

Ali Elmas

## Late Cenozoic tectonics and stratigraphy of northwestern Anatolia: the effects of the North Anatolian Fault to the region

Received: 31 July 2001 / Accepted: 9 February 2003 / Published online: 24 May 2003  
© Springer-Verlag 2003

**Abstract** In northwest Anatolia, there is a mosaic of different morpho-tectonic fragments within the western part of the right-lateral strike-slip North Anatolian Fault (NAF) Zone. These were developed from compressional and extensional tectonic regimes during the paleo- and neo-tectonic periods of Turkish orogenic history. A NE-SW-trending left-lateral strike-slip fault system (Adapazarı-Karasu Fault) extends through the northern part of the Sakarya River Valley and began to develop within a N-S compressional tectonic regime which involved all of northern Anatolia during Middle Eocene to early Middle Miocene times. Since the end of Middle Miocene times, this fault system forms a border between a compressional tectonic regime in the eastern area eastwards from the northern part of the Sakarya River Valley, and an extensional tectonic regime in the Marmara region to the west. The extension caused the development of basins and ridges, and the incursions of the Mediterranean Sea into the site of the future Sea of Marmara since Late Miocene times. Following the initiation in late Middle Miocene times and the eastward propagation of extension along the western part of the NAF, a block (North Anatolian Block) began to form in the northern Anatolia region since the end of Pliocene times. The Adapazarı-Karasu Fault constitutes the western boundary of this block which is bounded by the NAF in the south, the Northeast Anatolian Fault in the east, and the South Black Sea Thrust Fault in the north. The northeastward movement of the North Anatolian Block caused the formation of a marine connection between the Black Sea and the Aegean/Mediterranean Sea during the Pleistocene.

**Keywords** North Anatolian Fault · Adapazarı-Karasu Fault · North Anatolian Block · Compressional/

extensional tectonic regimes · Black Sea/Sea of Marmara/Mediterranean Sea connections · Northwestern Anatolia

### Introduction

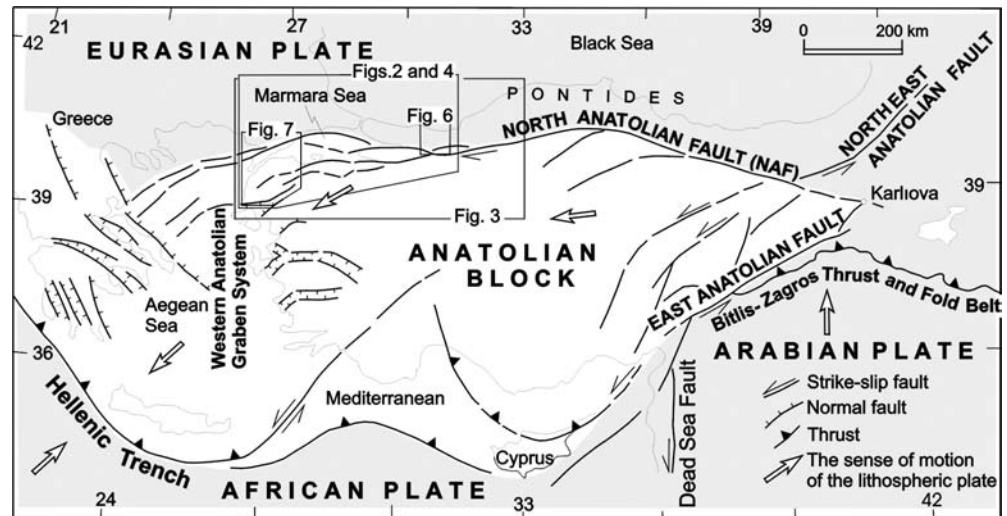
The North Anatolian Fault Zone (NAFZ) is a major, active right-lateral strike-slip fault (Ketin 1969; Jackson and McKenzie 1988; Barka 1992; Fig. 1) which constitutes the northern boundary of the westward-moving Anatolian Block and connects the compressional regime in eastern Anatolia with the extensional regime in the Aegean Sea region (McKenzie 1972; Şengör 1979; Şengör et al. 1985; Dewey et al. 1986; Le Pichon et al. 1995; Armijo et al. 1996; Reilinger et al. 1997; McClusky et al. 2000). Estimated ages for the initiation of motion along the NAF range from the late Miocene at ca. 12–13 Ma (Dewey and Şengör 1979; Şengör 1979; Şengör et al. 1985; Dewey et al. 1986; Hempton 1987; Le Pichon et al. 1995), the early Pliocene at ca. 5 Ma (Tatar 1975; Barka and Hancock 1984; Barka and Kadinsky-Cade 1988; Koçyiğit 1989; Barka 1992; Westaway 1994; Platzman et al. 1998), to the late Pliocene at ca. 2.5 Ma (Şaroğlu 1988). The NAF initiated soon after continental collision between the Arabian and Eurasian plates (Şengör 1979; Dewey et al. 1986), and reached to the west (Şengör et al. 1985; Barka 1996; Armijo et al. 1996; Schindler 1997). However, Chorowicz et al. (1999) and Adıyaman et al. (2001) proposed that NAF activity initiated in the west and propagated eastwards by steps.

In northwestern Turkey, the NAFZ passes across different morpho-tectonic units related to connections between the Black Sea, the Sea of Marmara, and the Aegean/Mediterranean seas. The intermittent seaway connection between the Mediterranean Sea and the Sea of Marmara during the late Miocene to Holocene interval was generally controlled by right-lateral strike-slip faulting (Ezine-Şarköy Fault; Elmas and Meriç 1998). Also, the initial connection between the Sea of Marmara and the Black Sea occurred during Pleistocene times (Pfannenstiel 1944; Kosswig 1954; Bilgin 1984; Tchapyalyga 1995;

A. Elmas (✉)

Department of Geology, Engineering Faculty,  
University of İstanbul,  
34850 Avcılar, İstanbul, Turkey  
e-mail: alielmas@istanbul.edu.tr  
Fax: +90-212-5911997

**Fig. 1** Tectonic map of the eastern Mediterranean region showing structures developed during Miocene to Holocene time (compiled from Şengör et al. 1985; Jackson and McKenzie 1988; Barka and Kadinsky-Cade 1988; Barka 1992; Armijo et al. 1999). The regions marked with *rectangles* show the locations of Figs. 2, 3, 4, 6 and 7



Meriç 1995a). However, the location and development mechanism of this connection are unclear.

An understanding of the features and interrelations of the major morpho-tectonic units of northwestern Turkey is of critical importance to solving the neo-tectonic problems of the region, and the development of the seaway connecting the Black and Mediterranean seas. The primary purpose of this paper is to present field observations on the stratigraphy and structure from the different morpho-tectonic units. Then, this information was combined with existing geological and geophysical data to establish the neo-tectonic evolution of the region.

## Regional framework

The geological evolution of northwestern Anatolia is divided into two major periods called the paleo-tectonic and neo-tectonic periods. There are five tectonostratigraphic units formed in the paleo-tectonic period, which constitute the basement for the Neogene–Quaternary units. They are the İstanbul-Zonguldak Tectonic Unit, the Armutlu-Ovacık Zone, the Sakarya Zone (Yiğitbaş et al. 1999), the Strandja Zone, and the Thrace Paleogene Basin (Fig. 2a). The NAFZ followed former tectonic lines in between paleo-tectonic units such as the İstanbul-Zonguldak Unit, the Armutlu-Ovacık Zone, and the Sakarya Zone in northwest Anatolia (Elmas and Yiğitbaş 2001).

The İstanbul-Zonguldak Tectonic Unit, Sakarya Zone and Strandja Zone contain different Paleozoic–Triassic sequences (Şengör and Yılmaz 1981). The Armutlu-Ovacık Zone, which lies between the İstanbul-Zonguldak Tectonic Unit and the Sakarya Zone, appears to represent a tectonic complex consisting of both zones brought together by faulting (Yiğitbaş et al. 1999; Elmas and Yiğitbaş 2001). A common sedimentary cover of the İstanbul-Zonguldak Tectonic Unit, the Sakarya Zone and the Armutlu-Ovacık Zone began to form in Late Campanian–Maastrichtian times (Elmas et al. 1997). Also, the

Thrace Paleogene Basin is a large depression to the south of the Strandja Zone (Fig. 2a). Its Lutetian–Oligocene volcanoclastic rocks were deposited in a south-facing fore-arc basin (Görür and Okay 1996).

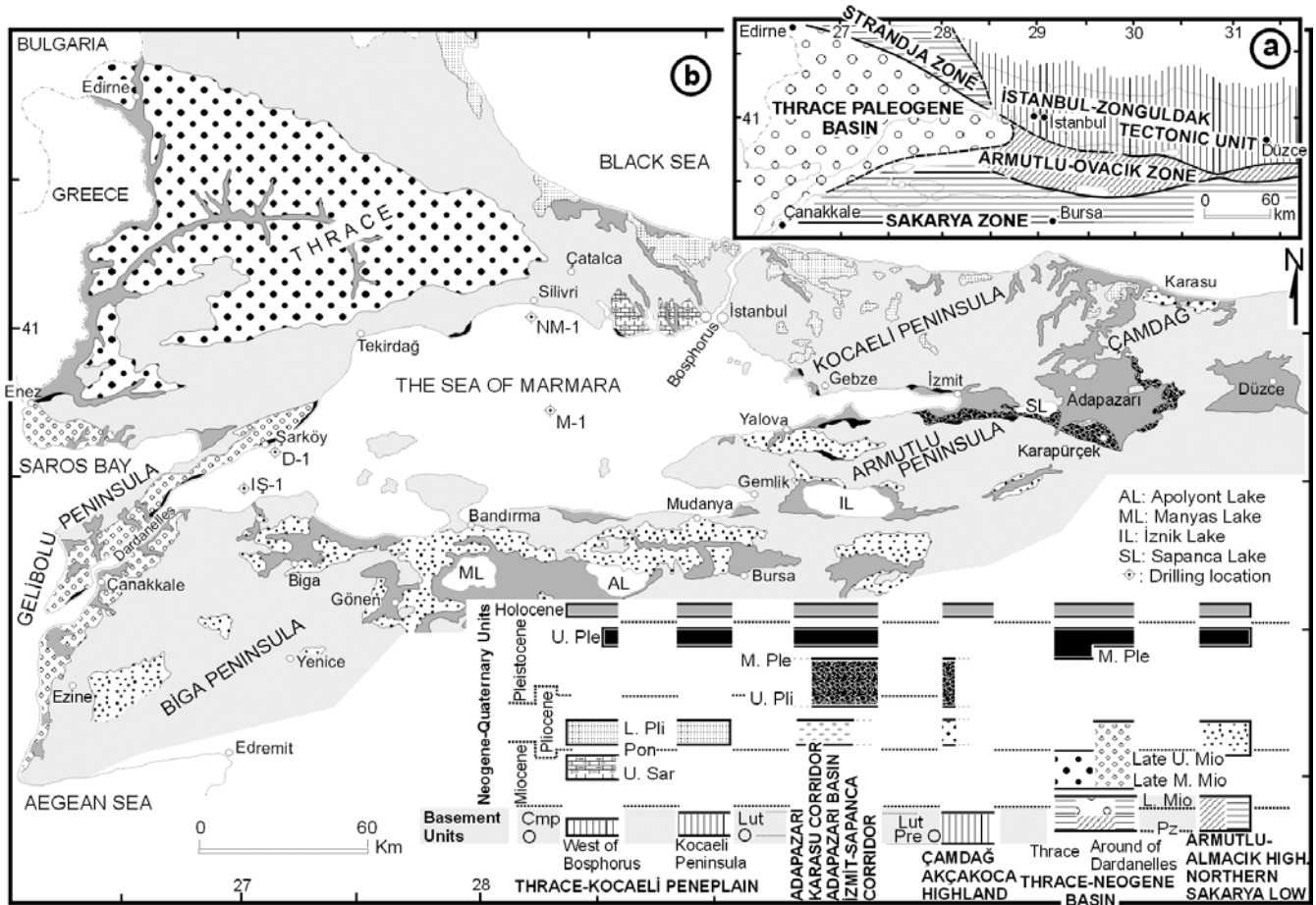
In northwest Turkey, all of the paleo-tectonic basement units are unconformably covered by Neogene–Quaternary strata (Fig. 2b). These strata range in age from the end of the Middle Miocene to the Holocene, and were deposited in morpho-tectonically different depositional environments. A digital elevation model (DEM) image showing the morphology (Fig. 3a), and field observations on the stratigraphy and structure indicate the existence of many morpho-structural units in northwestern Turkey. The Neogene–Quaternary morpho-tectonic units are the Thrace-Kocaeli Peneplain, the Çamdağ–Akçakoca/Armutlu-Almacık/southern Thrace/Gelibolu/southern Marmara/Sakarya/Strandja highlands, the Thrace Neogene/Adapazarı/Marmara basins, the Saros Graben, the Adapazarı-Karasu/İzmit-Sapanca corridors, the Northern Sakarya Low, and the Acarlar-Kocaeli Coastal Zone (Fig. 4b). In the following, the morphologic and geologic features of these neo-tectonic units will be described separately.

