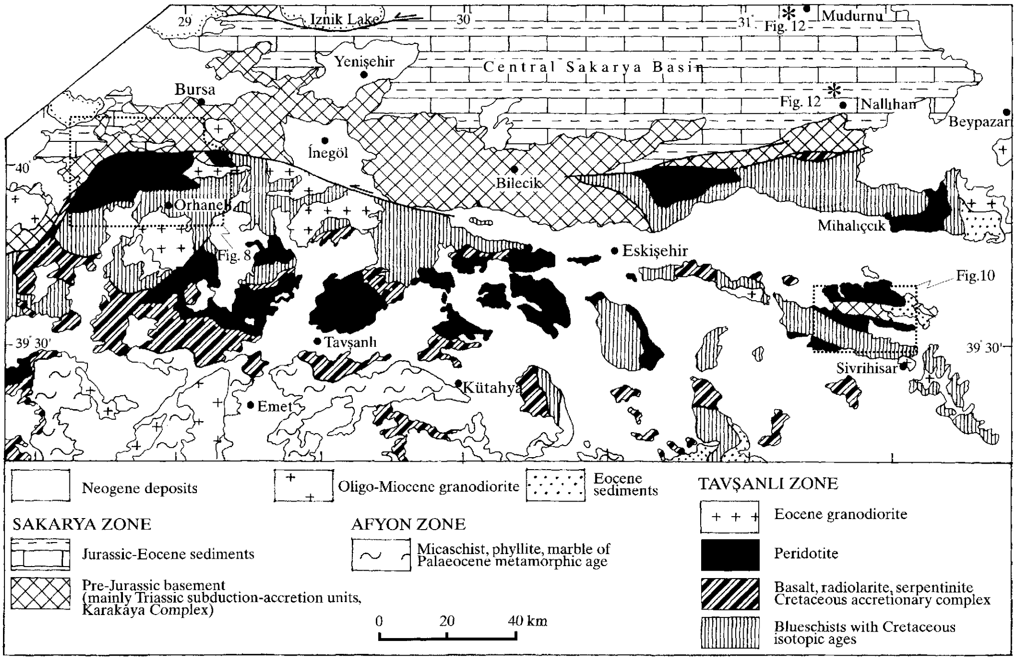

Fig. 7. Geological map of the region around the İzmir–Ankara–Erzincan suture between Bursa and Nallıhan (modified from Okay 1984*b*).

(Fig. 6). In the Kepsut region the sheared turbidites of the Bornova Flysch Zone lie tectonically over the Nilüfer Unit and the Triassic greywackes. This north-vergent thrust fault, named as the Bükdere Fault, represents the suture fault in the Kepsut region (Akyüz & Okay 1996). The Bükdere Fault is an upper crustal structure with a zone of cataclasis several metres thick. Prior to the Early Miocene updoming, related to the intrusion of the Çataldağ granodiorite, the fault plane must have had a shallow southward dip. The klippe of greywackes and glaucophane–lawsonite blueschists west of Söve (Fig. 6) indicate a minimum northward translation of 40 km. The movement on the Bükdere Fault is constrained to the latest Cretaceous to Late Oligocene interval.

The İzmir–Ankara–Erzincan Suture between Balıkesir and Beypazarı

Along this 280 km long east–west-trending segment of the İzmir–Ankara–Erzincan suture between Balıkesir and Beypazarı, the Sakarya Zone is in contact with a regional blueschist belt (the Tavşanlı Zone) of the Anatolide–Tauride Block (Fig. 7). To the north of the suture there are units of the Karakaya Complex and the overlying Jurassic–Cretaceous succession of the Sakarya Zone, whereas to the south there are regional blueschists with Cretaceous isotopic ages, a Cretaceous accretionary complex, ophiolite and Eocene granodiorites of the Tavşanlı Zone (Okay 1984*b*). In this segment of the suture, continuous transects across the suture exists south of Bursa and in the geologically poorly known region northeast of Eskişehir (Fig. 7). In addition, in the area north of Sivrihisar, a sequence belonging to the Sakarya Zone outcrops in a fault-bounded block surrounded by the blueschists and peridotites of the Tavşanlı Zone (Fig. 7).

The Orhaneli transect A well-exposed continuous transect across the suture between Bursa and Orhaneli based on the works of Lisenbee (1971), Okay & Kelley (1994) and Okay *et al.* (1998) is shown in Figs 8 and 9. Like in the Kepsut region, the Sakarya Zone in the Orhaneli region consists at the base of intercalated metabasite, marble and phyllite of Permo-Triassic age, over 3 km thick, strongly deformed and metamorphosed in greenschist facies during the latest Triassic. These are tectonically overlain by strongly deformed but unmetamorphosed Late

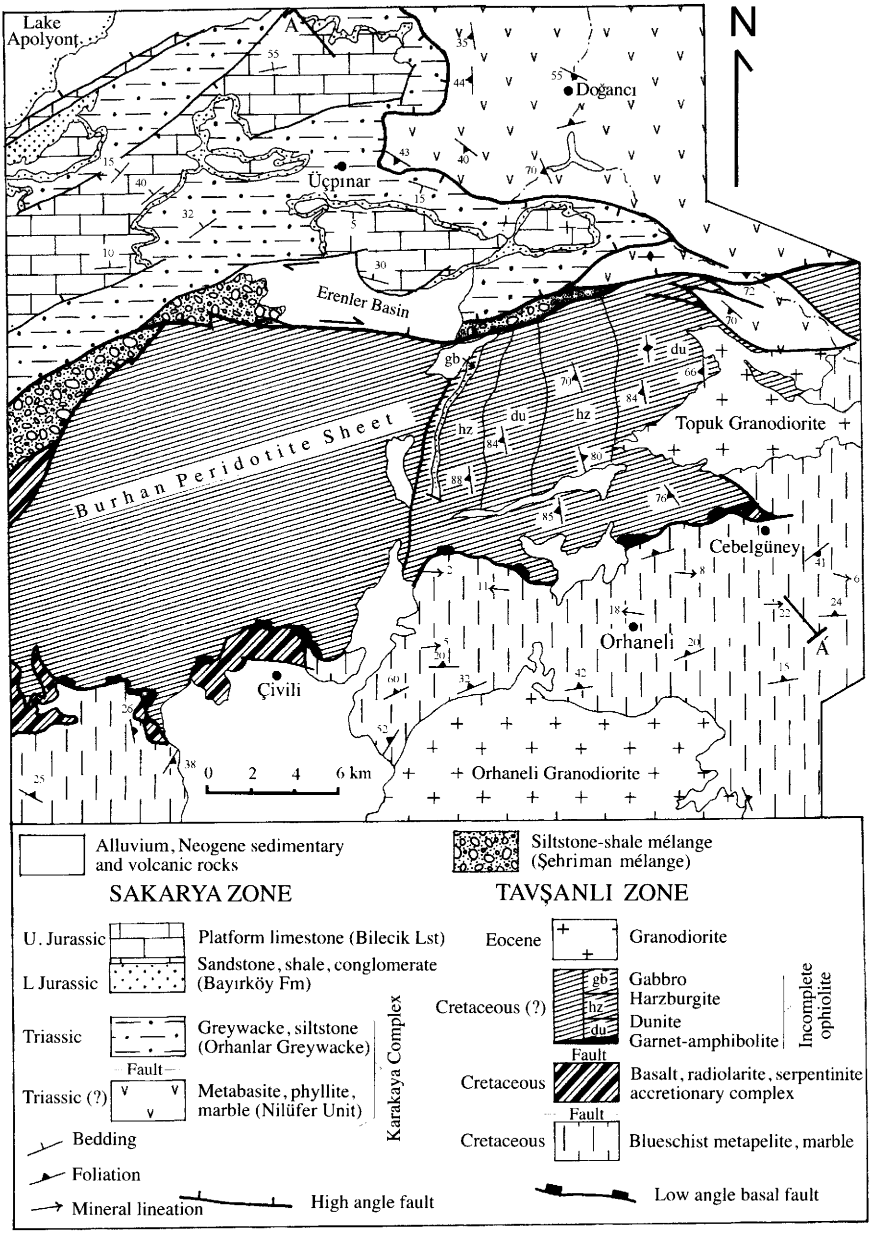

Fig. 8. Geological map of the suture region south of Bursa in northwest Turkey. For location see Fig. 7 (simplified from Okay *et al.* 1998).

Triassic greywackes, over 1 km in thickness, with exotic Permo-Carboniferous limestone olistoliths (Okay *et al.* 1998). The greywackes are unconformably overlain by 50–200 m thick continental to shallow-marine Liassic clastic rocks. Neritic Jurassic (Callovian to Tithonian) limestones, *c.* 800 m in thickness, lie disconformably on the Liassic sandstones and congomerates (Altıner *et al.* 1991).

The Tavşanlı Zone to the south is made up at the base of a coherent, clastic–limestone sequence, over 2 km in thickness, metamorphosed in blueschist facies. The blueschists are strongly deformed and show a well-developed

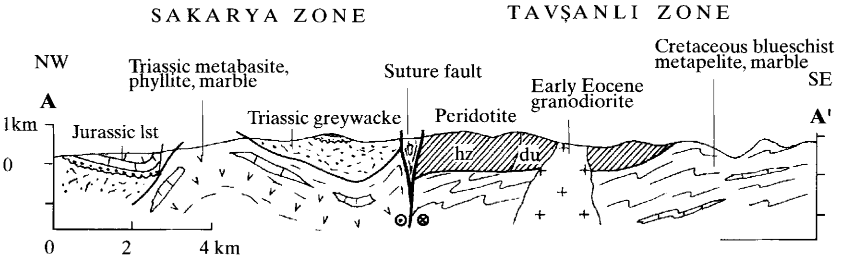

Fig. 9. Geological cross-section of the suture region south of Bursa. For location of the section see Fig. 8.

foliation, isoclinal folding and an east–west-trending mineral lineation (Okay *et al.* 1998). The metapelites contain the typical blueschist-facies minerals jadeite, glaucophane and lawsonite. Geothermobarometry indicates HP/LT metamorphism at 20 ± 2 kbar and 430 ± 30°C (Okay & Kelley 1994). Ar/Ar isotopic data indicate a Late Cretaceous age (80–90 Ma, Santonian/Campanian) for the blueschist metamorphism (Okay & Kelley 1994). The blueschists are overlain by a Cretaceous accretionary complex of basalt, radiolarian chert, pelagic limestone, shale and serpentinite (Fig. 8). A Senonian age has been obtained from the pelagic limestones in the accretionary complex. A large slab of ultramafic rocks with minor gabbro and diabase dykes lies with a subhorizontal contact over the accretionary complex and the blueschists (Figs 8 and 9). The mineralogy of the diabase dykes in the peridotite indicates that the peridotite has not undergone the HP/LT metamorphism observed in the underlying blueschists. At the base of the ultramafic slab there are isolated slices of garnet-amphibolite, similar to the metamorphic soles described from the base of other ophiolites (e.g., Williams & Smyth 1973; Spray *et al.* 1984). The garnet-amphibolite metamorphic soles give an Ar–Ar isotopic age of 101 ± 4 Ma (Harris *et al.* 1994).

Two granodiorites of Early Eocene age (52–48 Ma, Harris *et al.* 1994) intrude the blueschists and the overlying peridotite, and seal their contacts (Figs 8 and 9). The mineral assemblages in the contact metamorphic aureole of the granodiorites as well as Al-in-hornblende geobarometry indicates that the granodiorites were emplaced at a depth of *c.* 10 km (Harris *et al.* 1994). This indicates that the blueschists were exhumed from 60 km depth to 10 km in the Santonian–Early Eocene interval.

In the Orhaneli area the suture trace is delineated as a narrow well-defined discontinuity ranging from a single strike-slip fault to a maximum 3.5 km wide discontinuous fault zone bounding a tectonic mélange (Fig. 8). This Şehriman mélange consists of recrystallized limestone, greywacke, mafic volcanic rock and radiolarite blocks, ranging in scale from centimetre to kilometre, embedded in a highly sheared siltstone-shale matrix. Özkoçak (1969) reports poorly preserved *Globotruncana* sp. tests in the fine clastics suggesting a post-Late Cretaceous age for the formation of the mélange.

The suture fault system can be followed for 60 km along strike in the area studied (Fig. 7). Individual faults dip steeply (70–80°) towards the north or northwest. They are upper-crustal, brittle faults and the main fault branch cuts the Miocene conglomerates of the Erenler Basin northwest of Göktepe. The Erenler Basin is a small Miocene pull-apart basin, bounded to the north and to the south by two fault strands of the suture fault (Fig. 8). This suggests that the suture zone acted as a sinistral strike-slip fault during and after the Miocene. The zone was probably also active during the Eocene, as the Topuk granodiorite intrudes very close and parallel to an off-shoot of the main suture fault (Figs 7 and 8).