## Thrace-Kocaeli Peneplain

The Thrace-Kocaeli Peneplain (Fig. 4b; Pamir 1938) is an erosion surface which lies 120–200 m above sea level. It is bounded by fault scarps to the north, south and east. The scarps correspond to post-peneplain morphologic discordance, formed by reactivation of older faults.

The pre-Neogene units truncated by the peneplain are Ordovician–Triassic sediments of the İstanbul-Zonguldak Tectonic Unit (Fig. 5), and Turonian–Campanian volcanoclastics. The upper parts of the pre-Neogene units consist of Upper Campanian–Lower Lutetian deposits which crop out particularly west of the Sakarya River (Fig. 6a).

The Neogene sequence west of the Bosphorus is represented by terrestrial-lacustrine deposits (Çukurçeşme and Güngören formations) and macra-bearing limestones



**Fig. 2** a The major paleo-tectonic units of northwestern Turkey (partly compiled from Yiğitbaş et al. 1999, and Elmas and Yiğitbaş 2001). b The distribution of Neogene-Quaternary sequences in northwestern Turkey (sites of the Pleistocene marine terraces are

compiled from Barga and Sakıncı 1989; Sakıncı and Yaltrak 1997; Emre et al. 1998). Stratigraphic and lithological descriptions of the units are given in Fig. 5

(Bakırköy Limestone). Along the coast of the Marmara Sea, they rest on units of the Thrace Paleogene Basin in the south, and the İstanbul-Zonguldak Tectonic Unit in the north (Fig. 2a, b). Fossils from the Neogene strata (a, b in Fig. 5) indicate a Late Sarmatian-Pontian age (Sayar and Pamir 1933; Yalçınlar 1952). Other Neogene deposits in the İstanbul region consist of a loosely compacted, pebble-sand-clay sequence (Belgrad Formation). Cross bedding is observed in the middle and upper parts of the sequence. The average thickness of the unit is 10–20 m but it attains a thickness of 40 m in the northern part of the region. The pebbly and sandy Pontian-Lower Pliocene units in the Kocaeli Peninsula (Yalçınlar 1952) have been correlated to the deposits of the Belgrad Formation (c, d in Fig. 5).

### Çamdağ-Akçakoca Highland

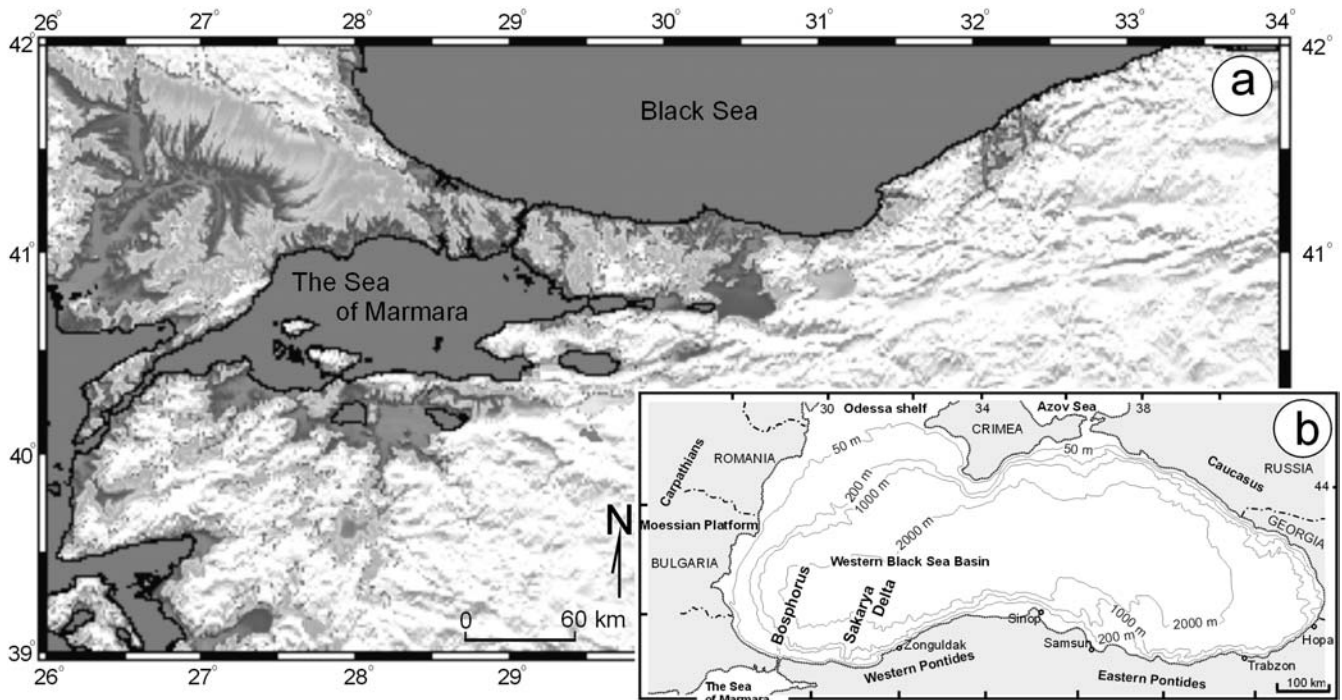
The Çamdağ-Akçakoca Highland (Yiğitbaş et al. 2003) is a mountainous region (Figs. 3a, 4b) with an elevation locally above 1,000 m. Erosion reached to the pre-

Ordovician units in the western part of the Çamdağ-Akçakoca Highland (Figs. 5, 6a). Three different erosion surfaces in the region were developed during the Miocene-Holocene interval (Uludağ 1993).

The Çamdağ-Akçakoca Highland is where Neogene-Quaternary strata are rarest among the morpho-tectonic units in the Marmara region. The northwest part of the uplift is partly overlain by the pebbly and sandy Pontian-Pliocene deposits (Karasu Formation; e in Fig. 5) which are observed on the Thrace-Kocaeli Peneplain. The southwestern part of this uplift is overlain by the Late Pliocene-Pleistocene sedimentary sequence of the Adapazarı Basin (Figs. 2b, 6a).

### Armutlu-Almacık Highland

The Armutlu-Almacık Highland is an E-W-trending mountainous region (Figs. 3a, 4b) more than 1,500 m high. The high is bounded by branches of the NAF in the north and south (Fig. 4a).



**Fig. 3** a Shadow image of the digital elevation model (DEM) of northwestern Turkey. The DEM image is derived from GETOP030 data of the USGS, at 1-km horizontal ground pixel resolution,

illuminated from the north. Vertical exaggeration is 3 times. b Bathymetric map of the Black Sea (from Robinson et al. 1996)

The Neogene units in the Armutlu-Almacık Highland are observed in the high topographic areas, and the Quaternary units are located in depressed areas along the NAF zone. The Neogene sequence is represented by Upper Miocene–Lower Pliocene fluvial, lacustrine and marine units (Yalakdere Formation, Bargu and Sakiñç 1989; Yalova Formation, Emre et al. 1998). The units are unconformably overlain by Upper Pliocene alluvial deposits. They are cut by faults which controlled the deposition of the latest Pliocene–Pleistocene units in the İzmit-Sapanca Corridor (Emre et al. 1998). Upper Pleistocene marine terraces (Bargu and Sakiñç 1989; j in Fig. 5) are present at different levels due to episodic tectonic uplift.

### Thrace Neogene Basin

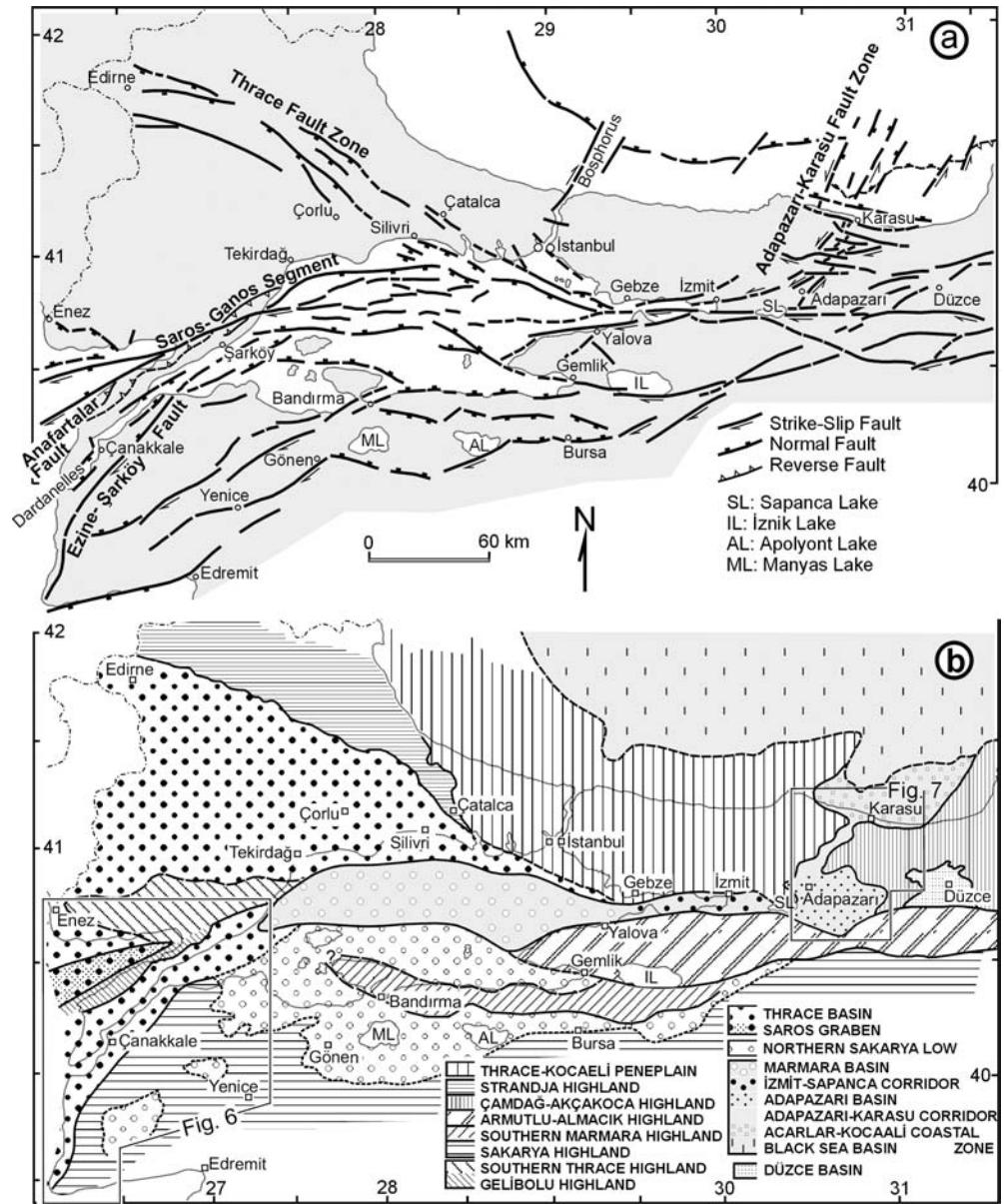
The Thrace Neogene Basin is a fault-controlled, triangular-shaped depression bounded by the Strandja Highland to the north and the Sakarya Highland to the southeast (Figs. 2b, 3a, 4). Neogene deposits of the basin were divided into two parts by a high area (Southern Thrace Highland; Fig. 4b) underlain by Eocene–Miocene deposits.

South of the Southern Thrace Highland (Fig. 7), the sequence (Dardanelles Group; Elmas and Meriç 1998; Fig. 5) in the Thrace Neogene Basin began with alluvial-fan (Sarıyar Member), fluvial (Gazhanedere Formation; Anafartalar Member) and lacustrine (Kirazlı Formation;

Göksu Member) deposits. The ages of these deposits (n in Fig. 5) extend from Late Aragonian–Early Vallasian (end of Middle Miocene) to Pannonian (Late Miocene; K. Şentürk and C. Karaköse, unpublished data). The flow directions in the fluvial deposits were westwards. All of the units pass gradually upwards into a shallow marine sequence consisting of clastics at the base and carbonates at the top (Alçitepe Formation, Y. Önem, unpublished data; Bayraktepe Member, K. Şentürk and C. Karaköse, unpublished data). They also overlies transgressively the basement rocks of the Sakarya Zone in the east. Ostracods obtained from the unit (o in Fig. 5) indicate a Middle–Late Pannonian age (A. Nazik 1996, personal communication).

The shallow marine carbonates are unconformably overlain by a Turolian–Lower Pliocene (K. Şentürk and C. Karaköse, unpublished data; p in Fig. 5) clastic unit (Conkbayırı Formation; H.E. Kellog, unpublished data) which was deposited in an alluvial-fan environment on the slope of a topographically high area (Gelibolu Highland) in the western part of the Gelibolu Peninsula (Fig. 7). The unit passes eastwards into fluvial deposits of the Bayramiç Formation. The lacustrine carbonates (Gülpınar Formation) at the top of the fluvial deposits interfinger with basaltic rocks (Taştepe Basalt; Siyako et al. 1989) extruded along the Ezine-Şarköy Fault (Elmas and Meriç 1998). The lavas are dated by the Rb/Sr method at 3.8 Ma (Y. Yılmaz 1994, personal communication).

**Fig. 4 a** Tectonic map of northwestern Turkey, showing faults developed during Miocene to Holocene times. Data for the area around the Dardanelles are from Elmas and Meriç (1998), the area between Adapazarı and Karasu from Yiğitbaş et al. (2003), the area between Çorlu and Edirne from Perinçek (1991), the region around the Bosphorus modified from Gökaşan et al. (1997) and Alpar (1999), and the Sea of Marmara compiled from data by Smith et al. (1995), Okay et al. (1999), İmren et al. (2001), and the Turkish Petroleum Company (unpublished data). **b** Morpho-tectonic units in northwestern Turkey. The stratigraphic and lithologic descriptions of the units are given in Fig. 5. The regions marked with rectangles show the locations of Figs. 6 and 7



A Late Pleistocene sequence (Gaziköy Formation; Fig. 5) deposited in fluvial and shallow marine environments unconformably overlies the Middle Miocene–Lower Pliocene unit (Dardanelles Group) in the Gelibolu Peninsula.

To the north of the Southern Thrace Highland, the Thrace Neogene Basin is represented by terrestrial, fluvio-lacustrine deposits (Fig. 5). In the northeast part of the basin, these deposits consist of an alternation of mudstone, sandstone and weakly cemented clastics (Çantaköy and Kurtdere formations; M. Umut et al., unpublished data), and rest on the Thrace Paleogene Basin units. Some bivalve and mammal fossils (k in Fig. 5) obtained from these rocks indicate a late Middle Miocene–Late Miocene age (M. Umut et al., unpublished data). These units pass laterally and vertically into latest Middle Miocene–Upper Miocene (Ünay and De Bruijn

1984; 1 in Fig. 5) fluvial-lacustrine deposits of the Ergene Formation (M.R. Holmes, unpublished data). The fluvial-lacustrine deposits in the northeast part of the basin unconformably lie on the Strandja Zone units. These deposits pass laterally and vertically into a sequence composed of an alternation of limestone, marl and claystone (Çelebi and Sinanlı formations; M. Umut et al., unpublished data). The units are present in the northwest and west parts of the Southern Thrace Highland. The mammal fauna (M. Umut et al., unpublished data) obtained from this sequence indicates a latest Miocene age, and the bivalve fauna (Ternek 1949) in the upper part of the sequence yield a Pontian age (m in Fig. 5). The Middle Miocene–Upper Miocene units are unconformably overlain by fluvial clastics (Thrace Formation; M. Umut et al., unpublished data).

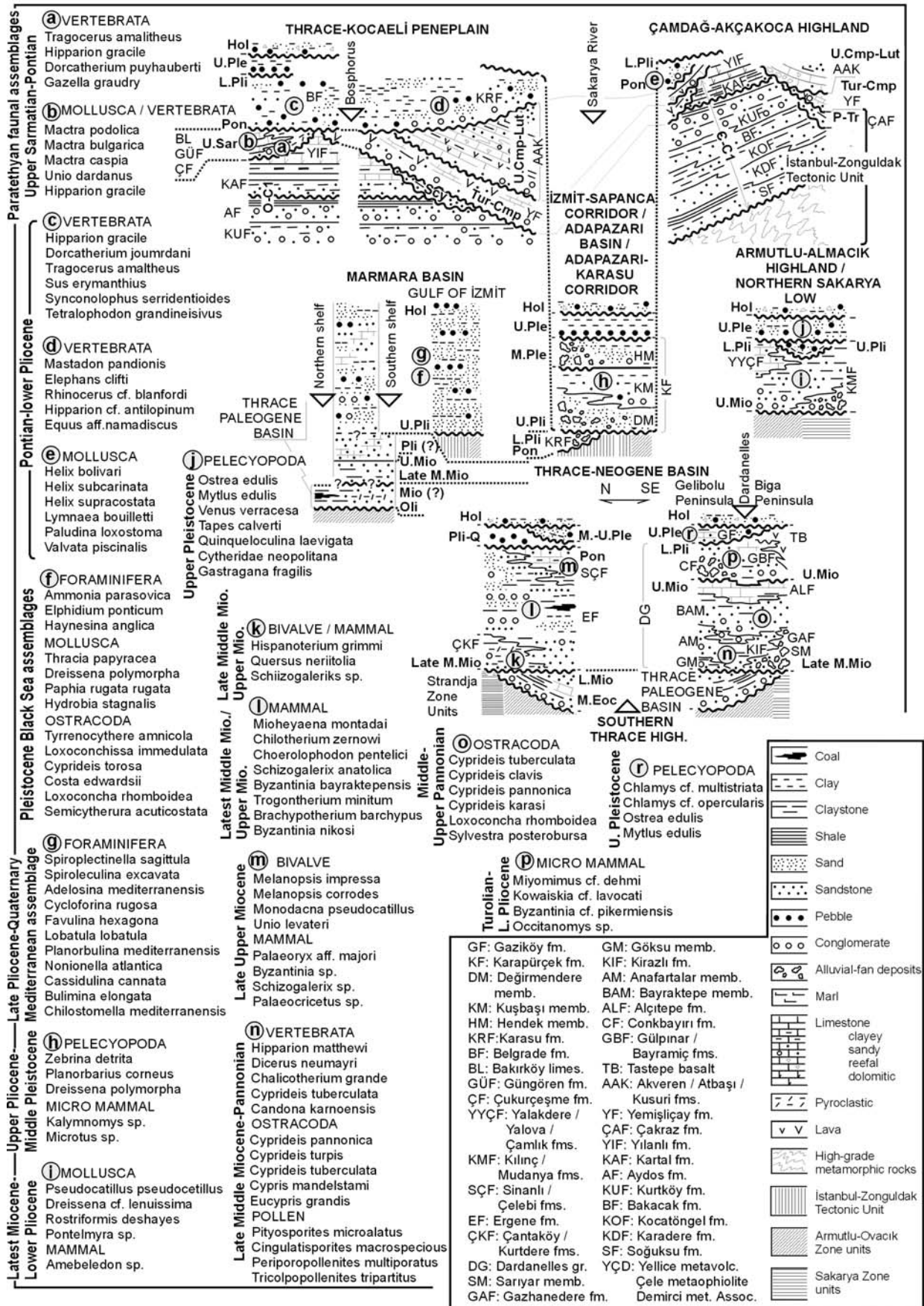
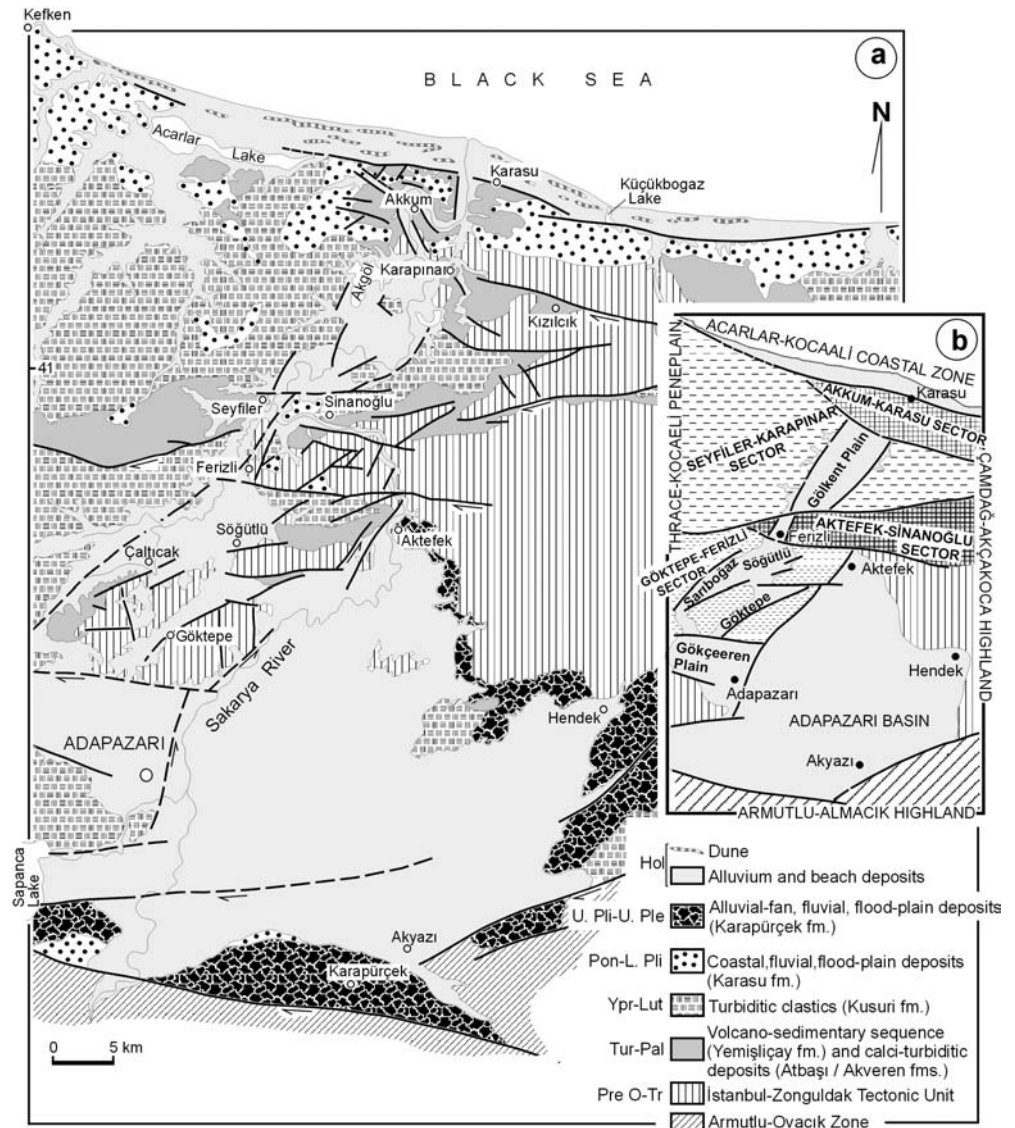


Fig. 5 Representative stratigraphic sections from the different morpho-tectonic zones of northwestern Turkey. Letters (a, b, etc.) indicate the listed fossil assemblage

**Fig. 6 a** Geologic map of the area surrounding the Sakarya River (from Yiğitbaş et al. 2003). **b** Morpho-tectonic elements of the Adapazarı-Karasu Corridor