The Sivrihisar transect In the Sivrihisar region, 50 km south of the main suture trace, rocks of the Sakarya Zone occur as an east–west-trending fault block, 30 km long and 3 km wide (Fig. 7). A geological map and cross-section of this region, based on the works of Kulaksız (1981), Gautier (1984) and Monod *et al.* (1991) are given in Fig. 10. In the Sivrihisar region the Sakarya Zone is represented at the base by strongly sheared greywackes and shales with exotic blocks of basalt and Carboniferous, Permian and Middle Triassic limestone, forming part of the Karakaya Complex (Monod *et al.* 1991). These are unconformably overlain by basal clastic rocks of Jurassic age, which pass up to Middle Jurassic (Bathonian) to Lower Cretaceous (Upper Berriasian) limestones, 800 m in thickness (Gautier 1984). Senonian sandstone

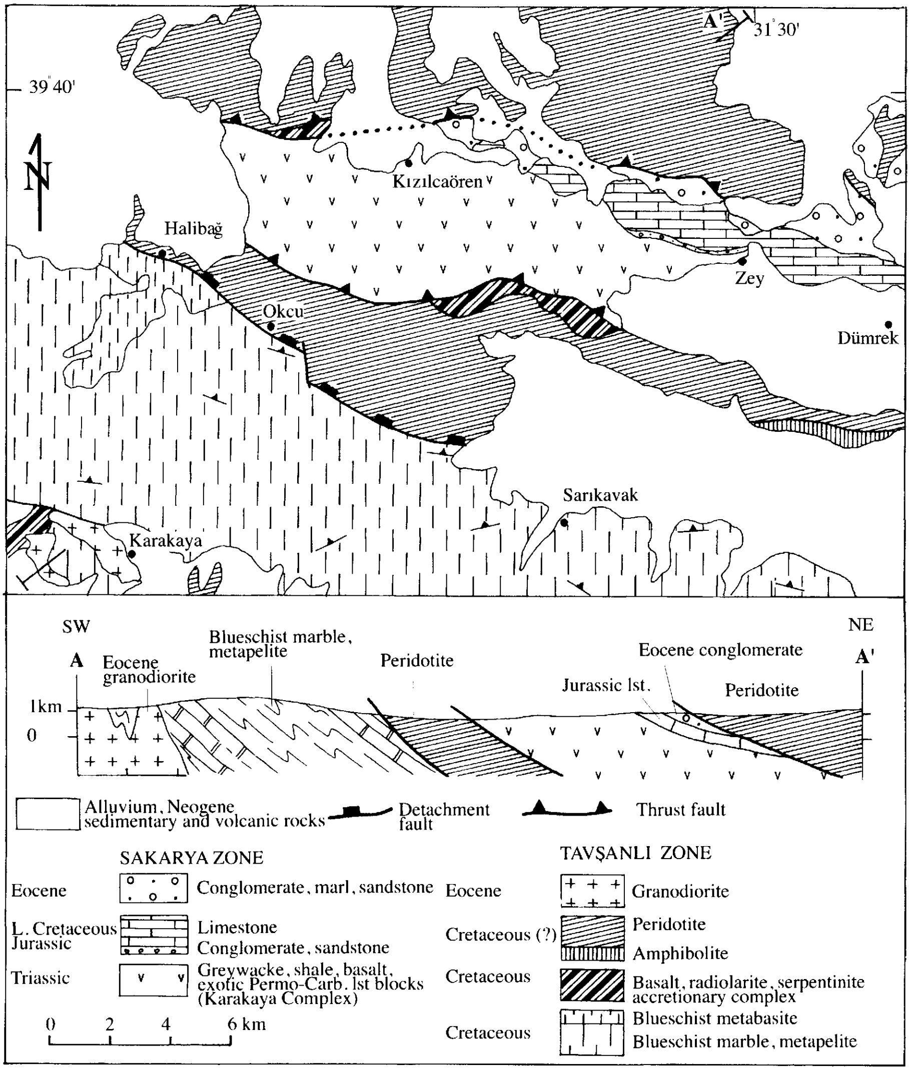

Fig. 10. Geological map and cross-section of the Sivrihisar region. For location of the section see Fig. 8 (simplified and modified from Monod *et al.* 1991).

and shales with *Globotruncana* sp., probably representing the uppermost part of this cover sequence, occur as a fault-bounded block north of Dümrek (Fig. 10, Gautier 1984).

The Tavşanlı Zone in the Sivrihisar region consists of a marble–schist sequence showing a well-developed foliation and isoclinal folding. This sequence contains generally greenschist-facies mineral assemblages, however, relicts of lawsonite and sodic amphibole in the schists indicate an earlier period of blueschists facies metamorphism (Monod *et al.* 1991). In an area south of Halibağı the metamorphic sequence is rich in metabasic rocks, and the blueschist minerals, including glaucophane, lawsonite, sodic pyroxene and garnet, are well preserved. K–Ar and Ar–Ar isotopic ages from this Halibağı region indicate a Senonian age for the HP/LT metamorphism (Sherlock *et al.* 1997). The blueschists are tectonically overlain by ultramafic rocks and are intruded by Mid-Eocene granodiorites (Fig. 10). Tectonic slices of accretionary complex and sub-ophiolitic garnet-amphibolites occur under the peridotites. A

Campanian age has been obtained from a pelagic limestone block in the accretionary complex west of the village of Karakaya (Fig. 10, Gautier 1984).

In the Sivrihisar region the Sakarya sequence lies tectonically over the blueschists with an intervening tectonic slice of ultramafic rocks (Fig. 10). An upper age limit for the thrusting of the Sakarya Zone over the Tavşanlı Zone is given by the Lower to Middle Eocene terrigenous to shallow marine sedimentary rocks, which lie unconformably over both the Sakarya sequence and the ultramafic rocks (Fig. 10). A lower age limit for the thrusting is provided by the Campanian pelagic limestones in the accretionary complex. A second phase of thrusting occurred after the Mid-Eocene, when the initial thrust stack was imbricated and the ultramafic rocks were emplaced over the Eocene clastic rocks (Fig. 10).

The Sakarya sequence in the Sivrihisar region, which is stratigraphically similar to that observed in the Central Sakarya Basin north of Bilecik (Figs 4 and 7), represents a klippe of the Sakarya Zone, comparable with the Dent Blanche Nappe in the Western Alps (e.g., Trümpy 1980). This Sivrihisar klippe indicates that during the Eocene, the front of the suture thrust was at least 50 km farther south than the present suture.

Evolution of the İzmir–Ankara–Erzincan suture between İzmir and Beypazarı

Age of the İzmir–Ankara–Erzincan ocean. The best evidence for the age span of the İzmir–Ankara–Erzincan ocean would be the ages recorded in the accretionary complex, which represent the cover sediments of the subducted Tethyan oceanic crust. However, at present there are very few documented radiolarian ages from the widespread accretionary complexes in the western Anatolia. Servais (1982) mentions Upper Jurassic–Lower Cretaceous radiolaria from cherts from an accretionary complex north of Kütahya, while Okay & Kelley (1994) describe *Pithonella ovalis*, a foraminifera characteristic for Cenomanian–Maastrichtian from a limestone–radiolarian chert slice from southwest of Bursa (Fig. 7). A more precise Campanian age, based on species of *Globotruncana*, has been obtained from Couches Rouges limestone blocks in the accretionary complex in the Sivrihisar region (Fig. 10, Gautier 1984). The ages of the ophiolites overlying the accretionary complex are not known directly, as only the lower plutonic parts of the ophiolite sequence are preserved. However, isotopic studies in the metamorphic soles of several ophiolite bodies, e.g., in the Semail ophiolite in Oman (Lanphere 1981), in Greek and Yugoslavian ophiolites (Spray *et al.* 1984), have shown that the age of the metamorphic sole is very similar to that of the overlying ophiolite. The isotopic ages from the subophiolite metamorphic rocks from northwest Turkey (*c.* 101 Ma, Önen & Hall 1993; Harris *et al.* 1994) suggest an Albian–Cenomanian age at least for some of the ophiolites. These data give a minimum age span of Late Jurassic to Campanian for the İzmir–Ankara–Erzincan ocean.

Senonian HP–LT metamorphism and deformation. The first Alpide orogenic event south of

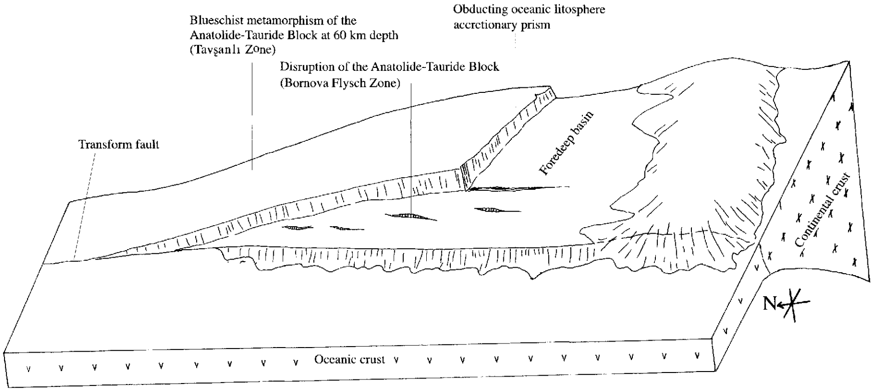

Fig. 11. Block diagram illustrating the Senonian evolution of the northwestern margin of the Anatolide–Tauride Block.

the suture is the blueschist metamorphism and related deformation of the Anatolide–Tauride Block, which took place during the early Senonian (Okay *et al.* 1998). During the Senonian there was continuous marine sedimentation in the Sakarya Zone north of the suture (Fig. 4), which shows that the HP–LT metamorphism and related deformation were not related to the continental collision between the Anatolide–Tauride Block and the Sakarya Zone. The HP–LT metamorphism was caused by the deep burial of the northern margin of the Anatolide–Tauride Block under a southward obducting oceanic lithosphere (Fig. 11) in a similar manner to that inferred in Oman (e.g., Goffe *et al.* 1988; Michard *et al.* 1991). The Senonian corresponds to a major change in sedimentation in the westernmost part of the Anatolide–Tauride carbonate platform as observed in the limestone blocks in the Bornova Flysch Zone. In different limestone blocks in the Bornova Flysch Zone Senonian red pelagic limestones rest unconformably over Triassic or Jurassic neritic limestones indicating a period of erosion prior to the deposition of the pelagic carbonates (Poisson & Şahinci 1988; Okay & Siyako 1993). This phase of uplift and erosion of the Triassic–Lower Cretaceous carbonate platform must have been related to the Late Cretaceous loading of the Anatolide–Tauride Block by ophiolite, accretionary prisms, and continental margin sediments, widespread relicts of which are preserved as erosional remnants. The progressive southwestward migration of this disruption of the carbonate platform starting from the beginning of Santonian in the Savaştepe-Soma region through end of Santonian in the area between İzmir and Seferihisar and finally to Campanian in the Karaburun peninsula indicates a northeasterly origin for the allochthons, which supports a temporal and causal relation between the blueschist metamorphism and disruption of the Mesozoic carbonate platform (Okay & Siyako 1993; Okay *et al.* 1996). However, the absence of regional metamorphism in the Bornova Flysch Zone indicates that it was never deeply buried under the southward obducting ophiolite and accretionary complexes, which therefore must have by-passed this westernmost margin of the Anatolide–Tauride Block (Fig. 11). This also provides an explanation for the scarcity of oceanic accretion complexes and ophiolite along the suture between İzmir and Balıkesir, while they are common to the east farther away from the suture (Fig. 5).

The İzmir–Ankara–Erzincan suture between

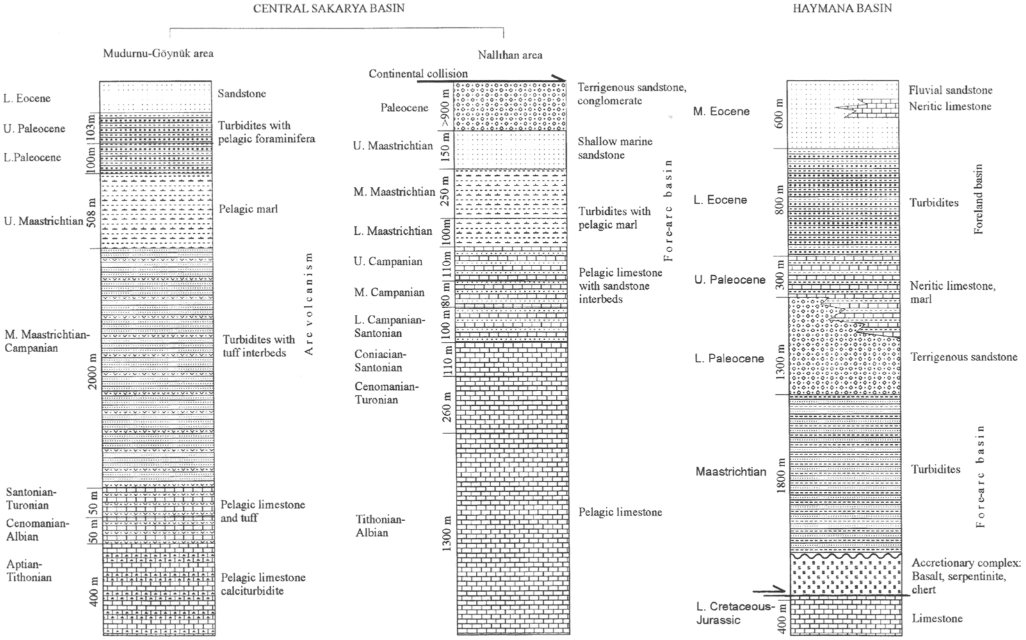

Fig. 12. Stratigraphic sections of the northern (Mudurnu-Göynük area, after Meriç & Şengüler 1986 and Altıner *et al.* 1991) and southern margins (Nallıhan area, after Tansel 1980, and Altıner *et al.* 1991) of the Central Sakarya Basin, and the Haymana Basin (after Ünalan *et al.* 1976). For location of the sections in the Central Sakarya Basin see Fig. 7. All the stages and substages shown have been determined palaeontologically.