### Northern Sakarya Low

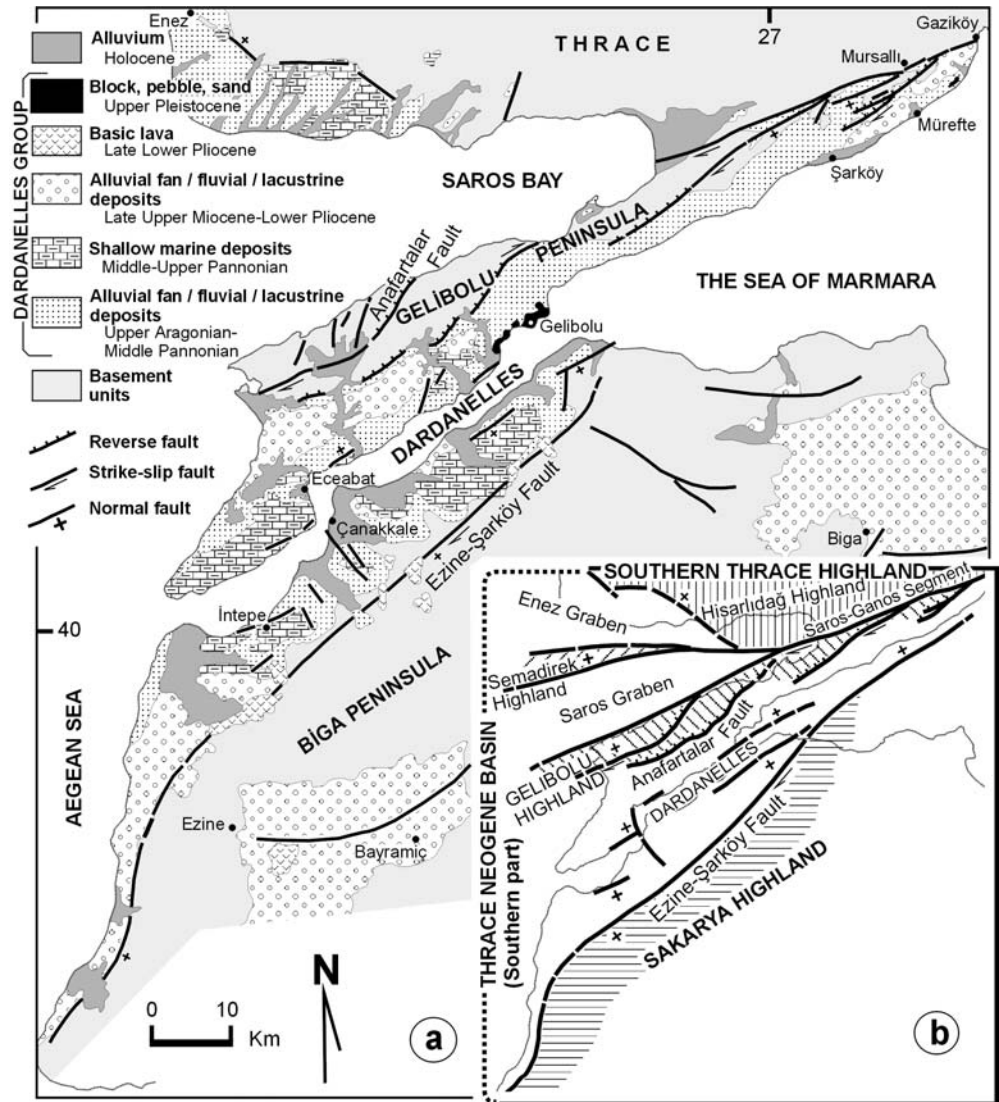
The Northern Sakarya Low (Elmas 2000) is an E-W-trending depression to the north of the Sakarya Highland. It is divided into two parts by a structural high area (Southern Marmara Highland; Figs. 3a, 4b) underlain by Paleozoic–Oligocene units.

The lower part of the Neogene sequence (Fig. 5) is represented by Upper Miocene (Sichenberg et al. 1975) fluvial, alluvial-fan, and deltaic clastics (Mudanya Formation; S. Görmüş et al., unpublished data) in the southern part of the Northern Sakarya Low. The Upper Miocene unit passes upwards into a transgressive sedimentary unit (Çamlık Formation; S. Görmüş et al., unpublished data) which is the first marine unit in the eastern Marmara region. The fossil assemblage (Sichenberg et al. 1975; Emre et al. 1998; i in Fig. 5) of Mediterranean origin indicates a latest Miocene–Early Pliocene age.

### The Marmara Basin

In on-shore areas around the Sea of Marmara, the Neogene–Quaternary sequences begin with upper Middle/Upper Miocene deposits on the various paleo-tectonic units (Fig. 2). These sequences contain terrestrial, lacustrine, and marine deposits. Marathon Oil Company has drilled several wells in the Sea of Marmara (Fig. 2b). One of them (the Marmara-1/M1), situated on the southern side of the Marmara Basin (Fig. 4b), contains the following section: (1) an upper part consisting of Upper Pliocene–Holocene units (Fig. 5) underlain by (2) calcareous sandstone of Pliocene age, and (3) Pannonian sandstone-mudstone, and tuff/coal-bearing sandstone-mudstone. Cretaceous strata were reached at 2,000 m. However, in the borehole North Marmara-1 (NM-1), on the northern shelf of the Sea of Marmara, Paleozoic rocks were reached at 1,100 m (Ergün and Özel 1995). On this basement, only Oligocene units are present. In the

**Fig. 7 a** Simplified geological map of the southern Thrace, Gelibolu and Biga peninsulas (from Elmas and Meriç 1998). **b** Morpho-tectonic elements around Saros Bay and the Dardanelles (compiled from Saner 1985; Elmas and Meriç 1998; Uçan et al. 2001)



boreholes Doluca-1 (D-1) and Işıklar-1 (IŞ-1), which are on the southern shelf of the Sea of Marmara, Cretaceous–Oligocene basement units were reached at 900 m. They are overlain by the upper Middle Miocene–Upper Miocene unit, similar to the on-shore areas.

The Gulf of İzmit in the eastern part of the Sea of Marmara is a tectonic corridor controlled by the NAFZ (Ketin 1969). Two of nine boreholes drilled in the Gulf of İzmit reached basement units. The basement rocks are overlain by thick Upper Pliocene–Holocene (Meriç 1995b) clastic deposits which were deposited under tectonic control. The fossil assemblage (g in Fig. 5) indicates a Mediterranean origin (Meriç 1995b). In addition, the fossil assemblages (f in Fig. 5) obtained from the units around the Sapanca Lake and from offshore wells in the Gulf of İzmit indicate a Black Sea origin (Taner 1995; Meriç 1995a; Gülen et al. 1995).

The Marmara region was influenced by a transgression during Pleistocene times (Görür et al. 1997). The products

of this transgression, represented by Middle/Upper Pleistocene marine terraces, are found at different levels because of the tectonic activity in the region. Holocene deltaic-beach deposits are present along the northern and southern shorelines, and floodplain deposits are present along the eastern coast of the gulf (Emre et al. 1998).

### **İzmit-Sapanca Corridor, Adapazarı Basin and Adapazarı-Karasu Corridor**

The İzmit-Sapanca Corridor (Bilgin 1984), the Adapazarı Basin and the Adapazarı-Karasu Corridor (Yiğitbaş et al. 2003) constitute adjacent lowlands between the Thrace-Kocaeli Peneplain and the Armutlu-Almacık/Çamdağ-Akçakoca highlands (Figs. 3a, 4b). The lowlands were filled by similar Neogene–Quaternary sequences. The oldest sequence consists of Pontian–Lower Pliocene (İnadık 1953) terrestrial deposits (Figs. 2b, 5, 6a) in



the Adapazarı Basin. Similar units are also observed in the northern part of the Adapazarı-Karasu Corridor. In this area, the Neogene units crop out generally both on the slope of the Sakarya Valley and on the ridges extending along the Black Sea coast (Figs. 2b, 6a). The units consist of loosely cemented clastic strata (Karasu Formation; Fig. 5). Cross bedding, imbricated pebbles and red mudstone-gray marl levels indicate they were deposited in coastal, fluvial and floodplain environments. In the southern part of the Adapazarı-Karasu Corridor, the Neogene strata are red terrestrial clastics, locally deposited on the basement rocks. The position, facies and lithologic features of the Neogene unit (Karasu Formation) in the Adapazarı-Karasu Corridor and the Adapazarı Basin indicate that it is equivalent to the Pontian-Lower Pliocene deposits (Belgrade Formation) on the Kocaeli-Thrace Peneplain.

The Pontian-Lower Pliocene terrestrial deposits in the Adapazarı Basin are unconformably overlain by thin- and coarse-grained clastic strata (Karapürçek Formation; Emre et al. 1998). The clastic sequence rests on the basement units in the İzmit-Sapanca Corridor. The sequence begins with Upper Pliocene-Lower Pleistocene alluvial-fan deposits (Değirmendere Member; Fig. 5) whose deposition was controlled by the NAF to the south (Figs. 4a, 6a). These deposits pass laterally into a fluvial/floodplain unit (Kumbaşı Member). In the İzmit-Sapanca Corridor, the fossils (h in Fig. 5) obtained from these rocks indicate a Late Pliocene-Middle Pleistocene age (Emre et al. 1998). In the Adapazarı Basin, the upper part of the Karapürçek Formation is represented by alluvial-fan deposits (Hendek Member). The deposits of the Karapürçek Formation are the terrestrial equivalents of the Upper Pliocene-Pleistocene marine units in the Gulf of İzmit (Emre et al. 1998).

The Karapürçek Formation is overlain by Upper Pleistocene terrace deposits and Holocene fluvial/floodplain deposits. The Holocene deposits in the Adapazarı-Karasu Corridor are represented by the beach sands to the north, and alluvium/terrace deposits to the south.

#### Faults in the Adapazarı-Karasu Corridor

The Adapazarı-Karasu Corridor may be divided into four morpho-tectonic sectors (Fig. 6b)—from south to north, the Göktepe-Ferizli, Aktefek-Sinanoğlu, Seyfeler-Karapınar and Akkum-Karasu sectors (Yiğitbaş et al. 2003).

The Seyfeler-Karapınar (Gölkent Plain) and Göktepe-Ferizli sectors (Söğütlü and Göktepe plains; Bilgin 1984) are low floodplain areas where the Sakarya River flows in a wide, meandering channel. Both the west and east sides of the plains are defined by NE-SW-trending left-lateral strike-slip faults (Adapazarı-Karasu Fault Zone; Yiğitbaş et al. 2003; Fig. 6a). These faults have controlled the deposition of Quaternary alluvial fans along the Sakarya River, such as in the Seyfeler-Karapınar sector. The Göktepe-Ferizli sector constitutes a transition zone between the Adapazarı Plain and the Adapazarı-Karasu

Corridor. The Aktefek-Sinanoğlu and Akkum-Karasu sectors constitute high topographic areas which are defined by E-W-trending right-lateral strike-slip faults parallel to the NAF (Fig. 6). In these areas, the Sakarya River flows through deep, narrow valleys cut into basement units. The E-W-trending faults have a significant vertical slip component. The southern side of the E-W fault in the northernmost part of the Adapazarı-Karasu Corridor is overlain by marine sands which belong to the Acarlar-Kocaali Coastal Zone. This indicates that the E-W faults are young and active (Yiğitbaş et al. 2003).

---

#### Acarlar-Kocaali Coastal Zone

The E-W-trending Acarlar-Kocaali Coastal Zone (İnandık 1963), which is one of the largest coastal plains in North Anatolia, is separated from the Adapazarı-Karasu Corridor, Thrace-Kocaeli Peneplain and Çamdağ-Akçakoca Highland to the south by a fault scarp 75–80 m high and which parallels the Black Sea coast (Fig. 6). This zone contains old and recent sand dunes, swamps and barrier lakes. A band of beach dunes 50 km long constitutes an important part of the Acarlar-Kocaali Coastal Zone. Beach deposits are generally composed of well-sorted, thin-grained, sand-sized material. There are E-W-trending dunes a few meters high extending along the coast behind this beach. These dunes form a continuous slope which constitutes the southern boundary of the Acarlar-Kocaali Coastal Zone.

---

#### Discussion and structural evolution

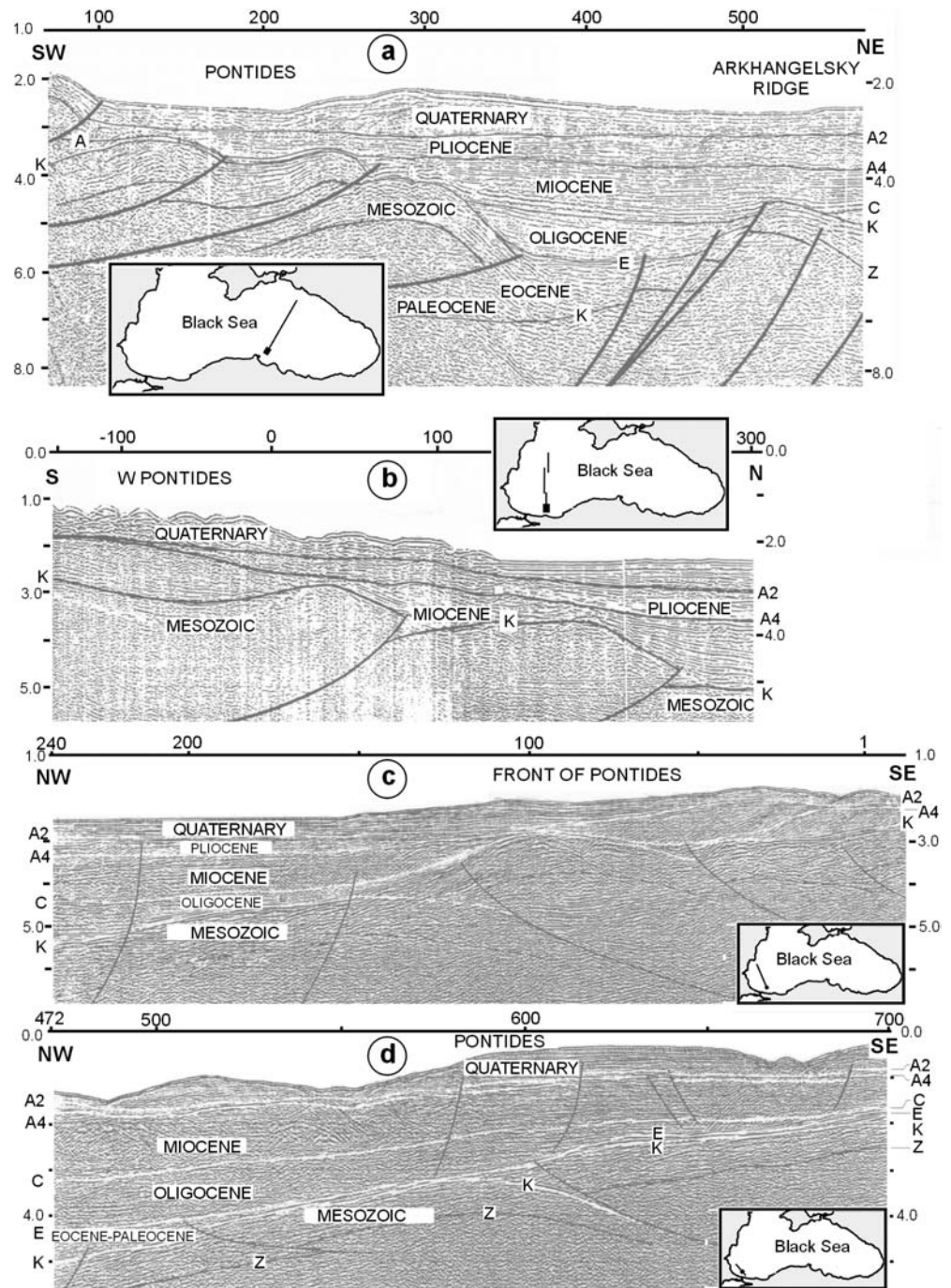
Considering the geology of northwest Anatolia outlined above, two major stages can be distinguished in the geological evolution of the region: (1) a pre-NAF stage, and (2) a north-south extensional stage. These stages are discussed below, followed by an assessment of effects of the N-S extensional regime on the region.

#### The pre-NAF stage

This stage corresponds to the Lutetian-early Middle Miocene time period. The development of many neotectonic units in northwest Anatolia coincided in both time and space with the initiation of the NAFZ. However, the Çamdağ-Akçakoca/Southern Thrace/Strandja highlands obtained most of their present shapes prior to late Middle Miocene times.

The uplift of the Çamdağ-Akçakoca area may have begun before the development of the NAFZ, because all units up to the Eocene have not been eroded in the eastern part of the Thrace-Kocaeli Peneplain to the west, whereas in the Çamdağ-Akçakoca Highland deep erosion occurred into the Lower Paleozoic units (Figs. 5, 6a). In addition, there is an elevation difference of about 1,000 m between the two areas (Fig. 3a). The Pontian-Lower Pliocene

**Fig. 8a–d** Seismic profiles from the southern Black Sea shelf (from Finetti et al. 1988). The *insets* show the locations of the seismic profiles. **a** Seismic line in the eastern part of the southern Black Sea shelf (east of the Sakarya River) shows the presence of a thrust fault affecting Quaternary deposits. **c**, **d** Seismic lines in the western part of the southern Black Sea shelf (west of the Sakarya River) show the presence of normal faults affecting Quaternary deposits

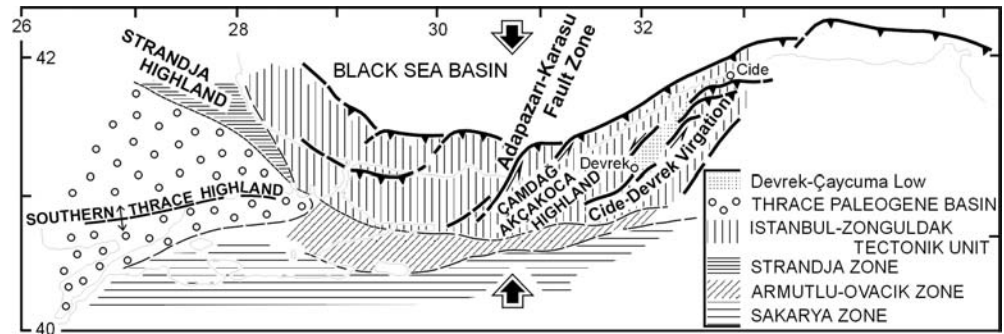


deposits of the Thrace-Kocaeli Penplain (Belgrade and Karasu formations) can be observed only on the northern slope of the Çamdağ-Akçakoca Highland. For these reasons, the uplift of the Çamdağ-Akçakoca area may have caused the formation of a fault zone (the Adapazarı-Karasu Fault) between the Thrace-Kocaeli Penplain and the Çamdağ-Akçakoca Highland.

Finetti et al. (1988) suggested that there are clear compressive deformational structures in the southern margin of the Black Sea, which are of Middle Eocene age. On their seismic profiles, however (Fig. 8), it appears that

the compressive structures associated with overthrust deformation occurred from Eocene to Early Miocene times. The deformation continued in the eastern Pontides offshore (Fig. 8a) to the present (Göktaşan 1996). In addition, in areas to the east of the Sakarya River, the compressive structures of Lutetian–Miocene age are represented by E–W-trending, north-vergent thrust faults and NE–SW-trending left-lateral strike-slip faults (Cide-Devrek Virgation of Yiğitbaş and Elmas 1997; Fig. 9). In this case, it is thought that the Adapazarı-Karasu Fault is one of the left-lateral strike-slip faults related to this N–S

**Fig. 9** Tectonic map depicts the tectonic evolution of the northern part of Turkey from the Lutetian to the Middle Miocene



compressional tectonic regime which developed since the Lutetian. Within this tectonic regime, following the deposition of the Thrace Paleogene Basin units, the Southern Thrace Highland was formed as an E-W-trending anticline during late Early Miocene–early Middle Miocene times. In addition, the Strandja Highland, which bounded the Middle Eocene–Oligocene fore-arc units (Görür and Okay 1996) in the south, obtained most of its present shape since Eocene times.

#### The north–south extensional stage

Western Anatolia has long been known to represent a broad zone of extension (Phillipson 1915) stretching from Bulgaria in the north to the Hellenic arc in the south (McKenzie 1972; Mercier et al. 1989). Estimated ages for the initiation of north–south extension (Dewey and Şengör 1979; Le Pichon and Angelier 1981; Şengör et al. 1985; Jackson and McKenzie 1988; Görür et al. 1995, 1997; Armijo et al. 1996, 1999; Yılmaz et al. 2000) in western Anatolia range from the late Oligocene (Jolivet et al. 1994; Jolivet and Patriat 1999), the late Oligocene–early Miocene (Seyitoğlu and Scott 1991), to the early–middle Miocene (Altherr et al. 1982; Lyberis 1984). The ages of the first strata (the units of the Thrace Neogene Basin) on the pre-Neogene basement units indicate that back-arc extension related to the Hellenic trench (McKenzie 1972; Le Pichon and Angelier 1981; Adıyaman et al. 2001) reached to the northern area (the Marmara region) since the late Middle Miocene. The extension propagated eastwards through time along the NAF (Chorowicz et al. 1999; Adıyaman et al. 2001). Along the NAFZ, first-stage extension was followed by strike-slip tectonics in the second stage (Adıyaman et al. 2001).

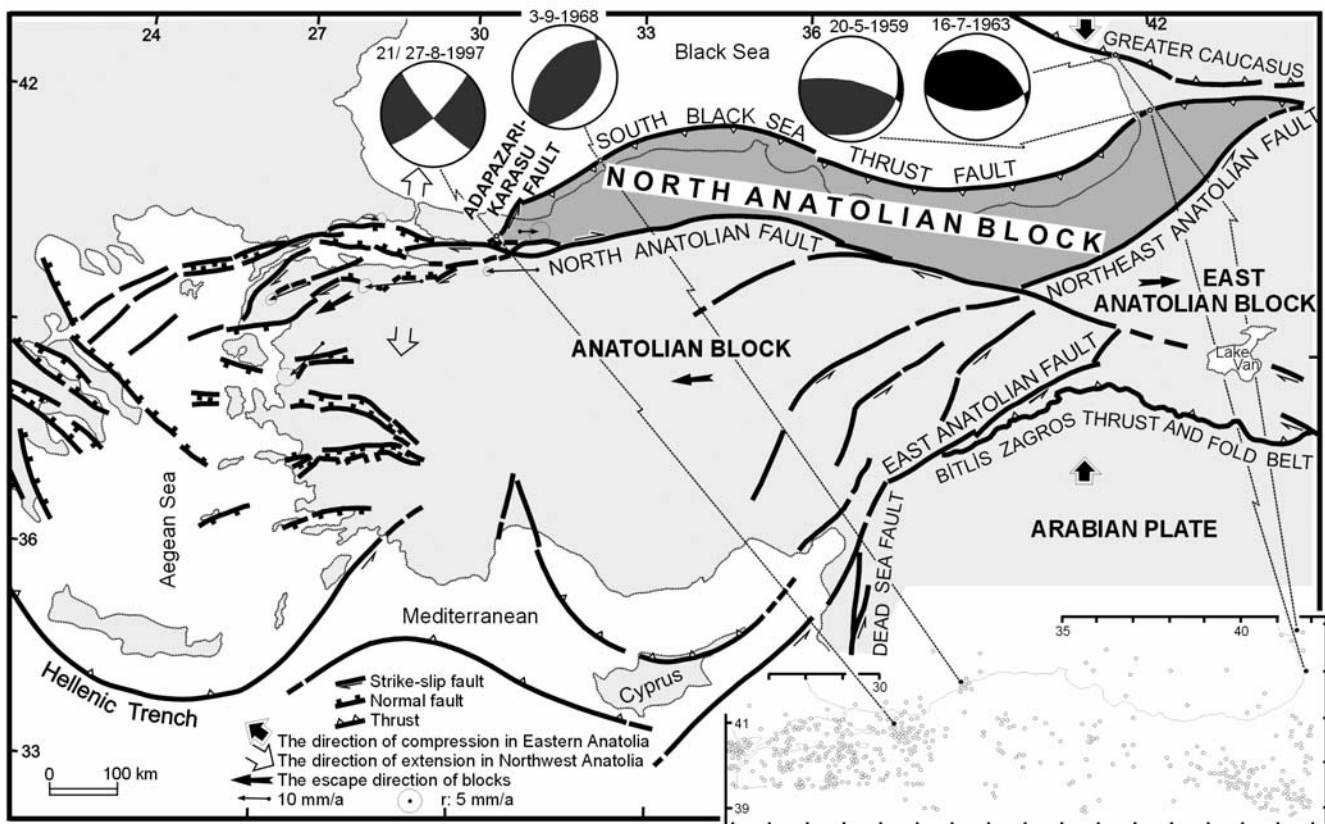
Following initiation in the west and eastward propagation of the western part of the NAFZ, a block began to form in the northern Anatolia region. The block, bounded by significant seismically active zones, is named the North Anatolian Block (Elmas 2000, Fig. 10); the Çamdağ-Akçakoca Highland constitutes the western part of this block. It is bounded by the right-lateral North Anatolian Fault Zone (Ketin 1969; Jackson and McKenzie 1988; Barka 1992; Chorowicz et al. 1999; Adıyaman et al. 2001) in the south, the left-lateral Adapazarı-Karasu Fault (Yiğitbaş et al. 2003) in the west, and the left-lateral

Northeast Anatolian Fault (NEAF) in the southeast. The NEAF is active (Chorowicz et al. 1999) and locally has a south-verging thrust component (Philip et al. 1989; Lyberis et al. 1992). The northern border of the North Anatolian Block is formed by a thrust fault, named the South Black Sea Thrust Fault, which extends parallel to the southern coast of the Black Sea from Bartın eastwards. The existence of this fault was suggested by Letouzey et al. (1977). Seismic activity has been observed along the southern margin of the Black Sea, especially during the destructive M:6.8 Bartın earthquake in 1968; the source mechanism of the Bartın earthquake (Fig. 10) indicated thrust faulting (Alptekin et al. 1986).