İzmir and Balıkesir forms a discordant segment between the northwest-trending Vardar suture and east trending İzmir–Ankara–Erzincan suture east of Balıkesir (Fig. 1). A number of observations suggest that this is an original feature reflecting a transform fault margin connecting two passive continental margin segments (Okay *et al.* 1996). These observations are: (a) The Triassic to Lower Cretaceous limestone blocks in the Bornova Flysch Zone are neritic and betray no evidence of a proximity to a passive continental margin; (b) the Senonian obduction, which led to the 60 km deep burial and HP–LT metamorphism of the northern margin of the Anatolide–Tauride Block, did not result in the regional metamorphism in the Bornova Flysch Zone, which would have been highly unlikely if the northern margin of the Anatolide–Tauride Block was rectilinear; (c) arc-magmatism of Late Cretaceous age, common farther east, is not found northwest of the suture between İzmir and Balıkesir; (d) an originally northeast-trending passive continental margin would be unlikely in the Tethyan ocean, which was an east–west-trending seaway characterized by similar trending passive continental margins and subduction zones (e.g., Şengör *et al.* 1988; Ricou 1994); (e) in Greece, the ophiolites were obducted during the earliest Cretaceous southwestward over the Vardar and Pelagonian zones (e.g., Burchfiel 1980; Jacobshagen 1986). This earliest Cretaceous ophiolite obduction can be traced as far east as the Sporades islands in the Aegean Sea (Jacobshagen & Wallbrecher 1984), while in the Karaburun peninsula the carbonate sedimentation continues without a break from Ladinian to the Albian (Erdoğan *et al.*, 1990) with no evidence of an Early Cretaceous deformation. All of these features suggest that a transform fault formed the northwestern margin of the Anatolide–Tauride Block. During the Early Cretaceous the transform fault relayed the movement associated with the ophiolite obduction in Greece to an intra-oceanic subduction zone north of the Anatolide–Tauride platform (Okay *et al.* 1996), while during the Senonian it initiated and controlled the western limit of the obducting ophiolite (Fig. 11).

Senonian subduction and earliest Palaeocene continental collision. The onset and duration of subduction is probably best dated by the arc magmatism. In the Central Sakarya Basin, north of the suture between Balıkesir and Beypazarı (Fig. 7), the Valanginian to Aptian sequence is represented by pelagic micrites deposited in a south-facing passive continental margin (Fig. 12, Saner 1980; Altıner *et al.* 1991). These pass up into a heterogeneous and lateraly variable sequence of siliciclastic turbidites, pelagic limestones, olistostromes, tuffs and lava flows of Cenomanian to Maastrictian age, which were deposited in a fore-arc basin above the northward subducting İzmir–Ankara–Erzincan ocean (Şengör & Yılmaz 1981). Blocks of serpentinite, radiolarian chert and basalt, which occur in the Maastrichtian turbidites (Saner 1980) are probably derived from the emergent segments of the accretionary complex in the south.

Collision between an arc and passive margin would be reflected in a change of subsidence and sedimentation pattern in the opposing continental margin. The onset of collision would produce a regressive siliciclastic sequence and will be followed by regional folding and thrusting, and finally by uplift. Therefore, high-resolution stratigraphic data would be able to date the onset of collision fairly accurately (e.g., Rowley 1996). However, as shown in this study, the region south of the suture bears the strong imprint of the obduction-related, pre-collisional deformation and metamorphism, and most of the Mesozoic and Lower Tertiary cover has been stripped off from a several-kilometres-wide belt north of the suture between İzmir and Beypazarı (Figs 5 and 7). The Cretaceous–Lower Tertiary sequence nearest to the suture is found in region of Nallıhan (Fig. 7). Here, the Tithonian to Early Campanian is represented by pelagic micrites, the first sandstone interbeds begin in the Early Campanian and by the Early Maastrichtian the sequence has been transformed into siliciclastic turbidites with rare marl intervals with planktonic microfossils probably deposited in a fore-arc basin (Fig. 12, Tansel 1980). The turbidites show a regressive development so that by the Late Maastrichtian the sequence consists of conglomerate and sandstones with benthic foraminifera. These pass up without a break into terrigeneous red conglomerates and sandstones presumably Early Palaeocene in age (Tansel 1980). This is followed by south-vergent thrust imbrication whereby the Cretaceous sequence is emplaced over the Palaeocene red beds. The stratigraphic data from the Nallıhan region indicates that the arc-continent collision occurred at around the Maastrictian–Palaeocene boundary at about 65 Ma. Geological relations in the Sivrihisar region indicate that during the Palaeocene collision the Sakarya sequence was sheared off from a level below the Karakaya Complex and was thrust south for at least 50 km over the Anatolide–Tauride Block. The major southward translation and subsequent erosion of the Sakarya Zone also provide an explanation for

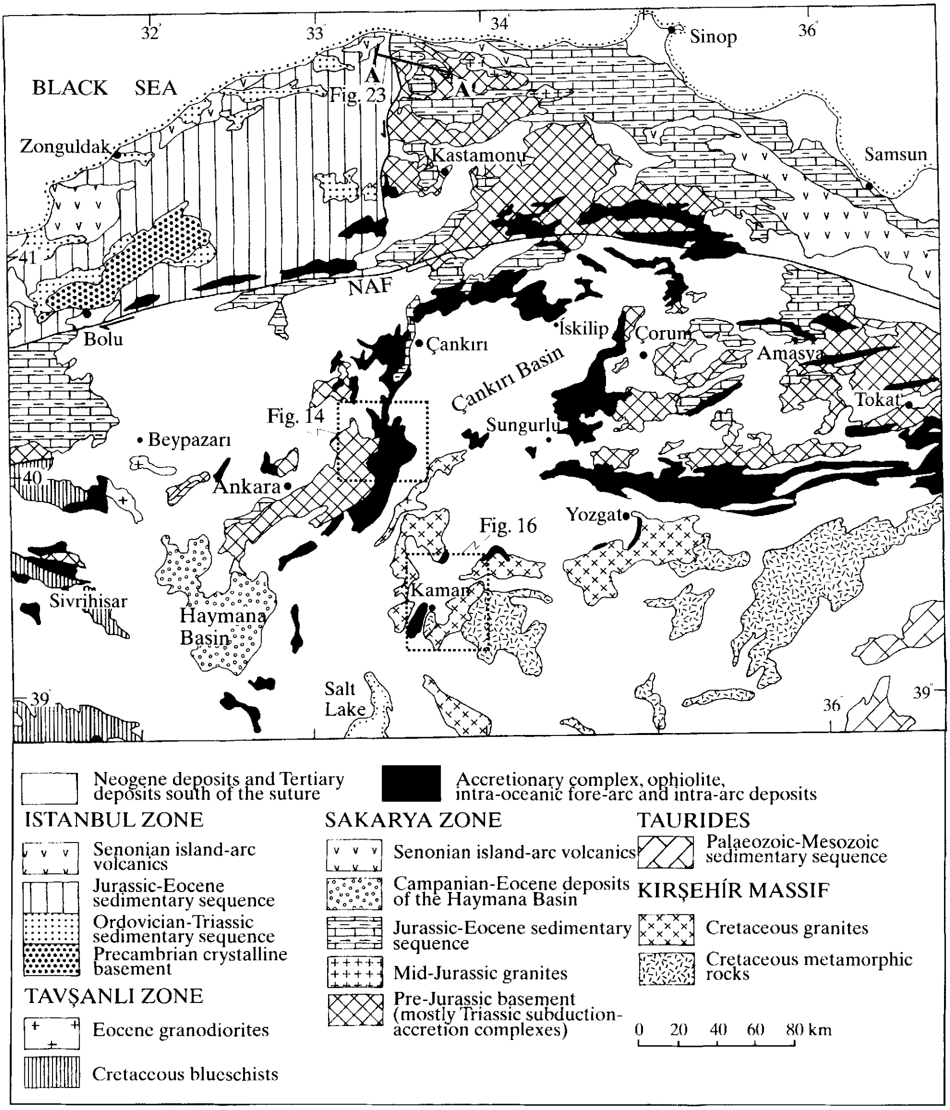

Fig. 13. Geological map of the region around the İzmir–Ankara–Erzincan suture between Nallıhan and Tokat.

the apparent anomaly that the Jurassic sandstones and limestones, which south of Bursa approach as near as 1.5 km to the suture (Fig. 8), still retain their shallow-marine character and show no evidence of a proximity to a continental margin. The collision-related southward thrusting was followed by the intrusion of Early Eocene granodiorites. During the Miocene the suture was locally used by the strike-slip faults related to the North Anatolian Fault.

The Haymana loop of the İzmir–Ankara–Erzincan suture between Beypazarı and Ankara

The width of the Tavşanlı Zone increases towards the east and shows its widest extent of about 150 km south of Beypazarı and then is abruptly terminated along a poorly defined line trending south from Beypazarı (Fig. 13). To the east of this line there is a major turbidite-dominated Late

Cretaceous to Eocene basin, called the Haymana Basin. The contact between the Haymana Basin and blueschists are covered by extensive, post-tectonic Neogene sedimentary rocks but is likely to be tectonic.

The basement of the Haymana Basin consists of an accretionary complex and the structurally underlying Jurassic–Lower Cretaceous carbonates of the Sakarya Zone (Fig. 12, Ünalan *et al.* 1976; Batman 1978; Görür *et al.* 1984; Koçyiğit, 1991). The sequence in the Haymana Basin starts with a few tens of metres-thick basal conglomerates, which pass up into a 1800 m thick distal turbidites of Upper Campanian to Maastrichtian age. The basin shallows in the latest Maastrichtian and the turbidites are overlain by Palaeocene terrigeneous conglomerate and sandstones up to 1300 m in thickness (Ünalan *et al.* 1976; Görür *et al.* 1984). Ophiolite and blueschist detritus, including pebbles of glaucophane–lawsonite schists, have been described in the Upper Campanian–Maastrichtian turbidites (Batman 1978) and Palaeocene clastic rocks (Norman & Rad 1971). The Palaeocene terrigenous siliciclastic rocks are overlain by a second cycle of regressive turbidite sequence, up to 2000 m thick, of Early to Mid-Eocene age (Fig. 12, Ünalan *et al.* 1976, Görür *et al.* 1984, Koçyiğit 1991).

The stratigraphic position of the Haymana Basin over an accretionary complex, its tectonic setting along a suture and the clastic dominated Upper Cretaceous–Eocene sequence, over 5 km in thickness, led to its interpretation as a fore-arc basin on the southern edge of the Sakarya Zone (Görür *et al.* 1984; Koçyiğit 1991). The shallowing of the basin during the latest Maastrichtian, and evidence for earliest Palaeocene continental collision from farther west, indicate that the Haymana Basin is a composite basin; the lower section of Campanian–Maastrichtian age represents a fore-arc basin, whereas the overlying Paleocene–Middle Eocene sequence has been deposited in a foreland basin formed during and after the continental collision. The lower part of the Haymana sequence can be compared with the turbidites of the same age in the Central Sakarya Basin, which had a similar tectonic setting (Fig. 12). However, the accretionary complex which occurs below the Upper Campanian turbidites of the Haymana region is not observed to the west. This enigmatic mid-Cretaceous event of northward obduction of the accretionary complex over the Sakarya Zone, just before the onset of northward subduction, is a feature observed throughout the rest of the İzmir–Ankara–Erzincan suture.

The Çankırı loop of the İzmir–Ankara–Erzincan suture

Between the Haymana Basin and Sivas the İzmir–Ankara–Erzincan suture defines the contact between the Sakarya Zone and the Kırşehir Massif. In this large region the suture is generally represented by post-Eocene thrusts which emplace rocks of the Sakarya Zone over the Tethyan subduction–accretion complexes. The Tethyan subduction–accretion complexes form a 5–10 km wide tectonic belt, which circles and radially thrusts the Eocene–Miocene sedimentary rocks of the Çankırı Basin resulting in a large loop of the suture (Fig. 13).

The Ankara transect. A geological map and cross-section of a relatively well-studied part of the suture east of Ankara is given in Figs 14 and 15 (Akyürek *et al.* 1988). This region forms part of the classical area of Ankara Mélange studied by Bailey & McCallien (1953). The Sakarya Zone in this region shows a similar stratigraphy as that in the previous traverses (cf. Figs 8 and 10). At the base there is a metabasite–phyllite–calc-schist sequence with rare ultramafic lenses metamorphosed in greenschist facies (Koçyiğit 1987; Akyürek *et al.* 1988). This is overlain tectonically, by a chaotically deformed Late Triassic series of greywacke, siltstone, basalt and exotic blocks of Carboniferous and Permian neritic limestone. Little deformed Liassic conglomerate, sandstone and siltstone with ammonitico rosso horizons lie with a pronounced unconformity over the deformed Triassic series (Fig. 14). The Liassic clastic rocks pass up into hemipelagic limestones of Upper Jurassic–Aptian age, which are preserved as small erosional outliers (Fig. 14; Koçyiğit 1987; Akyürek *et al.* 1988). This Sakarya sequence is thrust eastward over the Cretaceous subduction–accretion units. A minimum eastward translation of 30 km can be estimated from the small tectonic windows in the Sakarya basement exposing ophiolitic units (Akyürek *et al.* 1988).