The data indicate that the Adapazarı-Karasu Fault is a NE–SW active zone (Yiğitbaş et al. 2003). These data are summarized as follows:

1. geologic data such as the presence of very young faults (Fig. 6),
2. the bathymetric features of the southwestern Black Sea region (Fig. 3b),
3. the linear earthquake epicenters, which have been recorded since 1985 by the Earthquake Research Institute in the area between Adapazarı and Karasu, and their fault mechanism solutions (Fig. 10), and
4. the evaluation by Yiğitbaş et al. (2003) of the seismic profiles offshore of the Sakarya River which indicate the Adapazarı-Karasu Fault Zone extends along the Sakarya River and continues into the Black Sea (Fig. 4a).

The Adapazarı-Karasu Fault Zone is a block boundary fault in the northern Anatolia region. North of the Kocaeli Peninsula, traces of extensional tectonics indicated by normal faults of Neogene–Quaternary age were observed on the seismic profiles of Finetti et al. (1988; Fig. 8c, d). However, from the Sakarya River offshore to the east, traces of extensional tectonics during the same period are not observed (Fig. 8a). In addition, (1) the existence of a mountain chain known as the Black Sea Mountain, to the east of the Sakarya River, (2) the presence of the Thrace-Kocaeli Peneplain to the west, and (3) the positions of the Quaternary terraces (Erinç 1984) in both sections indicate that a compressional tectonic regime is present east of the Sakarya River, in contrast to areas farther west (Gökaşan 1996). Consequently, the left-lateral Adapazarı-Karasu



**Fig. 10** Simplified tectonic map of the Anatolian region and surroundings, showing the main tectonic domains developed during Miocene to Holocene times (modified from Letouzey et al. 1977; Jackson and McKenzie 1988; Şengör et al. 1985; Barka and Kadinsky-Cade 1988). Available fault plane solutions for earthquakes (magnitudes between 3 and 4.5) which occurred at the west and north margin of the North Anatolian Block are shown. The solution for 20-5-1959 is taken from Shirokova (1967), the solution

for 16-7-1963 from McKenzie (1972), the solution for 3-9-1968 from Alptekin et al. (1986), and the solution for 21/27-8-1997 from E. Yiğitbaş et al. (unpublished data). The GPS measurements for northwestern Anatolia are taken from Straub (1996). The inset shows the seismicity of northern Turkey from 1990 to 1999. The points represent earthquakes with magnitudes bigger than 4. Data are from the Boğaziçi University Kandilli Observatory and Earthquake Research Institute Seismology Laboratory

Fault which extends along the northern part of the Sakarya River Valley separates an extensional regime in northwestern Anatolia from a compressional regime in the east. According to Göktaşan (1996), these two different tectonic regimes were separated by a N–S line through Ereğli.

The results of the N–S extension in northwestern Anatolia

The upper Middle Miocene units of the Thrace Neogene Basin are the first strata to be deposited in the extensional regime in northwestern Turkey (Fig. 11, map a). The Thrace Fault (Perinçek 1991) to the north was formed prior to Pliocene times (probably in the late Middle Miocene). Also, sedimentation (Dardanelles Group) in the Thrace Neogene Basin was mainly controlled by the NE–SW-trending Ezine-Şarköy Fault (Elmas and Meriç 1998) to the southeast during late Middle Miocene times. The absence of the units deposited in a high-energy depositional environment in the northern part of the basin

indicates that displacement on the Thrace Fault was less than on the Ezine-Şarköy Fault.

Due to the extensional tectonic regime in the region, a marine tongue transgressed from the north over the area along the northern coast of the future Sea of Marmara in Late Miocene times (Fig. 11, map b). The presence of abundant *Mastra* in the marine limestone (Bakırköy Limestone; b in Fig. 5) west of İstanbul indicates that during the Late Miocene the invading sea in this area was not the Mediterranean but the Paratethyan (Muratov and Nevesskaya 1982; Görür et al. 1997).

Late Sarmatian–Pontian deposits (Çukurçeşme and Güngören formations, and Bakırköy Limestone) of the Paratethys commonly form the cover unit of the Thrace Paleogene Basin and the İstanbul-Zonguldak Tectonic Unit (Fig. 2). The covering of the Strandja Zone and the Sakarya Zone by Upper Miocene fluvio-lacustrine deposits (the upper parts of the Ergene Formation) and Pannonian shallow marine deposits (Alçitepe Formation), respectively, indicates that the Thrace and Ezine-Şarköy faults of the Thrace Neogene Basin had ceased their

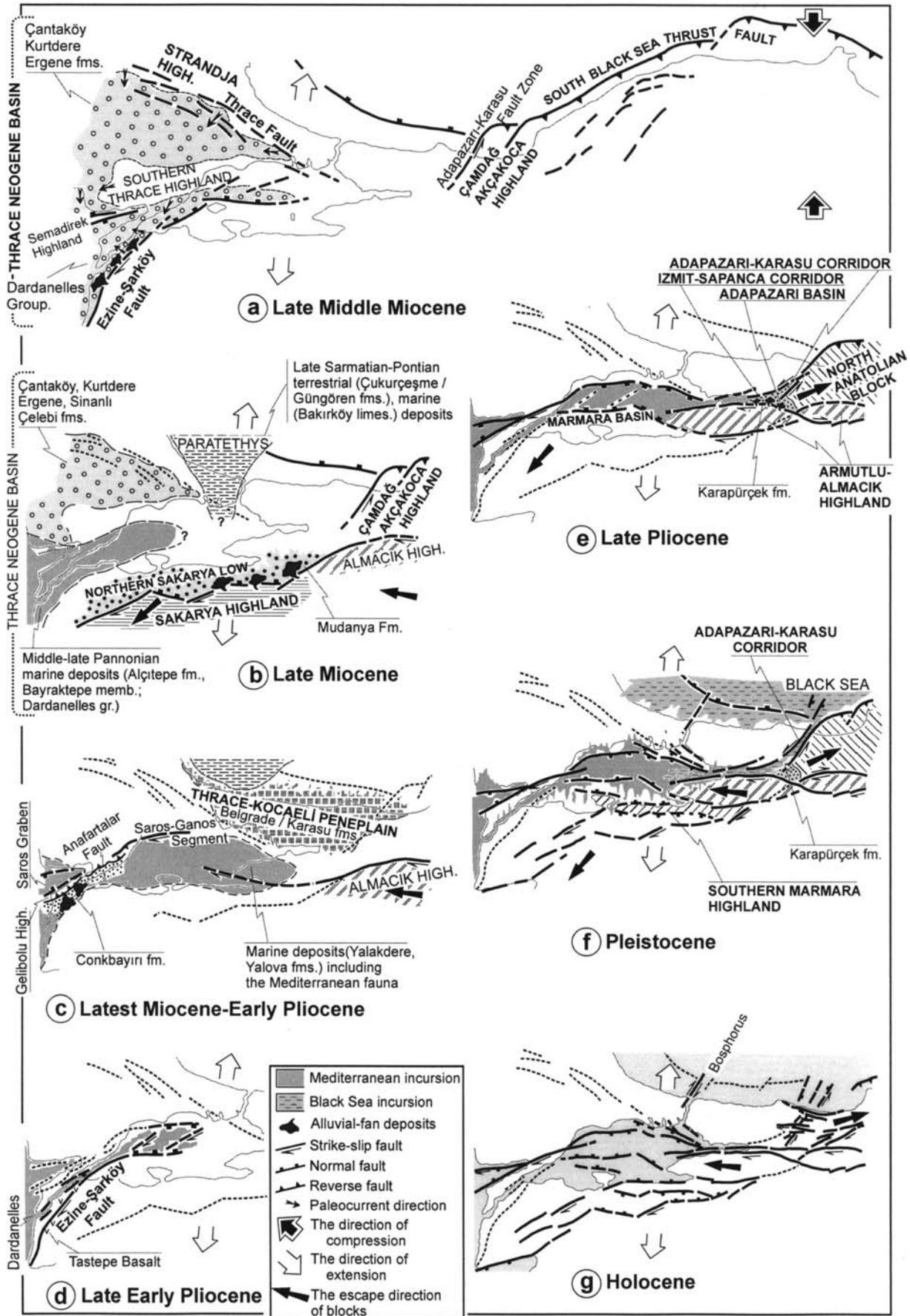


Fig. 11 Tectonic maps (a-g) depicting the tectonic evolution of northwestern Turkey from the Late Middle Miocene to the present

activities during the latest Middle Miocene to early Late Miocene interval (Fig. 11, maps a, b).

The extensional regime caused the Mediterranean incursion to the region. Stratigraphic and paleontologic data obtained from the shallow marine deposits (Alçitepe Formation and Bayraktepe Member of Dardanelles Group in the Thrace Neogene Basin) indicate an initial incursion of Mediterranean waters to the site of the future Sea of Marmara during Middle to Late Pannonian times, extending from southern Thrace to the west of the Biga Peninsula (Elmas and Meriç 1998; Fig. 11, map b).

The characteristics of the Upper Miocene (Sichenberg et al. 1975) alluvial-fan/deltaic deposits (Mudanya Formation) in the northern parts of the Sakarya Zone indicate fault-controlled deposition (Fig. 11, map b). According to Schindler (1997), during the Tortonian the NAFZ existed in the southern Marmara region in a first phase of activity. This fault may have been the NE-SW-trending active branch of the NAF between Bursa and Yenice (Fig. 4a). The existence of latest Miocene–Early Pliocene Mediterranean fauna (Emre et al. 1998) in the marine deposits (Yalakdere, Yalova and Çamlık formations) to the north indicates that Mediterranean waters reached the eastern areas of the future Sea of Marmara during this time (Fig. 11, map c). The northern part of the Sakarya Zone, the Northern Sakarya Low, is thought to be the result of the eastward widening of the Thrace Neogene Basin by the NE-SW-trending faults (Fig. 11, maps a, b).

The geological evolution of the Thrace Neogene Basin and the Northern Sakarya Low is consistent with the model of eastward propagation of extension and the NAF. In the model of Chorowicz et al. (1999) and Adıyaman et al. (2001), it was suggested that within Anatolia there are many triangular-shaped sectors formed by the NAF, and NE- to ENE-striking late Neogene faults which branch from the central and eastern NAF (Dewey et al. 1986; Barka 1992; Chorowicz et al. 1995; Tatar et al. 1995; Bozkurt and Koçyiğit 1996; Dhont et al. 1998; Barka et al. 2000). The sectors constitute an escape wedge which has migrated by successive jumps from west to east, creating NE-SW-trending fault zones (Chorowicz et al. 1999; Adıyaman et al. 2001).

During latest Miocene–Early Pliocene times, the Saros-Ganos segment and the Anafartalar Fault (Fig. 4a) developed as a positive flower structure (Christie-Blick and Biddle 1985) in the second phase of NAFZ activity (Schindler 1997) in northwestern Turkey (Fig. 11, map c). This positive feature (Gelibolu Highland) and the alluvial-fan deposits (Conkbayırı Formation) to the east obstructed the previous Mediterranean incursion during Early Pliocene times (Elmas and Meriç 1998). Also, the development of an erosion surface in the Thrace-Kocaeli area began during the Pontian, as shown by the unconformable relationship of the terrestrial Pontian–Pliocene deposits (Belgrade Formation) with the underlying Upper Miocene rocks (Fig. 5). Consequently, the erosion surface of the Thrace-Kocaeli Peneplain obstructed the previous Paratethys incursion from the south (Fig. 11, map c).

In the western part of the Biga Peninsula, the existence of late Middle Miocene basic lavas (Taştepe basalt), extruded along the Ezine-Şarköy Fault, indicates that the fault which controlled the geometry of the Thrace Neogene Basin during the late Middle Miocene (Fig. 11, map a) was reactivated in the late Early Pliocene (Fig. 11, map d). This tectonism caused the opening of the Dardanelles and the second incursion of Mediterranean waters into the future Sea of Marmara (Elmas and Meriç 1998). Fossil assemblages (g in Fig. 5) of Mediterranean origin (Gülen et al. 1995; Toker and Şengüler 1995; Meriç 1995b), determined from wells in the Gulf of İzmit, indicate that Mediterranean waters reached this area during Late Pliocene times (Fig. 11, map e).