The Cretaceous subduction–accretion complex in the Ankara region can be divided into two composite thrust sheets (Akyürek *et al.* 1988; Tüysüz *et al.* 1995). The upper sheet consists essentially of ophiolite imbricates including peridotite, gabbro, basalt, Cenomanian to Maastrichtian pelagic limestone and radiolarian chert, a few metres to a few kilometres in size (Fig. 14, Tüysüz *et al.* 1995). The lower thrust sheet, termed the Kalecik Unit, has a more ordered stratigraphy and consists of a Cenomanian to Maastrichtian volcano-sedimentary sequence, *c.* 3500 m thick, deposited on an ophiolitic

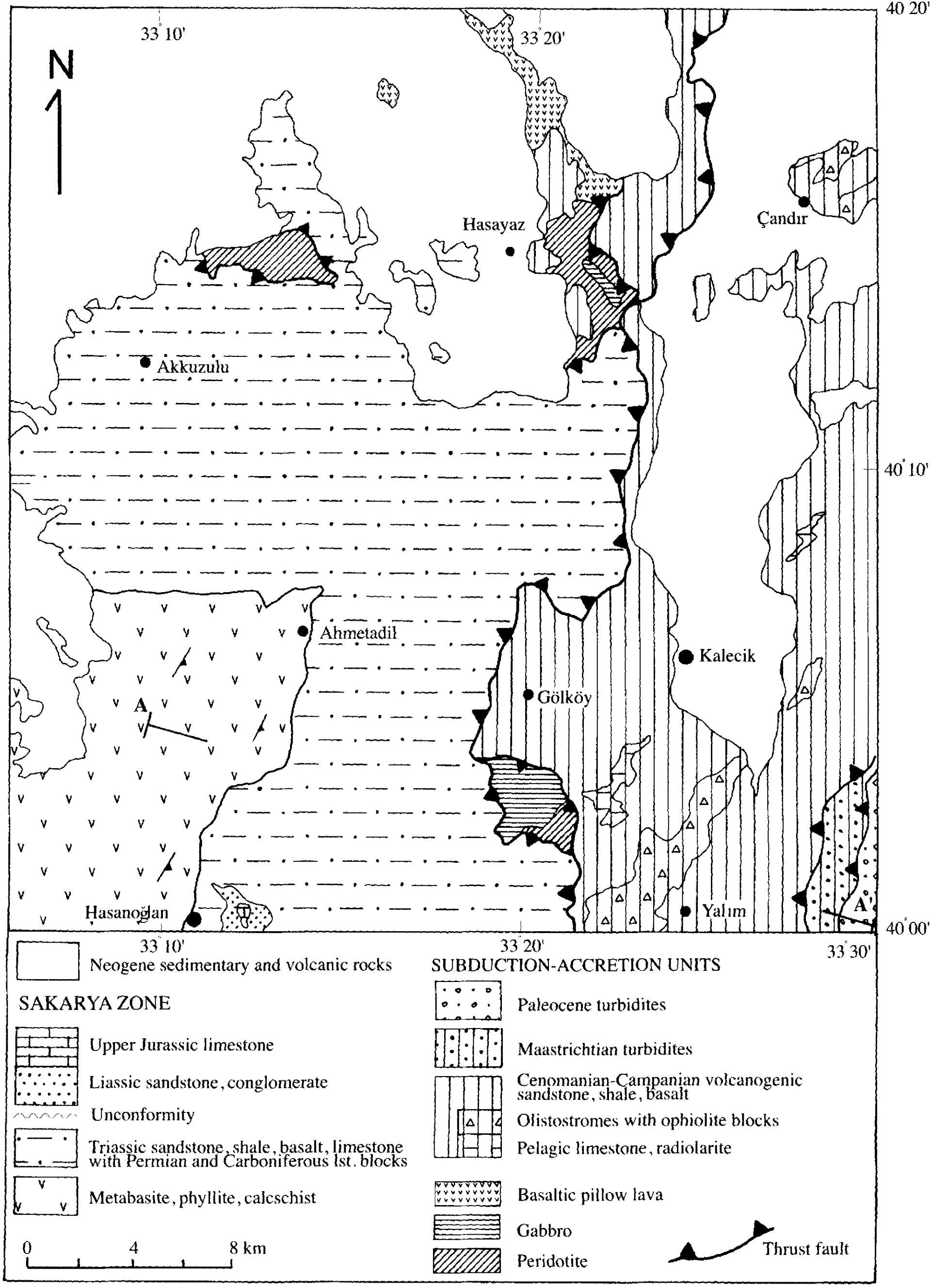

Fig. 14. Geological map of the suture region northeast of Ankara (simplified from Akyürek *et al.* 1988).

substratum (Fig. 14, Tüysüz *et al.* 1995). The sequence consists essentially of pelagic limestones intercalated with basalts and basaltic andesites with geochemical signatures suggestive of island-arc and/or hot-spot magmatism (Floyd 1993; Tüysüz *et al.* 1995). Debris flow and olistostrome horizons, up to several hundred metres in thickness, with blocks of peridotite, gabbro,

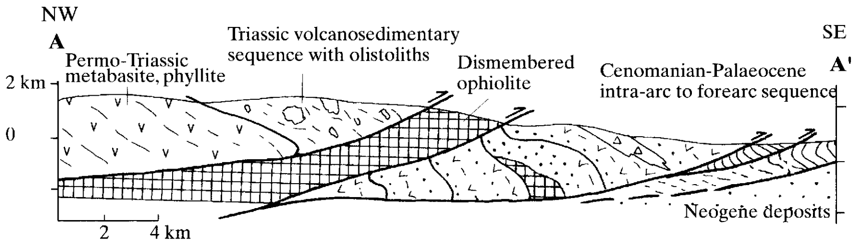

Fig. 15. Geological cross-section of the suture region northeast of Ankara. For location of the section see Fig. 14.

basalt, occur in the pelagic limestone or pyroclastic rocks. This volcanic rock-pelagic limestone sequence is overlain by an over 1000 m thick regressive turbidite sequence of sandstone, siltstone and shale of Maastrichtian age. Tüysüz *et al.* (1995) suggested an ensimatic intra-arc for the depositional setting of the lower part of the Kalecik Unit. This is based on its ophiolitic basement, the close intercalation of basalt and pelagic limestone, absence of continent-derived detritus, and on the geochemistry of the magmatic rocks. The ophiolite olistoliths in the Kalecik sequence were probably derived from emerged segments of the oceanic accretionary complex. The turbididic upper part of the Kalecik Unit was probably deposited in a fore-arc basin following a possible landward migration of the magmatic arc.

The Kaman transect. Around the Çankırı loop the Cretaceous subduction–accretion units are thrust over the Eocene–Miocene sedimentary rocks. Their relation with the Kırşehir Massif is best observed in the region of Kaman northeast of the Salt Lake (Fig. 16, Seymen 1981, 1983, 1984). In the Kaman region the lowest exposed unit is an isoclinally folded sequence of gneiss, migmatite, micaschist, metaquarzite, calc-silicate rock and marble metamorphosed in amphibolite to granulite facies. The clinopyroxene + orthopyroxene + hornblende + plagioclase + quartz paragenesis in the gneisses, and the presence of sillimanite, cordierite and garnet in the micaschists indicate *P–T* conditions of 700 to 800°C and 3–5 kbar (Seymen 1981). The age of this HT/LP metamorphism is believed to be Cretaceous based on K–Ar cooling ages from farther southeast (Göncüoğlu 1986). The metamorphic rocks in the Kaman region are tectonically overlain by an unmetamorphosed Cretaceous accretionary complex of gabbro, dolerite, basalt, radiolarian chert, pelagic limestone, greywacke, shale, and serpentinite. Campanian ages have been obtained from the pelagic limestones from the accretionary complex (Seymen 1983). A large ultramafic slab lies structurally above the accretionary complex (Fig. 16, Seymen 1981). Although the contact between the metamorphic rocks and the overlying accretionary complex has been interpreted as a thrust (Seymen 1981, 1983), it could be a detachment fault with a normal sense of displacement, which allowed the exhumation of the metamorphic rocks. Both the metamorphic rocks and the overlying accretionary complex are cut by a granodiorite with a Rb/Sr age of 71 ± 1 Ma (Ataman 1972). Terrigenous to shallow-marine clastic rocks and limestones of Maastrichtian to Lower Palaeocene age lie unconformably over the accretionary complex (Fig. 16; Görür *et al.* 1984; Seymen 1984).

Evolution of the İzmir–Ankara–Erzincan suture region between Beypazarı and Tokat

Age of the İzmir–Ankara–Erzincan ocean. Recent determination of radiolaria from different chert blocks from a single locality of Cretaceous accretionary complex northwest of Ankara has yielded Upper Norian, Lower Jurassic, Kimmeridgian–Tithonian and Albian–Turonian ages (Bragin & Tekin 1996). These radiolarian chert blocks occur in an ophiolitic mélange and are associated with blocks and thrust slices of gabbro, basalt, pelagic limestone and volcano-clastic rocks. Red radiolarian chert blocks with Tithonian radiolaria are also recently described from a slice of accretionary complex, several metres thick, imbricated in the basement of the Sakarya Zone north of Tokat (Bozkurt *et al.* 1997). These data indicate that the age of the İzmir–Ankara–Erzincan ocean spans at least from Late Norian to Albian, while the age of the Kalecik Unit further extends the age of the ocean to the end of Maastrichtian.

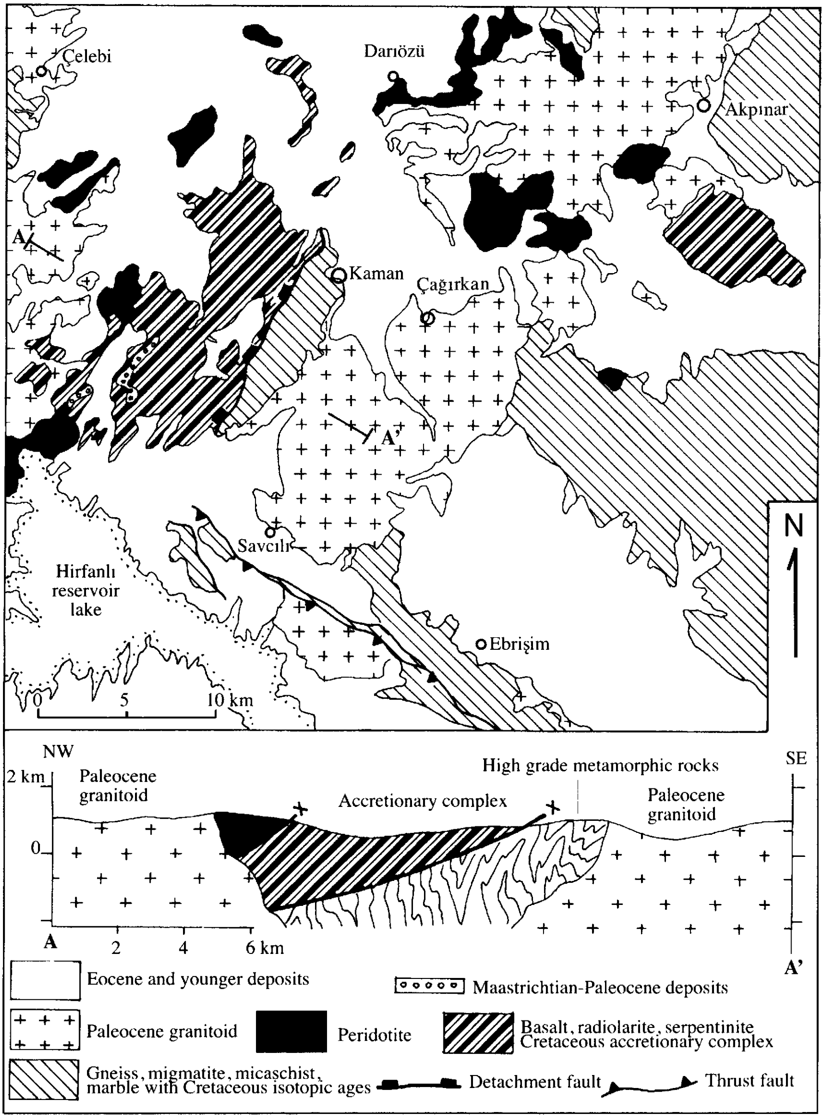

Fig. 16. Geological map and cross-section of the western part of the Kırşehir Massif illustrating the relation between Cretaceous metamorphic rocks, accretionary prism and granitoids (simplified from Seymen 1984).

Senonian subduction and latest Maastrichtian collision. The age of the Kalecik Unit, interpreted as intra-arc to fore-arc deposits, indicates that the subduction in the İzmir–Ankara–Erzincan Ocean in this segment started during the Cenomanian–Turonian, which ties well with the inception of arc volcanism in the Central Pontides during the Coniacian (Fig. 4, Tüysüz 1993). The Senonian subduction must have built up a very wide accretionary complex south of the Sakarya Zone; even after the shortening following the collision, the width of the accretionary complex, estimated from erosional outliers, is in excess of 80 km. This wide accretionary complex was thrust over the Kırşehir Massif during the early Maastrichtian.

The relation between the subduction–collision processes in the İzmir–Ankara–Erzincan, and granitic magmatism and associated regional metamorphism in the Kırşehir Massif is difficult to ascertain in the absence of reliable and precise geochronological data, especially on the

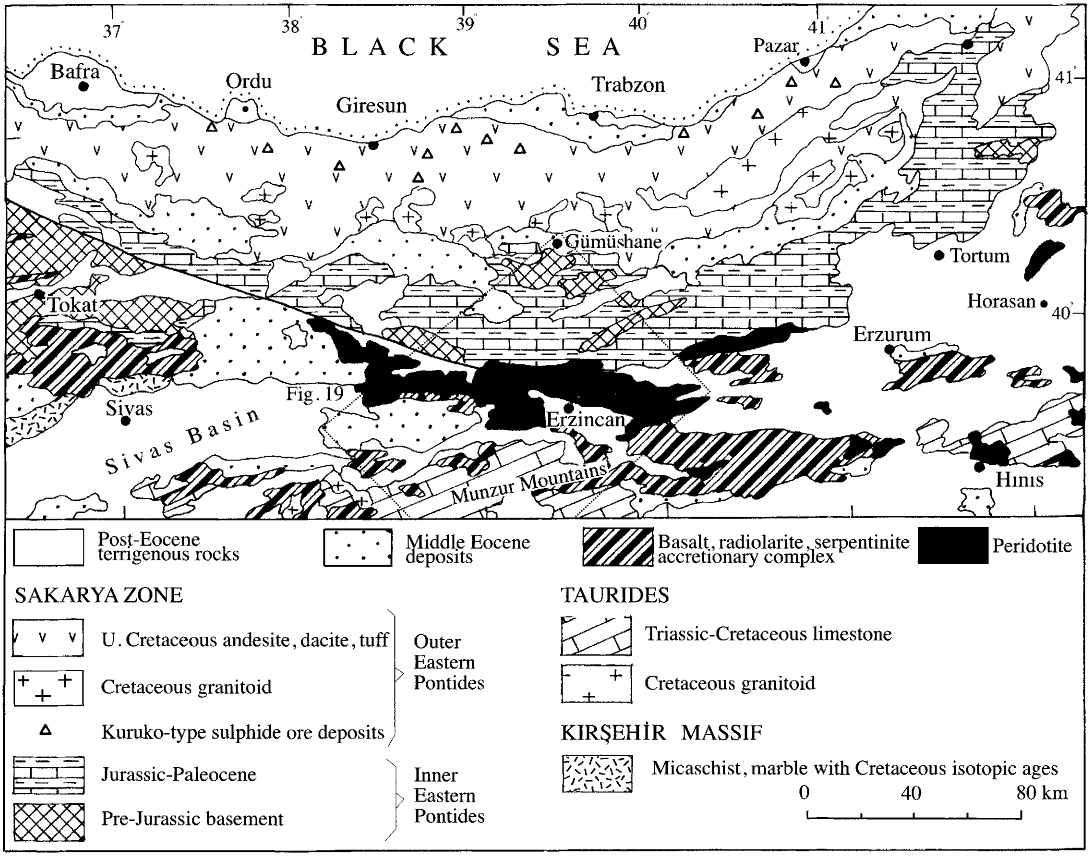

Fig. 17. Geological map of the Eastern Pontides (modified from Okay & Şahintürk 1998).

age of regional metamorphism. If the regional metamorphism in the Kırşehir Massif is Aptian–Cenomanian in age, as seems likely from Rb/Sr isotopic data from the intrusive granitoids (e.g., Güleç 1994), then it can not be genetically related to the subduction or collision along the İzmir–Ankara–Erzincan suture. A possible cause for the HT/LP regional metamorphism and granitic magmatism in the Kırşehir Massif is mid-Cretaceous northward subduction of the Inner Tauride Ocean under the Kırşehir Massif (Fig. 1).

Collision between the Kırşehir Massif and the Sakarya Zone is poorly constrained, especially since the Cretaceous sequences have been eroded in the Sakarya Zone up to 60 km north of the suture (Fig. 13). However, the regressive development of the Maastrichtian turbidites of the Kalecik Unit, interpreted to have been deposited in a fore-arc, suggests uplift of the fore-arc during the latest Maastrichtian due to underthrusting of the Kırşehir Massif. A collision of latest Maastrichtian age would also explain the upper Maastrichtian and Palaeocene terrigeneous to shallow marine clastic and carbonate rocks, which lie unconformably over the accretionary complex in the Kaman region (Fig. 16). Like the case farther west, the collision in the Ankara-Tokat segment involved the delamination of the Sakarya Zone and the southward thrusting of the upper part of the sequence over the ophiolitic units and accretionary complex (Fig. 15). The steep belt, marking the subduction of the lower continental crust must lie farther north than the present suture trace.

The İzmir–Ankara–Erzincan suture south of the Eastern Pontides

The Kırşehir Massif tapers out towards the east, and the Sakarya Zone comes again in direct contact with the Anatolide–Tauride Block in the region south of the Eastern Pontides (Fig. 1). In this 320 km long east–west-trending segment the Alpide orogen shows an organization as expected from a classical collisional orogeny (Fig. 17). To the north in the Outer Eastern Pontides there is a well-developed major Upper Cretaceous magmatic island arc, which borders to the south a Senonian fore-arc region represented by the Inner Eastern Pontides. Farther south there is a wide suture zone marked by large bodies of peridotite and accretionary complex. To the south of the suture is a thick Mesozoic carbonate platform overlain by a thrust sheet of ophiolite and accretionary complex. Below we first outline the main geological features of the Eastern Pontide magmatic arc, which forms one of the largest Tethyan magmatic arcs, then describe a wide transect from Gümüşhane to the Munzur mountains.

The Eastern Pontide Magmatic Arc. The Eastern Pontide Magmatic Arc is a 40 km wide zone bordering the Black Sea characterized by an over 2 km thick sequence of Senonian volcanic and intercalated sedimentary rocks and intrusive granodiorite plutons (Boccalatti *et al.* 1974; Akın 1978; Şengör & Yılmaz 1981; Okay & Şahintürk 1998). The magmatic arc is interpreted to have formed during the northward subduction of the İzmir–Ankara–Erzincan ocean under the Sakarya Zone (Akın 1978; Şengör & Yılmaz 1981).

Small inliers of Upper Jurassic–Lower Cretaceous limestones in the outer Eastern Pontides indicate that the magmatic arc has been constructed on the Lower Cretaceous and older rocks of the Sakarya Zone. The Senonian volcanic cycle starts with basalts and andesites and passes to dacitic and rhyolitic lavas and breccias and tuffs with limestone intercalations and ends with a variegated series of mudstone, marl, tuff, radiolarian chert and limestone (Schultze-Westrum 1962; Zankl 1962; Hirst & Eğin 1979; Akıncı 1984). The volcanic sequence, over 2000 m in thickness, is well dated through the intercalated limestones and extends from Turonian (Taner & Zaninetti 1978) to Late Maastrichtian and Danian (Hirst & Eğin 1979), which places tight constraints on the duration of subduction. The Senonian volcanic rocks are generally subalkaline and give typical island arc geochemical signatures (Peccerillo & Taylor 1975; Akın 1978; Eğin *et al.* 1979; Manetti *et al.* 1983; Akıncı 1984). Large number of granodiorite intrusions are associated with the Cretaceous volcanic rocks (Fig. 17). Their isotopic ages range from about 95 to 65 Ma (Taner 1977; Moore *et al.* 1980). Although they show a wide modal scatter, they are dominantly hornblende–biotite granodiorite and quartz–diorite; geochemically the granitoids show a typical calc-alkaline trend (Taner 1977; Moore *et al.* 1980). In the Eastern Pontide magmatic arc there are also numerous massive and stockwork-type polymetallic (Fe, Cu, Pb, Zn) sulphide ores, which occur within the Maastrichtian dacitic–rhyolitic lavas, breccias and tuffs (Akın, 1978; Eğin *et al.*, 1979; Hirst and Eğin, 1979; Akıncı 1984). These are very similar to the Japanese Kuroko sulphide ores of Miocene age formed during arc volcanism around the volcanic centres (Mitchel & Garson 1976). The Cretaceous magmatic arc of the outer Eastern Pontides is little deformed. The structure of the Mesozoic series is characterized by block-faulting and gentle seaward dips. To date no major folds or thrusts have been mapped. The steep-dipping faults defining complex horst and grabens are generally conjugate and follow NE and NW directions (Schultze-Westrum 1962; Zankl 1962; Kronberg 1970; Akın 1978).

The Senonian volcanic arc of the Eastern Pontides was an extensional arc as shown by the submarine nature of the volcanism. The marginal basins behind extensional arcs usually develop by the splitting of the volcanic arc axis (e.g., Karig 1971). The distribution of the Kuroko type ore deposits in the Eastern Pontides indicates that during the Maastrichtian the volcanic arc axis was located close to the present day Black Sea coast (Fig. 17, Okay & Şahintürk, 1998). Thus, the East Black Sea Basin probably started to open during the Maastrichtian by the splitting of this arc axis.

The Gümüşhane–Munzur transect. The Gümüşhane–Munzur transect is the best exposed and continuous transect across the İzmir–Ankara–Erzincan suture. In addition, the preservation of Upper Cretaceous and Lower Tertiary sequences in the suture region allow a precise dating of the subduction and collision events in the İzmir–Ankara–Erzincan ocean (Fig. 18). A geological map and cross-section of a wide region from Gümüşhane to the Munzur mountains is given in Figs 19 and 20. This region will be described in three parts: (1) the Inner Eastern Pontides, which constitute the southern margin of the Sakarya Zone, (2) the Munzur sequence representing the northern margin of the Anatolide–Tauride Block and (3) the suture zone itself.

(1) *Inner Eastern Pontides south of Gümüşhane.* The Inner Eastern Pontides south of Gümüşhane show the typical stratigraphic features of the Sakarya Zone including a complex pre-Jurassic basement, a major Liassic

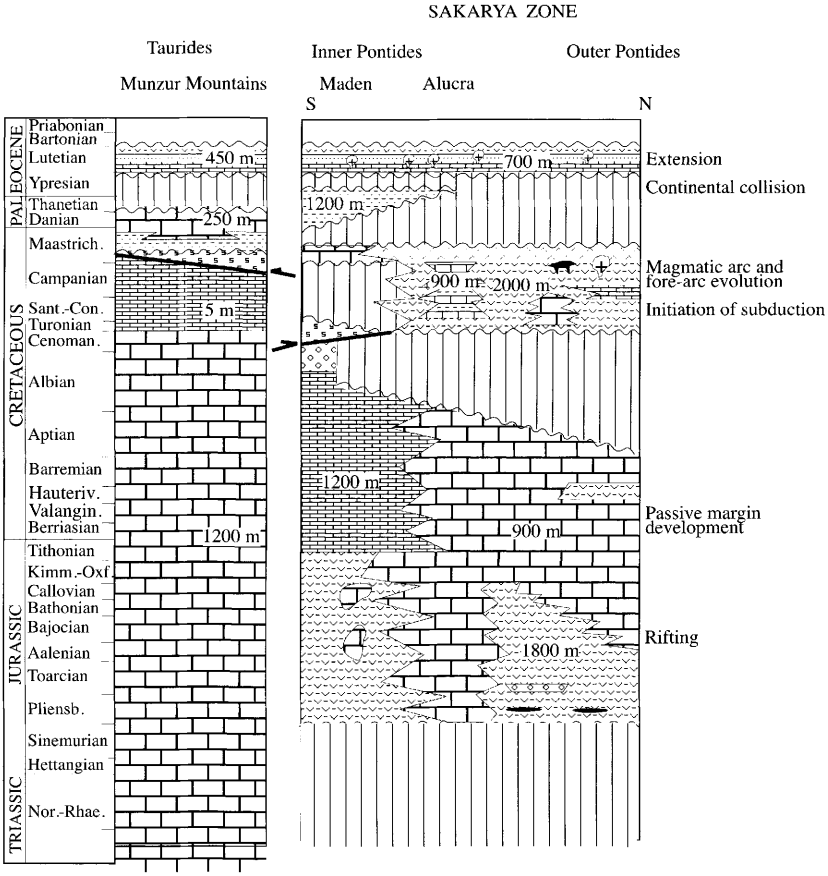

Fig. 18. Stratigraphic sections of the Sakarya Zone and the Anatolide-Tauride Block in the Eastern Pontides (modified from Okay & Şahintürk 1998). Symbols as in Fig. 2.

transgression, and the ubiquitous Upper Jurassic–Lower Cretaceous carbonates overlain by accretionary prism obducted northward during Cenomanian–Turonian times. During the Senonian the Inner Eastern Pontides were in a fore-arc position and received volcano-clastic sediments. Structurally the Inner Eastern Pontides is a north-vergent fold and thrust belt formed during the Palaeocene continental collision (Okay *et al.* 1997).

The pre-Jurassic basement of the Inner Eastern Pontides is exposed in a number of north-vergent thrust sheets. In contrast to the regions farther west, the pre-Jurassic basement is heterogeneous and consists of Hercynian and Cimmeride sequences. The Hercynian crystalline units comprise sillimanite–cordierite–garnet-bearing high-grade metamorphic rocks (Okay 1996) with mid-Carboniferous Sm–Nd garnet ages (322–312 Ma, Topuz *et al.* 1997), as exposed in the Pulur Massif (Fig. 19) and granites with Early Carboniferous Rb/Sr isochron ages (360 Ma, Bergougnan 1987), which cover large areas south of Gümüşhane (Fig. 19). Similar Hercynian metamorphic and granitic rocks have been described from the Lesser Caucasus (Adamia *et al.* 1983). An uppermost Carboniferous sequence of conglomerate, sandstone, neritic limestone and quartzites, which crop out east of Kelkit at the base of the thrust stack (Figs 19 and 20, Ketin 1951; Okay & Leven 1996), probably lies unconformably over the Hercynian crystalline basement. This Upper Carboniferous sequence of shallow marine to terrigenous origin, can be compared with the Rotliegende formation of Central Europe. The Cimmeride units, which are rare in the Eastern Pontides, include the metabasite–marble–

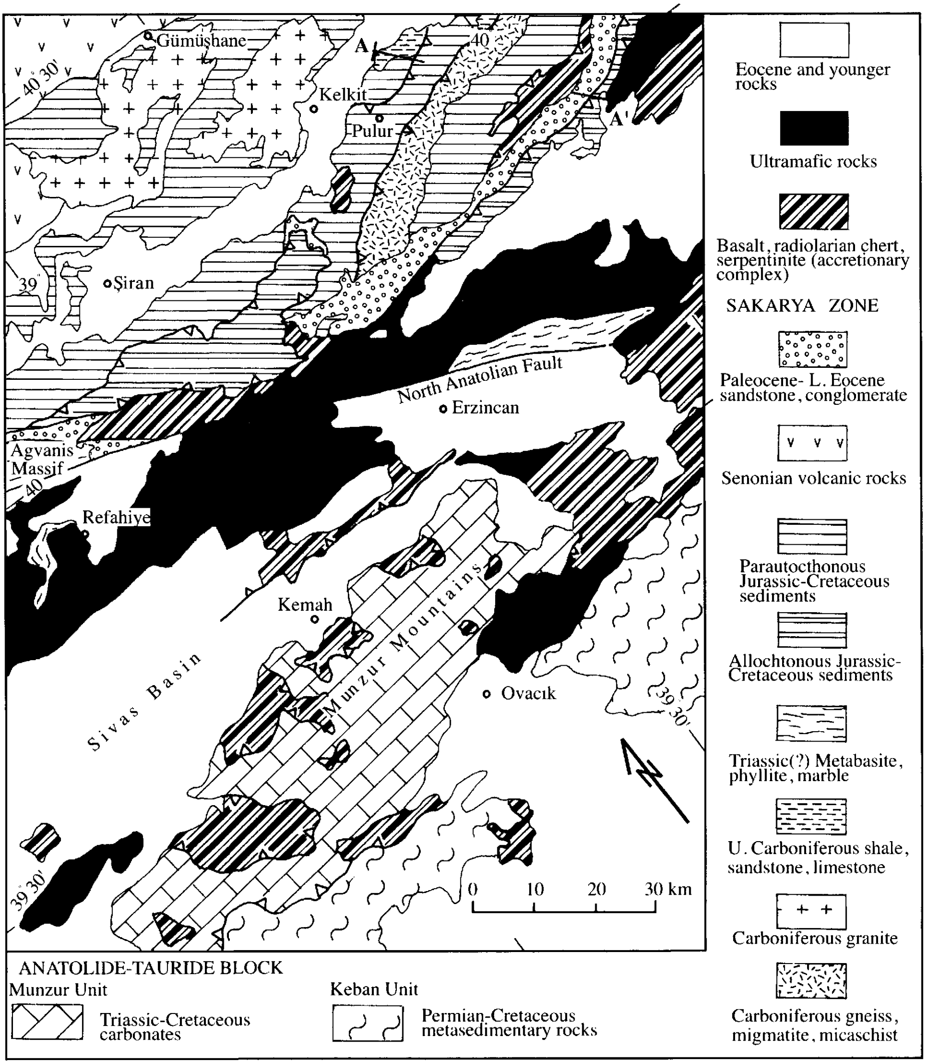

Fig. 19. Geological map of the suture region between Gümüşhane and Munzur mountains (modified from Özgül & Turşucu 1984 and Okay & Şahintürk 1998).

phyllite sequence in the Ağvanis Massif (Okay 1984*a*).