The existence of the Upper Pliocene–Pleistocene alluvial-fan deposits (Karapürçek Formation) through the southern border of the İzmit-Sapanca Corridor and the Adapazarı Basin indicates that the branch of the NAF in the north of Armutlu-Almacık Highland has been active since the Late Pliocene (Fig. 11, map e). North of this right-lateral NAF, the northeastward movement of the North Anatolian Block east of the left-lateral Adapazarı-Karasu Fault initiated the development of the Adapazarı Basin at the corner of the fault blocks, and the formation of the İzmit-Sapanca/Adapazarı-Karasu corridors since the Late Pliocene. In addition, the westward compressional movement of the Armutlu-Almacık Highland accelerated the north–south opening of the Marmara Basin (Fig. 11, map e). According to Armijo et al. (1999), the Marmara Basin is assumed to be Plio-Pleistocene.

Fossil assemblages (f in Fig. 5) from the Black Sea, determined from wells in the Gulf of İzmit, indicate that Black Sea waters reached the Marmara region during the Pleistocene (Pfannenstiel 1944; Kosswig 1954; Bilgin 1984; Tchapylyga 1995; Meriç 1995a). Continuity of Late Pliocene tectonism (Fig. 11, map e) may have caused the widening of the Adapazarı-Karasu Corridor (Fig. 11, map f). Consequently, the Adapazarı-Karasu Corridor, the Adapazarı Basin, the İzmit-Sapanca Corridor, the Marmara Basin and the Dardanelles formed a seaway connecting the Black Sea and the Aegean/Mediterranean during Pleistocene times.

The existence of Upper Pleistocene marine terraces around the Sea of Marmara (Figs. 2b, 5) indicates that marine waters had a greater expanse in Late Pleistocene times than today (Sakıncı and Yalıtırak 1997). However, the absence of these Upper Pleistocene marine terraces in the area between Bandırma and Mudanya (Fig. 2b) indicates that the area (Southern Marmara Highland) was uplifted prior to the Late Pleistocene (probably in Pleistocene times; Fig. 11, map f).

Topographically high areas (Akkum-Karasu and Aktefek-Sinanoğlu sectors; Fig. 6b) in the Adapazarı-Karasu Corridor obtained their present shapes due to the E-W-trending faults parallel to the NAF. Seismic activity in this region is caused by these E-W-trending faults and the reactivation of the NE-SW-trending Adapazarı-Karasu Fault (Yiğitbaş et al. 2003). Due to these E-W-trending areas of uplift, the previous connection between the Black

Sea and the Sea of Marmara (Fig. 11, map f) was obstructed during the Holocene (Fig. 11, map g).

The recent connection between the Black Sea and the Sea of Marmara has been through the Bosphorus and formed in Holocene times (Gökaşan et al. 1997; Çağatay et al. 2000; Meriç et al. 2000; Fig. 11, map g). A bathymetric indentation north of the Sakarya River offshore also extends north of the Bosphorus under the Black Sea waters (Fig. 3b). NE-SW-trending faults affecting the bathymetry and recent sediments in the Bosphorus (Gökaşan et al. 1997) are the prolongation of this indentation. Thus, it is suggested that the Bosphorus was also controlled by NE-SW-trending faults, as in the Adapazarı-Karasu Corridor.

## Conclusion

Many morpho-tectonic units of Late Cenozoic age are distinguished in northwestern Turkey. Three of them, the Strandja/Southern Thrace highlands and the Çamdağ-Akçakoca Highland which was uplifted by the NE-SW-trending left-lateral Adapazarı-Karasu Fault, obtained most of their present shapes in the Lutetian-early Middle Miocene, N-S compressional regime in northern Anatolia.

The N-S extensional regime began in the Marmara region during late Middle Miocene times. Following the initiation in the late Middle Miocene and eastward propagation of the western part of the NAF, the North Anatolian Block began to form in the northern Anatolia region since Late Pliocene times. The block is bounded by the right-lateral NAF in the south, the left-lateral North-east Anatolian Fault in the southeast, and the South Black Sea Thrust Fault in the north. The left-lateral Adapazarı-Karasu Fault in the west of the North Anatolian Block is like a block boundary fault, and has separated the compressional regime in the east of the northern part of the Sakarya River Valley from the extensional regime in the west since the late Middle Miocene.

The N-S extension caused the development of basins and ridges (the Thrace Neogene/Marmara/Adapazarı basins, the Northern Sakarya Low, the İzmit-Sapanca/Adapazarı-Karasu corridors, and the Southern Marmara/Armutlu-Almacık highlands), and the incursions of the Mediterranean Sea and the Paratethys into the site of the future Sea of Marmara since Late Miocene times. Also, northeastward movement of the North Anatolian Block created a marine connection between the Black Sea and the Aegean/Mediterranean seas through the Dardanelles, Marmara Basin and İzmit-Adapazarı/Adapazarı-Karasu corridors during Pleistocene times.

**Acknowledgements** This paper includes results of a decade-long field study supported by TUBITAK (Turkish Scientific and Technical Research Unit, project nos. YDABÇAG 594-G and 100Y061). I am grateful for their support. I thank Prof. B.C. Burchfiel and Dr. J. Chorowicz for incisive and comprehensive critiques and detailed review of the manuscript. Dr. E. Yiğitbaş also made valuable suggestions.

## References

- Adıyaman Ö, Chorowicz J, Arnaud ON, Gündoğdu N, Gourgaud A (2001) Late Cenozoic and volcanism along the North Anatolian Fault: new structural and geochemical data. *Tectonophysics* 338:135–165
- Alpar B (1999) Underwater signatures of the Kocaeli Earthquake (August 17<sup>th</sup> 1999). *Turkish J Mar Sci* 5:111–130
- Alptekin Ö, Nabelek JL, Toksöz MN (1986) Source mechanism of the Bartın earthquake of September 3, 1968 in Northwestern Turkey: evidence for active thrust faulting at the Southern Black Sea margin. *Tectonophysics* 122:73–88
- Altherr R, Kreuzer H, Wendt I, Lenz H, Wagner GA, Keller J, Harre W, Hohndorf A (1982) A late Oligocene/Early Miocene high temperature belt in the anti-cycladic crystalline complex (SE Pelagonian, Greece). *Geol Jahrb* 23:97–164
- Armijo R, Meyer B, King GCP, Rigo A, Papanastassiou D (1996) Quaternary evolution of the Corinth Rift and its implications for the Late Cenozoic evolution of the Aegean. *Geophys J Int* 126:11–53
- Armijo R, Meyer B, Hubert A, Barka A (1999) Westward propagation of the North Anatolian fault into the northern Aegean: timing and kinematics. *Geology* 27:267–270
- Bargu S, Sakıncı M (1989) Geology and structural features in the area between the Gulf of İzmit and İzmit Lake (in Turkish). *Bull Earth Sci Univ Istanbul* 6:45–76
- Barka AA (1992) The North Anatolian fault zone. *Ann Tectonicae* 6:164–195
- Barka AA (1996) Slip distribution along the North Anatolian fault associated with the large earthquakes of the period 1939–1967. *Seismol Soc Am Bull* 86:1238–1254
- Barka AA, Hancock PL (1984) Neotectonic deformation patterns in the convex-northwards arc of the North Anatolian fault. In: Dixon JE, Robertson AHF (eds) *The geological evolution of the Eastern Mediterranean*. *Geol Soc Lond Spec Publ* 20:763–773
- Barka AA, Kadinsky-Cade K (1988) Strike-slip fault geometry in Turkey and its influence on earthquake activity. *Tectonics* 7:663–684
- Barka AA, Akyüz HS, Cohen HA, Watchorn F (2000) Tectonic evolution of the Nizsar and Taşova-Erbaa pull-apart basins, North Anatolian Fault Zone: their significance for the motion of the Anatolian block. *Tectonophysics* 322:243–264
- Bilgin T (1984) Alluvial morphology and geomorphologic development in Quaternary of the Adapazarı Basin and the Sapanca Corridor (in Turkish). *Bull Univ Istanbul* 2572:1–199
- Bozkurt E, Koçyiğit A (1996) The Kazova basin: an active negative flower structure on the Almus Fault zone, a splay fault system on the North Anatolian Fault Zone, Turkey. *Tectonophysics* 265:239–254
- Çağatay N, Görür N, Algan O, Eastoe C, Tchapylyga A, Ongan D, Kuhn T, Kuşçu İ (2000) Late glacial-Holocene paleogeography of the Sea of Marmara: timing of connections with the Mediterranean and Black seas. *Mar Geol* 167:191–206
- Chorowicz J, Luxey P, Yürür T, Rudant JP, Gündoğdu N, Lyberis N (1995) Slip-motion estimation along the Ovacık fault near Erzincan (Turkey) using ERS-1 radar image: evidence of important deformation inside the Turkish plate. *Remote Sensing Environ* 52:66–70
- Chorowicz J, Dhont D, Gündoğdu N (1999) Neotectonics in the eastern North Anatolian fault region (Turkey) advocates crustal extension: mapping from SAR ERS imagery and Digital Elevation Model. *J Struct Geol* 21:511–532
- Christie-Blick N, Biddle KT (1985) Deformation and basin formation along strike-slip faults. *Soc Econ Paleontol Mineral Spec Publ* 37:1–34
- Dewey JF, Şengör AMC (1979) Aegean and surrounding regions: complex multiplate and continuum tectonics in a convergent zone. *Geol Soc Am Bull* 90:84–92
- Dewey JF, Hempton M, Kidd W, Şaroğlu F, Şengör AMC (1986) Shortening of continental lithosphere: the neotectonics of eastern Anatolia: a young collision zone. In: Coward MP, Ries AC (eds) *Collision tectonics*. *Geol Soc Lond Spec Publ* 19:3–36