The Mesozoic sedimentary sequence in the Inner Eastern Pontides starts, like elsewhere in the Sakarya Zone, with a major Liassic transgression possibly coming from the south (Fig. 18, Akın 1978). The Lower–Middle Jurassic throughout the Eastern Pontides is represented by a characteristic volcanosedimentary formation, up to 2000 m thick, of basaltic and andesitic lithic tuffs and lavas, volcanogenic sandstone, shale, conglomerate. Within this Kelkit Formation there are also thin, discontinuous coal and ammonitico rosso horizons (Pelin 1977; Bergougnan 1987). Ammonites from the ammonitico rosso horizons (Bassoullet *et al.* 1975; Bergougnan 1987), palynology of the coal horizons (Ağralı *et al.* 1965) and dinoflagellate and palynomorph assemblages (Robinson *et al.* 1995) indicate an age span for the Kelkit Formation from Early Pliensbachien up to at least the end of the Bathonian (Fig. 18). The Kelkit Formation shows rapid lateral facies and thickness changes and in general exhibits a deeper marine character towards the south.

In the Gümüşhane region, the Upper Jurassic–Lower Cretaceous carbonates lie conformably over the Kelkit Formation. They occur

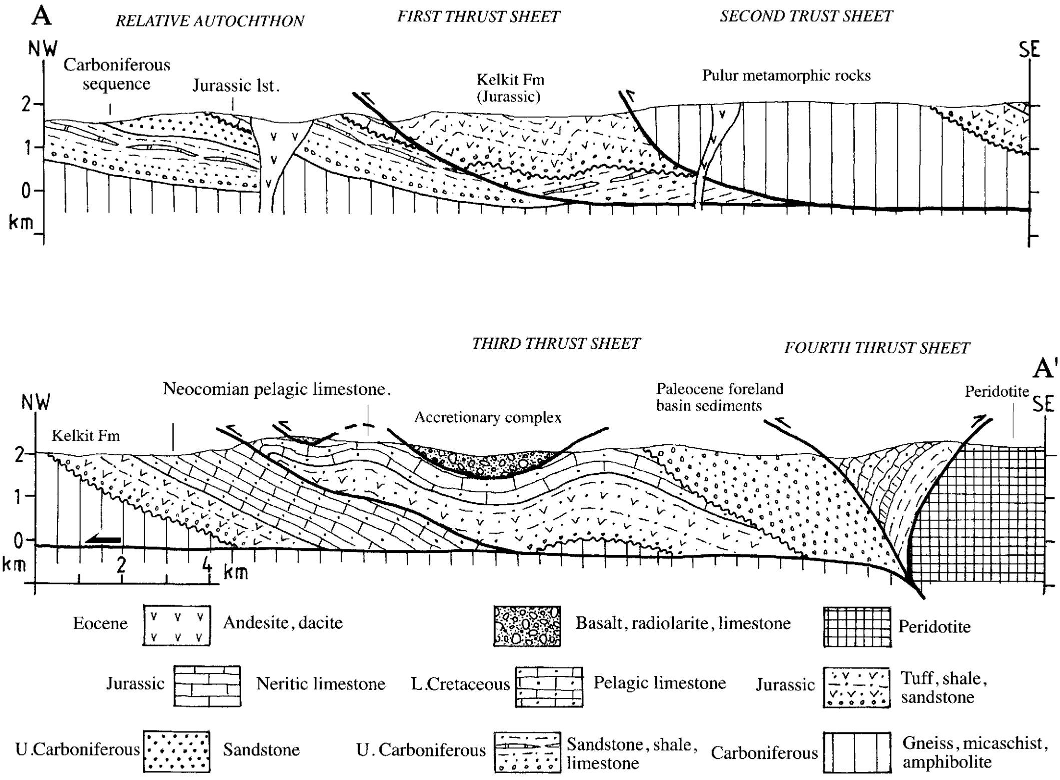

Fig. 20. Geological cross-sections of the Gümüşhane-Munzur area. For location of the sections see Fig. 19 (modified from Okay *et al.* 1997).

in all the thrust sheets as well as in the relative autochthon to the north. When the thrust sheets are palinspastically restored, the Upper Jurassic–Lower Cretaceous carbonate show a transition from *c.* 900 m thick neritic limestones and dolomites to the north to *c.* 1200 m thick pelagic radiolarian biomicrites and calciturbidites to the south (Fig. 18, Pelin 1977; Robinson *et al.* 1995; Okay *et al.* 1997; Okay & Şahintürk 1998). The carbonates range in age from Oxfordian to Barremian/Aptian and are bounded above by a major Cenomanian unconformity. A major episode of uplift and erosion occurred throughout the Eastern Pontides during the Cenomanian and Turonian. In many localities Campanian limestones lie unconformably over the Jurassic sediments (Pelin 1977; Bergougnan 1987; Robinson *et al.* 1995) and even on Carboniferous granites (Yılmaz 1972). This phase of uplift and erosion was caused by the northward obduction of ophiolitic accretionary complex over the south-facing Pontide continental margin, an episode observed both farther west and farther east in the Lesser Caucasus (Okay & Şahintürk 1998). The accretionary complex consists of tectonic slices of basalt, radiolarian chert, pelagic shale, Lower Cretaceous pelagic and neritic limestone, sandstone and serpentinite. It includes lithologies from the Tethyan oceanic crust as well as from the Pontide continental margin. The accretionary complex rests on the Lower Cretaceous pelagic carbonates and is unconformably overlain by Maastrichtian limestones (Ketin 1951; Fenerci 1994). During the Senonian the Inner Eastern Pontides were in a fore-arc position and a tuffaceous flyschoid sequence with pelagic limestone intercalations, 500–900 m thick, were deposited.

Major crustal shortening in the Inner Eastern Pontides occurred during the Palaeocene–Early Eocene and the continental margin was telescoped into a series of stacked north-vergent thrust slices. A major foreland basin, filled with *c.* 1200 m thick conglomerates and turbidites of Late Palaeocene–Early Eocene age formed in front of these thrust sheets (Figs 19 and 20, Norman 1976; Bergougnan 1976; Elmas 1996; Okay *et al.* 1997). In the outer Eastern Pontides this period was marked by a phase of folding, uplift and erosion, so that Lutetian sedimentary rocks lie with an angular unconformity on folded Jurassic and Cretaceous sediments as well as on the pre-Liassic basement (Nebert 1961; Pelin 1977; Okay 1984*a*).

(2) *Munzur mountains: the other side of the ocean.* To the south of the Eastern Pontides the Mesozoic lithologies of the Anatolide–Tauride Block are best exposed in the Munzur Mountains southwest of Erzincan, where late Triassic–Cenomanian is represented by platform carbonates, 1200 m thick, which are overlain by Turonian–upper Campanian pelagic micrites (Fig. 18, Özgül & Turşucu 1984). In the early Maastrichtian an accretionary complex with large slices of peridotite were emplaced southward over the carbonates, and the carbonate platform was internally sliced into south-vergent thrust sheets. The Mesozoic Munzur limestones were thrust southward over a similar platform carbonate sequence of Permian to Senonian age (Keban Unit), which, however, shows low-grade regional metamorphism (Fig. 19). Following this major compressive event of Early Maastrichtian age, Upper Maastrichtian–Palaeocene shallow marine limestones covered the thrust contacts as well as the accretionary complex over a 350 km long region between south of Sivas and Horasan (Yılmaz *et al.* 1988). The second period of carbonate deposition ended with uplift and erosion during the Late Palaeocene–Early Eocene, so that Lutetian sedimentary and volcanic rocks unconformably overlie all the older units.

(3) *Suture zone.* South of the Eastern Pontides the suture is characterized by a several ten kilometres wide belt of accretionary complex and peridotite (Figs 17 and 19), and unlike the regions farther west, here it is not possible to draw a single tectonic line to represent the Tethyan suture. The reason is the mushroom-type structure of the accretionary complex and peridotite, which lie both on the Pontide and Anatolide–Tauride units.

Evolution of the İzmir–Ankara–Erzincan ocean south of the Eastern Pontides

Significance of the Liassic rifting. Sedimentological features of the Lower to Middle Jurassic Kelkit Formation led to its interpretation as a rift facies related to the opening of the İzmir–Ankara–Erzincan ocean (Görür *et al.* 1983). These include the rapid lateral facies and thickness changes, the presence of basic volcanic and volcanoclastic rocks, and the deepening of the basin towards the south as inferred from the sediments of the Kelkit Formation. However, palaeontological data from the accretionary complexes from farther west indicate that the İzmir–Ankara–Erzincan ocean was in existence at least since the Late Triassic. Furthermore, the pre-Jurassic stratigraphy of the Eastern Pontides is very different from that of the Taurides. In the Munzur and Keban units of the Taurides there is a well developed Triassic and Permian carbonate succession not seen anywhere in the Pontides (Fig. 18; Özgül & Turşucu 1984). During the Liassic there were also faunal differences between the two sides of the suture (Bassoullet *et al.* 1975; Enay 1976); Liassic ammonites from the Pontides are similar to those from the southern Laurasian margin, whereas Liassic fauna from the Munzur mountains of the Taurides resemble those from the southern margin of the Tethys. Thus, all the data indicate that the Anatolide–Tauride Block was separated from the Sakarya Zone since at least from Late Triassic onwards. The rifting inferred from the Kelkit Formation might be related to the splitting of a different continental fragment from the eastern part of the Sakarya Zone. One possibility is that the Sanandaj–Sirjan Zone in southwest Iran, which shows evidence for Palaeozoic and Triassic orogenic activity and has an uppermost Triassic to Middle Jurassic unconformable cover of thick coal-bearing clastic rocks (Shemshak Formation), similar to the Kelkit Formation of the Eastern Pontides (e.g., Stöcklin 1968; Şengör 1990), could represent the continental fragment that rifted off from the Eastern Pontides during the Jurassic.

During the Late Jurassic–Early Cretaceous a passive continental margin was established in the Inner Eastern Pontides. This is shown by the Upper Jurassic–Lower Cretaceous carbonates in the thrust sheets, which when palinspastically restored, indicate a carbonate platform in the north, which passed into a carbonate ramp representing the northern passive continental margin of the İzmir–Ankara–Erzincan ocean (Görür 1988).

Late Cretaceous obduction and Late Palaeocene collision. In the suture region south of Gümüşhane there is well documented case of obduction of ophiolite and accretionary complex both northward during the Cenomanian–Turonian and southward during the early Maastrichtian. The northward obduction occurred just before the initiation of arc magmatism in the Outer Eastern Pontides. It is possibly related to the partial subduction of the Eastern Pontide passive continental margin into a south-dipping juvenile intra-oceanic subduction zone (Okay & Şahintürk 1998). This was

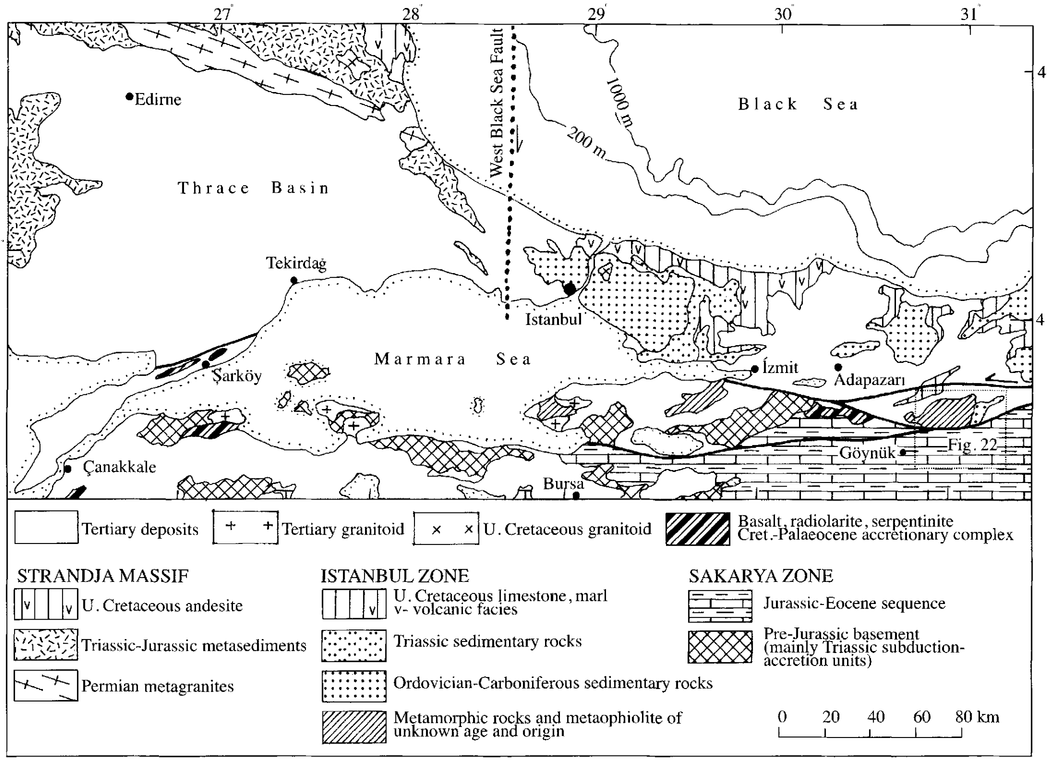

Fig. 21. Geological map of the Marmara Sea region.

followed by the flip of the subduction zone from a south- to north-dipping subduction, which is required to explain the start of the subduction-related volcanism in the Outer Eastern Pontides during the Turonian.