- Dhont D, Chorowicz J, Yürür T, Köse O (1998) Polyphased block tectonics along the North Anatolian Fault in the Tosya basin area (Turkey). *Tectonophysics* 299:213–277
- Elmas A (2000) In northwest Anatolia, the effects of the North Anatolian Fault Zone (in Turkish). The fourth meeting of the Active Tectonic Investigation Group (ATAG-4), Eskişehir, Abstracts, p 53
- Elmas A, Meriç E (1998) The seaway connection between the Sea of Marmara and the Mediterranean: tectonic development of the Dardanelles. *Int Geol Rev* 40:144–162
- Elmas A, Yiğitbaş E (2001) Ophiolite emplacement by strike-slip tectonics between the Pontide Zone and the Sakarya Zone in the NW Anatolia, Turkey. *Geol Rundsch* 90:257–269
- Elmas A, Yiğitbaş E, Yılmaz Y (1997) The geology of the Bolu-Eskipazar Zone: an approach to the development of the Intra-Pontide suture (in Turkish). *Geosound* 30:1–14
- Emre Ö, Erkal T, Tchapylyga A, Kazancı N, Keçer M, Ünay E (1998) Neogene-Quaternary evolution of the eastern Marmara region (in Turkish). *Bull Mineral Res Explor Inst Turkey* 120:61–79
- Ergün M, Özel E (1995) Structural relationship between the Sea of Marmara Basin and the Anatolian Fault Zone. *Terra Nova* 7:278–288
- Eriç S (1984) Geomorphology of the Black Sea Basin. *Bull Istanbul Univ* 1:15–22
- Finetti I, Bricchi H, Del Ben A, Pipan M, Xuan Z (1988) Geophysical study of the Black Sea. *Boll Geofis Teor Appl Monogr Black Sea* 30:194–324
- Göktaşan E (1996) An approach to neotectonic of the Black Sea coast in north Anatolia (in Turkish). *Geosound* 29:99–109
- Göktaşan E, Demirbağ E, Oktay F, Ecevitöğlü B, Şimşek M, Yüce H (1997) On the origin of the Bosphorus. *Mar Geol* 140:183–199
- Görür N, Okay A (1996) Origin of the Thrace Basin, NW Turkey. *Geol Rundsch* 85:662–668
- Görür N, Sakiç M, Barka A, Akkök R, Ersoy Ş (1995) Miocene to Pliocene palaeogeographic evolution of Turkey and its surrounding. *J Human Evol* 28:309–324
- Görür N, Çağatay MN, Sakiç M, Sümenen M, Şentürk K, Yaltrak C, Tchapylyga A (1997) Origin of the Sea of Marmara as deduced from Neogene to Quaternary paleogeographic evolution of its frame. *Int Geol Rev* 39:342–352
- Gülen D, Kubanç C, Altunsaçlı S (1995) Ostracod fauna of the Quaternary sequence in the Gulf of İzmit (Hersek Burnu-Kaba Burun) In: Meriç E (ed) Quaternary sequence of İzmit Bay (in Turkish). Military College Printing House, İzmit, pp 153–172
- Hempton MR (1987) Constraints on the Arabian plate motions; an extensional history of the Red Sea. *Tectonics* 6:688–705
- İmren C, Le Pichon X, Rangin C, Demirbağ E, Ecevitöğlü B, Görür N (2001) The North Anatolian Fault within the Sea of Marmara. A new interpretation based on multi-channel seismic and multi-beam bathymetry data. *Earth Planet Sci Lett* 186:143–158
- İnandık H (1953) Geomorphology of the Adapazarı Basin. *Bull Univ Istanbul* 2:107–138
- İnandık H (1963) Sakarya Delta (in Turkish). *Bull Univ Istanbul* 13:83–98
- Jackson J, McKenzie DP (1988) The relationship between plate motions and seismic moment tensors, and the rates of active deformation in the Mediterranean and Middle East. *Geophys J* 93:45–73
- Jolivet L, Patriat M (1999) Ductile extension and the formation of the Aegean Sea. In: Durand B, Jolivet L, Horvath F, Séranne M (eds) *The Mediterranean basins: Tertiary extension within the Alpine Orogen*. *Geol Soc Lond Spec Publ* 156:427–456
- Jolivet L, Dail JM, Truffert JM, Goffé B (1994) Exhumation of deep crustal metamorphic rocks and crustal extension in back-arc regions. *Lithos* 33:3–30
- Ketin İ (1969) About the North Anatolian Fault. *Bull Mineral Res Explor Inst Turkey* 72:1–25
- Koçyiğit A (1989) Susehri basin: an active fault-wedge basin on the North Anatolian fault zone, Turkey. *Tectonophysics* 167:13–29
- Kosswig C (1954) Zoogeography of fresh water fishes in Turkey. *Bull Hydrobiol Inst Istanbul Univ* 2:3–20
- Le Pichon X, Angelier J (1981) The Aegean Sea. *Philos Trans R Soc Lond* 300:357–372
- Le Pichon X, Chamot-Rooke N, Lallemand S, Noomen R, Veis G (1995) Geodetic determination of the kinematics of Central Greece with respect to Europe: implications for Eastern Mediterranean tectonics. *J Geophys Res* 100:12675–12690
- Letouzey J, Biju-Duval B, Dorkel A, Gonnard R, Kristchev K, Montadert L, Sungurlu O (1977) The Black Sea: a marginal basin. Geophysical and geological data. In: Biju-Duval B, Montadert L (eds) *Proc Int Symp The Structural History of the Mediterranean Basins*. Editions Technip, Paris, pp 363–376
- Lyberis N (1984) Tectonic evolution of the North Aegean trough. In: Dixon JE, Robertson AHF (eds) *The geological evolution of Eastern Mediterranean*. *Geol Soc Lond Spec Publ* 17:709–725
- Lyberis N, Yürür T, Chorowicz J, Kasapoğlu E (1992) The East Anatolian Fault: an oblique collisional belt. *Tectonophysics* 204:1–15
- McClusky S, Balassanian S, Barka A, Demir C, Georgiev I, Hamburger M, Kahle H, Kastens K, Kekelidse G, King R, Kotzev V, Lenk O, Mahmoud S, Mishin A, Nadaria M, Ouzounis A, Paradisissis D, Peter Y, Prilepin M, Reilinger R, Sanli I, Seeger H, Teableb A, Toksoz N, Veis G (2000) GPS constraints on crustal movements and deformations in the eastern Mediterranean (1988–1997): implications for plate dynamic. *J Geophys Res* 105:381–395
- McKenzie DP (1972) Active tectonics of the Mediterranean region. *Geophys J R Astron Soc* 30:109–185
- Mercier JL, Sorel D, Vergely P (1989) Extensional tectonic regimes in the Aegean basins during the Cenozoic. *Basin Res* 2:49–71
- Meriç E (1995a) The findings of the seaway connection between the Sea of Marmara and the Black Sea via the Gulf of İzmit, Sapanca Lake and Sakarya valley pre-development of Bosphorus (in Turkish). *Geosound* 27:149–158
- Meriç E (1995b) Stratigraphy and environmental evaluation of the Quaternary sequence in the Gulf of İzmit (Hersek Burnu-Kaba Burun) (in Turkish). In: Meriç E (ed) *Quaternary sequence of İzmit Bay*. Military College Printing House, İzmit, pp 153–172
- Meriç E, Kerey E, Avşar N, Tunoğlu C, Taner G, Kapan-Yeşilyurt S, Ünsal İ, Rosso A (2000) New findings of the connection between the Sea of Marmara and the Black Sea via Bosphorus in the Late Quaternary (in Turkish). *Bull Geol Soc Turkey* 43:73–118
- Muratov MV, Neveeskaya L (1982) Stratigraphy of the USSR Neogene system (in Russian). Nedra Press, Moscow
- Okay AI, Demirbağ E, Kurt H, Okay N, Kuşçu İ (1999) An active, deep marine strike-slip basin along the North Anatolian Fault in Turkey. *Tectonics* 18:129–147
- Pamir HN (1938) Development of Bosphorus. *Bull Mineral Res Explor Inst Turkey* 3:61–69
- Perinçek D (1991) Possible strand of the North Anatolian Fault in the Thrace Basin, Turkey—an interpretation. *Am Assoc Petrol Geol Bull* 75:241–257
- Pfannenstiel M (1944) Diluviale Geologie des Mittelmeergebietes: die diluvialen Entwicklungsstadien und die Urgeschichte von Dardanellen, Marmara Meer und Bosphorus. *Geol Rundsch* 34:342–334
- Philip H, Cisternas A, Gvishiani A, Gorshkov A (1989) The Caucasus: an actual example of the initial stages of continental collision. *Tectonophysics* 161:1–21
- Phillipson A (1915) *Reisen und Forschungen im Westlichen Kleinasien (1910–1915)*. Gotha, Justus Perthes, Petermanns Mitteil Ergänzungsheft 167, 172, 177, 180, 183
- Platzman ES, Tapirdamaz C, Sanver M (1998) Neogene anticlockwise rotation of Central Anatolia (Turkey): preliminary palaeomagnetic and geochronological results. *Tectonophysics* 299:175–189
- Reilinger R, McClusky S, Oral M, King R, Toksöz M, Barka A, Kinik I, Lenk O, Sanli I (1997) Global positioning system measurements of present-day crustal movements in the Arabia-



- Africa-Eurasia plate collision zone. *J Geophys Res* 102:9983–9999
- Robinson AG, Rudat JH, Banks CJ, Wiles RLF (1996) Petroleum geology of the Black Sea. *Mar Petrol Geol* 13/2:195–223
- Sakıncı M, Yaltrak C (1997) Marine Pleistocene deposits and Pleistocene paleogeography of the southern Thrace (in Turkish). *Bull Mineral Res Explor Inst Turkey* 119:43–62
- Saner S (1985) Tectonic implication and sequences around of Saros Bay, northeast Aegean Sea, Turkey. *Bull Geol Soc Turkey* 28:1–10
- Şaroğlu F (1988) Age and offset of the North Anatolian fault. *Middle East Tech Univ J Pure Appl Sci* 21:65–79
- Sayar M, Pamir HN (1933) Une faune de vertébrés fossiles Miocène près d'Istanbul. *C R Soc Géol Fr* 6:64–66
- Schindler C (1997) Geology of Northwestern Turkey: results of the Marmara poly-project. In: Schindler C, Pfister M (eds) *Active tectonics of Northwestern Anatolia—The Marmara Poly-Project*. ETH, Zürich, pp 329–373
- Şengör AMC (1979) The North Anatolian transform fault: its age, offset and tectonic significance. *J Geol Soc Lond* 136:269–282
- Şengör AMC, Yılmaz Y (1981) Tethyan evolution of Turkey: a plate tectonic approach. *Tectonophysics* 75:181–241
- Şengör AMC, Görür N, Şaroğlu F (1985) Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study. In: Biddle KT, Christie-Blick N (eds) *Strike-slip basin formation, and sedimentation*. *Soc Econ Paleontol Mineral Spec Publ* 37:227–264
- Seyitoğlu G, Scott BC (1991) Late Cenozoic crustal extension and basin formation in West Turkey. *Geol Mag* 128:155–166
- Shirokova EI (1967) General features in the orientation of principal stresses in earthquake foci in the Mediterranean-Asian seismic belt. *Izu Akad Nauk USSR Ser Geophys* 1:12–22
- Sichenberg O, Becker-Platen DJ, Benda L, Deitrich B, Gaziry W, Heissig K, Hinermann AK, Staesche V, Steffens P, Tobein H (1975) Die Gliederung des Höheren Jungtertiärs und Altquartärs in der Türkei nach Vertebraten und ihre Bedeutung für die Internationale Neogen-Stratigraphie. *Geol Jahrb Reihe B* 15:1–167
- Siyako M, Bürkan KA, Okay A (1989) Hydrocarbon possibility and geology of Biga and Gelibolu peninsulas (in Turkish). *Bull Turkish Assoc Petrol Geol* 1:183–199
- Smith AD, Taymaz T, Oktay F, Yüce H, Alpar B, Başaran H, Jackson AJ, Kara S, Şimşek M (1995) High-resolution seismic profiling in the Sea of Marmara: Late Quaternary sedimentation and sea-level changes. *Geol Soc Am Bull* 107:923–936
- Straub C (1996) Recent crustal deformation and strain accumulation in the Marmara Sea region, NW Anatolia referred from GPS Measurements. PhD Thesis, ETH, Zürich
- Taner G (1995) Pelecypoda and Gastropoda fauna of Quaternary sequence in the Gulf of İzmit (Hersek Burnu-Kaba Burun). In: Meriç E (ed) *Quaternary sequence of İzmit Bay*. Military College Printing House, İzmit, pp 219–239
- Tatar Y (1975) Tectonic structures along on the North Anatolian fault zone northeast of Refahiye (Erzincan). *Tectonophysics* 25:401–409
- Tatar O, Piper JDA, Park RG, Gürsoy H (1995) Paleomagnetic study of block rotations in the Niksar overlap region of the North Anatolian Fault zone, central Turkey. *Tectonophysics* 244:251–266
- Ternek Z (1949) Geology of Kesan-Korudağ region. PhD Thesis, İstanbul University
- Toker V, Şengüler I (1995) Nanoplankton fauna of Quaternary sequence in the Gulf of İzmit (Hersek burnu-Kababurun) (in Turkish). In: Meriç E (ed) *Quaternary sequence of İzmit Bay*. Military College Printing House, İzmit, pp 163–173
- Tchapalyga A (1995) Plio-Pleistocene Black Sea basins and their relationship with Mediterranean. In: Meriç E (ed) *Quaternary sequence of İzmit Bay*. Military College Printing House, İzmit, pp 303–311
- Uçan ON, Albora AM, Hisarlı ZM (2001) Comments on the gravity and magnetic anomalies of Saros Bay using wavelet approach. *Mar Geophys* 4:251–264
- Uludağ M (1993) Geomorphology of Çamdağ (in Turkish). *Bull Univ İstanbul* 4:345–352
- Ünay E, De Bruijn H (1984) On some Neogene rodent assemblages from both sides of the Dardanelles, Turkey. *Newslett Stratigr* 13:119–132
- Westaway R (1994) Present-day kinematics of the Middle East and eastern Mediterranean. *J Geophys Res* 99:12071–12090
- Yalçınlar I (1952) Les vertébrés fossiles Néogènes de la Turquie occidentale. *Bull Musée Paris Série 2* 24(4)
- Yiğitbaş E, Elmas A (1997) An approach to Late Mesozoic-Tertiary evolution of the western Pontides: generation of the Cide-Devrek virgation (in Turkish). *Geosound* 30:23–36
- Yiğitbaş E, Elmas A, Yılmaz Y (1999) Pre-Cenozoic tectono-stratigraphic components of the Western Pontides and their geological evolution. *Geol J* 34:55–74
- Yiğitbaş E, Elmas A, Sefunç A, Özer N (2003) Some major neotectonic features of western part of the North Anatolian Fault Zone; the development of the Adapazarı-Karasu Corridor and its significance. *Geol J* (in press)
- Yılmaz Y, Genç ŞC, Gürer F, Bozcu M, Yılmaz K, Karacık Z, Altunkaynak Ş, Elmas A (2000) When did the western Anatolian grabens begin to develop. In: Bozkurt E, Winchester JA, Piper JDA (eds) *Tectonics and magmatism in Turkey and the surrounding area*. *Geol Soc Lond Spec Publ* 175:353–384