The collision between the Eastern Pontide magmatic arc and the Anatolide–Tauride Block resulted in thrust imbrication of the active margin. The collision is well dated as Late Palaeocene from the age of the foreland basin sequence in front of the north-vergent thrust sheets in the Inner Eastern Pontides. This is corroborated by the end of the arc magmatism in the outer Eastern Pontides during the Late Paleocene (Elmas 1995; Okay & Şahintürk 1998). Data from the Tauride margin, where the strongest deformation occurred during the Early Maastrichtian, are more ambiguous but does not exclude a Late Palaeocene collision.

The Intra-Pontide suture

The Intra-Pontide suture forms the *c.* 400 km long boundary between the İstanbul Zone and the Sakarya Zone. It also extends for approximately another 400 km farther west through the Sea of Marmara defining the contact between the Rhodope–Strandja Massif and the Sakarya Zone, and bending south may join the İzmir–Ankara–Erzincan suture in the central Aegean Sea (Fig. 1). The Intra-Pontide suture can, thus, be divided into two segments, the eastern segment between the İstanbul and Sakarya zones and the western segment between Rhodope–Strandja Massif and the Sakarya Zone.

Intra-Pontide suture between the İstanbul and Sakarya zones

The Intra-Pontide suture in this segment can be subdivided into a 400 km long east–west-trending collisional suture, and the two limiting, north-trending transform faults, which during the Cretaceous also formed a plate boundary (Figs 13 and 21). Although the suture constitutes a profound stratigraphic, metamorphic, magmatic and structural boundary, the lithological units and structures along the suture are poorly known. Along most of its length the suture is defined by the North Anatolian Fault, a major post-Miocene strike-slip fault with a cumulate

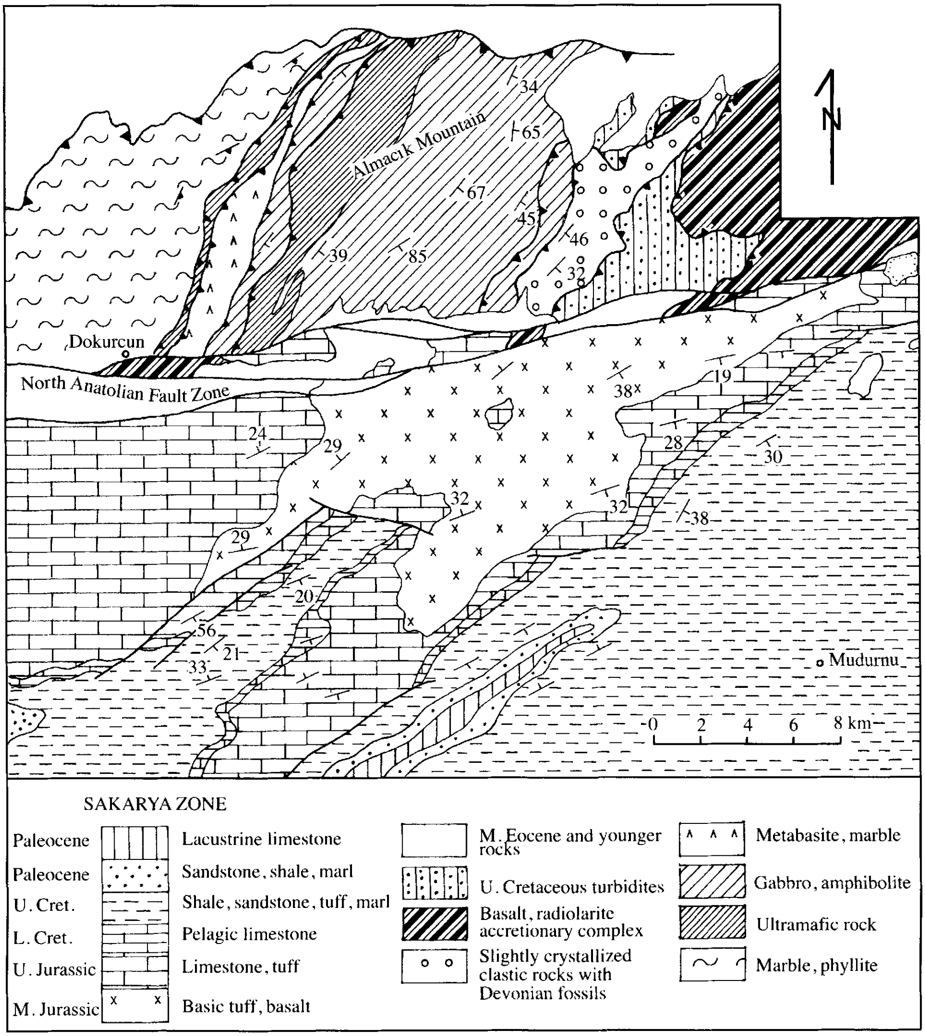

Fig. 22. Geological map of the region around the Intra-Pontide suture south of Almacık mountains (modified from Abdüsselamoğlu 1959; Yılmaz *et al.* 1982).

dextral offset of 25–40 km (Şengör 1979; Barka 1992). The North Anatolian Fault disguises the pre-Miocene relations between the İstanbul and Sakarya zones. Furthermore, there are large metamorphic areas along the suture, whose provenance and age are unknown. A good example of the problems associated with the Intra-Pontide suture is provided by the geology of the Almacık mountains east of Adapazarı studied by Abdüsselamoğlu (1959), Gözübol (1980), Yılmaz *et al.* (1982) and Greber (1996). A geological map based on these works is given in Fig. 22.

In the Almacık region the North Anatolian Fault defines the suture and divides the region into two parts (Fig. 22). To the south of the North Anatolian Fault there is a well-developed Jurassic to Eocene sequence of the Sakarya Zone (Fig. 12, Saner 1980; Gözübol 1980; Altıner *et al.* 1991), which indicates continuous marine deposition from Mid-Jurassic to Early Eocene. To the north the Intra-Pontide suture is defined by a few kilometre wide North Anatolian Fault zone, where elongate tectonic slivers of serpentinite, pre-Jurassic basement of the Sakarya Zone and terrigeneous Neogene deposits outcrop (Fig. 22). In the Almacık mountains north of the North Anatolian Fault there is a thrust stack separated by north–south-trending thrust traces (Fig. 22). Sarıbudak *et al.* (1990) have explained the discordance between the general east–west trend of the regional structures and the north–south thrust traces by the Miocene flake rotation of the Almacık thrust stack in the North Anatolian Fault Zone. At the base of the Almacık thrust stack there is a metamorphic sequence of quartzite, phyllite, micaschist and marble, over 1000 m in thickness. The metasedimentary sequence is overthrust by a dismembered and metamorphosed ophiolite of peridotite, pyroxenite, gabbro and basalt (Fig. 22, Abdüsselamoğlu 1959; Yılmaz *et al.* 1982; Gözübol 1980). The common greenschist to amphibolite facies metamorphic grade shown by the dismembered ophiolite and metasedimentary sequence indicates that the ophiolite was tectonically emplaced over the sedimentary sequence prior to the regional metamorphism. A slightly metamorphic clastic-limestone sequence with scarce Devonian fossils (Abdüsselamoğlu 1959) lies with a problematic contact on the metamorphosed ophiolite (Fig. 2). Abdüsselamoğlu (1959) and Gözübol (1980) regard the metasedimentary sequence and the meta-ophiolite as of pre-Devonian age. On the other hand, Yılmaz *et al.* (1982) consider the meta-ophiolite of Cretaceous age and regard the contact with the overlying Devonian rocks as tectonic. The only consensus on the age of the metamorphic rocks is the poorly preserved unconformable cover of Maastrichtian to Palaeocene neritic limestones (Greber 1996). A similar problem exists in the Armutlu peninsula farther west along the suture, where ages ranging from Precambrian to Devonian have been suggested for a similar pre-Upper Cretaceous metamorphic sequence (Akartuna 1968; Göncüoğlu & Erendil 1990; Yılmaz *et al.* 1995). As there are no data on the depositional or isotopic ages of these metamorphic complexes, the tectonics and geological evolution of the Intra-Pontide suture remain highly uncertain.

Onshore continuations of the West Black Sea and West Crimean faults

These fossil transform faults form the north–south-trending boundaries of the İstanbul Zone with the Strandja Massif to the west and the Sakarya Zone to the east (Fig. 1). Although they do not represent collision-related sutures, nevertheless they are former plate boundaries and form distinct stratigraphic, metamorphic, magmatic and structural discontinuities.

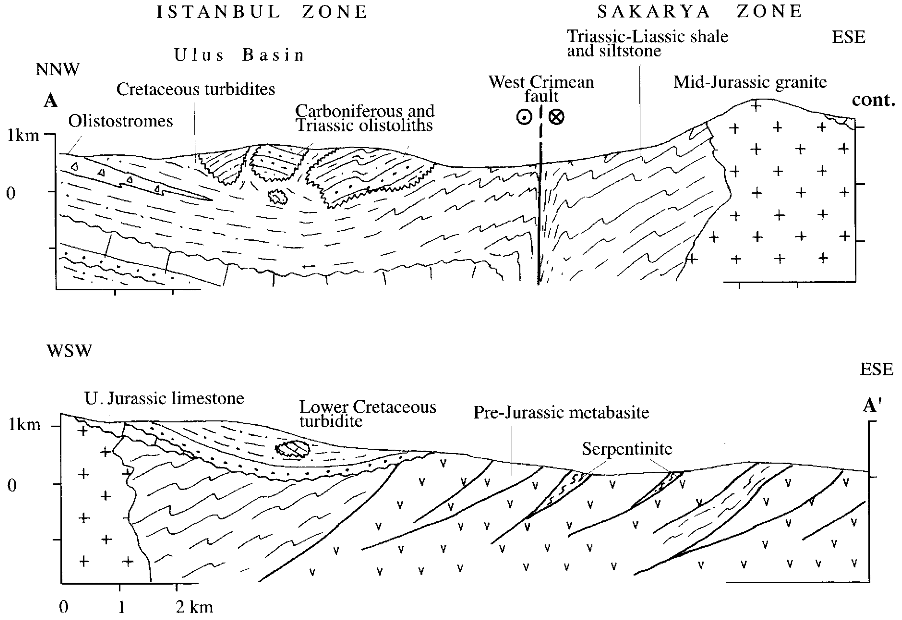

Fig. 23. East–west geological cross-section in the Central Pontides showing the onshore continuation of the West Crimean Fault. The section is continuous from top to bottom. For location of the section see Fig. 13.

Onshore continuation of the West Black Sea Fault. The West Black Sea Fault forms the boundary between the unmetamorphosed Palaeozoic sedimentary rocks of the İstanbul Zone and the regionally metamorphosed Lower Mesozoic sediments of the Strandja Zone. West of the city of İstanbul the Carboniferous greywacke, siltstone and shale sequence of the İstanbul Zone approach within 20 km of the Triassic metaquarzite, marble, phyllite sequence of the Strandja Zone (Fig. 21). The region between is occupied by undeformed Middle Eocene marl, limestone and shale, which places an upper age limit for the activity along the West Black Sea Fault.

Onshore continuation of the West Crimean Fault. The existence of a north–south-trending sinistral fault in the Central Pontides, forming the continuation of the West Crimean fault, was postulated by Okay *et al.* (1994). Recent fieldwork in this area has shown the presence of such a fault in the Central Pontides (Tüysüz in prep.). The İstanbul Zone within a few tens of kilometres west of the West Crimean Fault consists of Aptian–Albian turbidites, 2000 m thick, deposited in the Ulus basin, which opened during the late Barremian on the Upper Jurassic limestones (Figs 13 and 23). The Jurassic limestones and conglomerates rest unconformably on Triassic and Carboniferous clastic rocks (Akyol *et al.* 1974). The deformation which affected the fill of the Ulus Basin increases toward the east. In the western and central parts of the basin deformation style is clearly compressional while it is transpressional in the east. Close to the shear zone along the West Crimean Fault the rocks belonging to the Ulus Basin are penetratively deformed and generally foliated (Fig. 23). In this area all micro and mesostructures within the Ulus turbidites clearly indicate a left-lateral transpressional deformation.

The Sakarya Zone within a few tens of kilometres to the east of the West Crimean Fault consists mainly of Triassic to Early Liassic black shale and siltstone, comparable to the Tauridian Flysch in the Yayla Range in Crimea and to the upper parts of the Karakaya Complex (Şengör *et al.* 1980; Tüysüz 1990). However, unlike the other regions of the Sakarya Zone, in the Central Pontides post-tectonic Mid-Jurassic (165 Ma) granitoids intrude these fine-grained clastics (Boztuğ *et al.* 1984; Yılmaz & Boztuğ 1986), and both are unconformably overlain by the Upper Jurassic limestones and Aptian–Albian turbidites (Fig. 23, Tüysüz 1993). The Triassic to Early Liassic sequence is penetratively deformed with the deformation intensity increasing westward towards the West Crimean Fault. Thus, new field evidence support a transform-type suture between the İstanbul and Sakarya zones in the Central Pontides.

Westward continuation of the Intra-Pontide suture

The Intra-Pontide suture west of the West Black Sea Fault is disguised under the Marmara Sea and comes again onshore in the region of Şarköy in Thrace (Fig. 21). The Thrace Basin, filled with up to 8 km thick siliciclastics of Mid-Eocene to Oligocene age (Görür & Okay 1996), hides much of the pre-Eocene geology. However, an accretionary complex of serpentinite, blueschist, radiolarian chert, Upper Cretaceous and Lower to Middle Palaeocene pelagic limestone and basalt outcrops in basement uplifts, and is also found as olistoliths in the Middle Eocene turbidites north of Şarköy (Fig. 21, Şentürk & Okay 1984; Görür & Okay 1996). This region is taken as the suture trace of the Intra-Pontide Ocean (Şengör & Yılmaz 1981). West of Şarköy the Intra-Pontide suture is covered again by the Neogene sediments and the waters of the Aegean (Fig. 21). Sequences equivalent to the Sakarya Zone, in terms of stratigraphy and tectonic development, are apparently not present in the mainland Greece. Therefore, the Intra-Pontide suture joins the İzmir–Ankara–Erzincan suture in the northern Aegean Sea (Fig. 1).

Evolution of the Intra-Pontide ocean

The Intra-Pontide ocean formed an embayment of the İzmir–Ankara–Erzincan ocean, as indicated by the suture triple junction in the northern Aegean Sea (Fig. 1, Okay *et al.* 1996). There are no data on the age of opening of this embayment. The ocean was in existence by the Late Cretaceous, as indicated by the ages of pelagic limestone blocks, and started to close through northward subduction during the Senonian, as attested by the Senonian arc magmatism in the İstanbul and Strandja zones. The northward subduction gave rise to the opening of the West Black Sea Basin as a back arc basin.

The collision between İstanbul and Sakarya zones in the eastern part of the Intra-Pontide Ocean is constrained as Early Eocene based on the stratigraphy of the Sakarya Zone. In the Central Sakarya Basin north of Göynük, 12 km south of the suture (Fig. 22), there is a continuous deep marine transition from Upper Maastrichtian marls and pelagic micrites to Lower to Middle Paleocene (Danian–Montian) turbidites of sandstone and mudstone with a

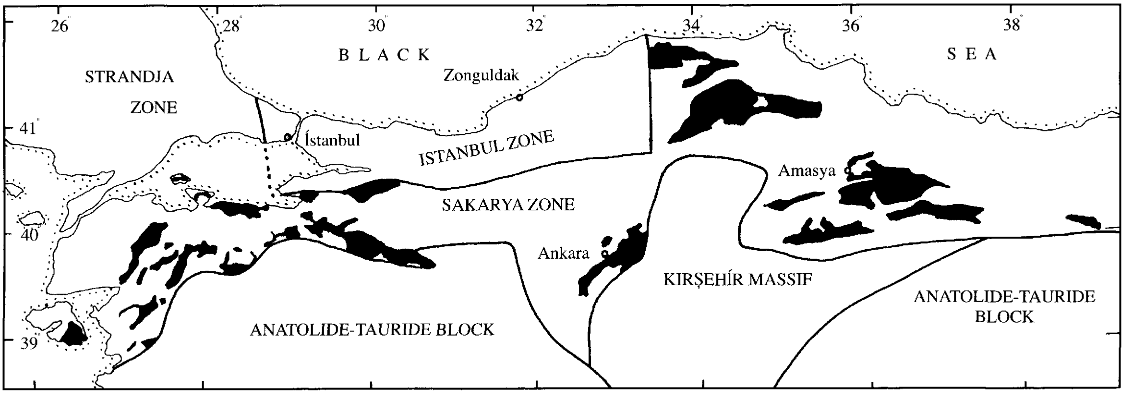

Fig. 24. Distribution of the Triassic subduction-accretion units in the northern Turkey.

pelagic microfauna (Fig. 12, Meriç & Şengüler 1986). Turbidites show a regressive development and the region became a land area during the Early Eocene (Saner 1978). An Early Eocene collision is also in agreement with the stratigraphic data from the northern and central parts of the İstanbul Zone, where continuous marine carbonate deposition has been documented throughout Late Cretaceous and Palaeocene (Dizer & Meriç 1983).

Blocks of pelagic radiolarian biomicrite of Early to Mid-Paleocene age, associated with serpentinite blocks north of Şarköy (Okay & Tansel 1994), suggests that continental collision in the western segment of the Intra-Pontide suture occurred later. Görür & Okay (1996) suggested that the continental collision in this segment occurred during the Oligocene. According to their model, the Thrace Basin developed as a fore-arc basin above the northward subducting Intra-Pontide ocean, which was locked in the east by the Early Eocene collision and could not drift northward. The tectonic setting must have been comparable to that of the present Hellenic subduction zone and the overlying Cretan Basin.

The question of the Palaeo-Tethyan suture

Palaeogeographic maps show the existence of a Tethyan ocean as a westward narrowing oceanic embayment between Gondwana and Laurasia since at least the Carboniferous (e.g., Smith *et al.* 1981; Scotese & Golonka 1992). However, almost all the subduction–accretion complexes and ophiolite preserved in the western and central Mediterranean, bear evidence only of Jurassic and younger oceans. This dilemma, pointed out by Smith (1973), led to the subdivision of the Tethys into Palaeo- and Neo-Tethys. In several papers Şengör (1979, 1984, 1987) argued that during the Triassic a continental fragment was rifted off from the northern margin of the Gondwana, and drifted north closing Palaeo-Tethys in its front and opening the Neo-Tethys at its back. This continental fragment, called the Cimmerian continent, finally collided with the Laurasian margin during the Triassic–Jurassic thereby ending the Palaeo-Tethyan evolution. According to this model a Palaeo-Tethyan suture of Triassic–Jurassic age should separate a Cimmerian continental fragment from the Laurasian margin.

Triassic subduction–accretion complexes occur widely in the Sakarya Zone (Fig. 24), where they form a separate and easly distinguishable tectonostratigraphic unit from the Neo-Tethyan subduction–accretion complexes. In the last ten years extensive geological data have been collected on these Triassic subduction–accretion complexes in northern Turkey (Koçyiğit 1987; Tüysüz 1990; Okay *et al.* 1991, 1996; Ustaömer & Robertson 1994; Genç & Yılmaz 1995; Pickett & Robertson 1996). Although the details are still obscure, these data suggest Triassic southward subduction of an oceanic lithosphere probably as old as Carboniferous and substantiate the Palaeo- and Neo-Tethyan subdivision. However, although there are scattered, small outcrops of pre-Jurassic granitic and metamorphic rocks of continental origin, it has not been possible to identify a coherent Cimmerian continent in the Sakarya Zone. Similarly a Karakaya suture, representing the closure of a Permo-Triassic marginal basin in the Sakarya Zone (Şengör & Yılmaz 1981) could not be mapped in the field. There is no real distinction between the various units of the Karakaya Complex in northwestern Turkey and the pre-Jurassic orogenic sequences in the Central Pontides; both represent Triassic subduction–accretion complexes and occur very close to the İzmir–Ankara–Erzincan suture. Thus, a Palaeo-Tethyan suture as distinct from the 'Neo-Tethyan' İzmir–Ankara–Erzincan suture appears not to exist. This suggests that the latest Triassic orogeny recorded in the Sakarya Zone resulted largely from the obduction of an ensimatic subduction-accretion complex over the Laurasian margin. In such a case, the İzmir–Ankara–Erzincan suture represents a lithospheric plate margin for at least the Carboniferous–Palaeocene period.

Conclusions

The 2000 km long İzmir–Ankara–Erzincan suture forms the main geological boundary between Laurasia and Gondwana in the Turkish transect for the period from at least Carboniferous to Palaeocene. However, the intervening Tethys ocean was not a single lithospheric plate for the whole duration of this period but consisted of at least two plates of Carboniferous–Late Triassic and Triassic–Palaeocene ages respectively. The final continental collision, which led to the formation of the İzmir–Ankara–Erzincan suture was slightly diachronous and occurred in the earliest Palaeocene to the west and in the Late Palaeocene to the east. This period corresponds to a major slow down of the motion of Africa relative to Europa in the vicinity of Turkey (Livermore & Smith 1984; Patriat *et al.* 1982), which might be related to this major continental collision.

Throughout most of its length the İzmir–Ankara–Erzincan suture is represented by an easily recognizable and mappable fault or fault zone of thrust or strike-slip nature, which constitutes a profound stratigraphic, structural, magmatic and metamorphic divide. However, many of these upper crustal brittle structures are generally of Eocene and younger ages, and do not represent structures formed during the Paleocene collision.

During the continental collision the upper plate, represented by the Sakarya Zone, was delaminated and the upper crustal part was thrust for at least 50 km, and probably for much larger distance, over the lower plate with the Cretaceous subduction–accretion complexes forming an intermediate composite thrust sheet (Fig. 25). Along most of its length the İzmir–Ankara–Erzincan suture marks the erosional limit of this major southward translation. This provides an explanation for the frequent presence of terrigenous to shallow marine Jurassic rocks of the Sakarya Zone within a few

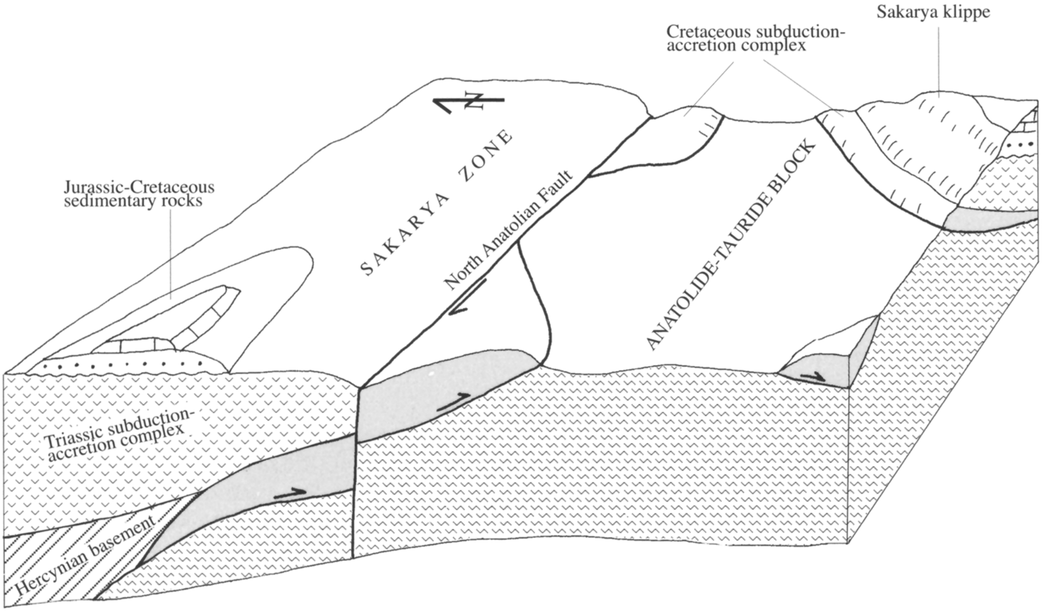

Fig. 25. Block diagram showing the schematic geometry of the İzmir–Ankara–Erzincan suture.

kilometres of the İzmir–Ankara–Erzincan suture (Fig. 25). The lower crust and lithospheric mantle of the Sakarya Zone must have been subducted along a line, which lies north of the İzmir–Ankara–Erzincan suture.

The İzmir–Ankara–Erzincan suture is not rectilinear but is strongly segmented (Fig. 1). Some of these segments, like that between İzmir and Balıkesir, probably reflect an originally irregular plate boundary. Others, like the major southward concave loop in Central Anatolia is probably an effect of the extensive Late Tertiary cover.

To the south of the İzmir–Ankara–Erzincan suture there are extensive Cretaceous subduction–accretion complexes, comprising mainly basalt, radiolarian chert, pelagic limestone, pelagic shale and serpentinite. Palaeontological data from the subduction–accretion complexes indicate that they have formed during the Late Cretaceous subduction of an oceanic lithosphere of Late Triassic to Cretaceous age. The presence of a major Late Cretaceous magmatic arc and fore-arc to the north of the İzmir–Ankara–Erzincan suture, as well as the south-vergent structures to the south of the suture indicate unambiguously north-directed subduction starting in the Senonian. In this context an enigmatic feature observed in the eastern part of the İzmir–Ankara–Erzincan suture is northward thrusting of an accretionary complex during the Cenomanian–Turonian just before the onset of the northward subduction.

The active margin to the north of the İzmir–Ankara–Erzincan suture shows much less lateral geological variation than the passive margin to the south, which in some segments was metamorphosed during the pre-collisional ophiolite obduction. In fact, in the region south of the İzmir–Ankara–Erzincan suture obduction-related deformation is much stronger than collision-related deformation.

Subduction–accretion complexes formed during the Triassic subduction of a Carboniferous to Triassic oceanic lithosphere occur immediately north of the İzmir–Ankara–Erzincan suture suggesting southward polarity of subduction for the Palaeo-Tethys. They are distinguished from Cretaceous subduction–accretion complexes by the dominance of siliciclastic sedimentary rocks, and scarcity of radiolarian chert and pelagic limestone.

The *c.* 800 km long Intra-Pontide suture formed as a result of closure of a major embayment of the İzmir–Ankara–Erzincan ocean. The final continental collision occurred during the Early Eocene to the east but may have been as young as Oligocene to the west. The Intra-Pontide suture consists of an east–west-trending segment, used later in some parts by the North Anatolian Fault, and two north–south-trending limiting branches.

Even on a very high structural level in the orogen, the faults, which form major geological discontinuities and thus represent sutures can be mapped and shown precisely on detailed geological maps. This is because the subduction–accretion complexes and ophiolite of the intervening oceanic lithosphere occur as flat-lying allochthonous sheets, thrust over the passive continental margin rather than as steeply dipping wide belts (Fig. 25). Thus, suture zones made up of subduction–accretion complexes several tens of kilometres wide, as shown for example in Koçyiğit (1991), are not warranted.

A second general conclusion is the subdivision of the sutures into collisional and the much rarer transform-fault-type sutures. The latter are easy to distinguish from the collisional sutures, as they are not associated with ophiolite and subduction–accretion complexes. Two examples for the transform-fault-type sutures are the offshore continuations of the West Black Sea and West Crimean faults.

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