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Major neotectonic features of eastern Marmara region, Turkey: development of the Adapazarı–Karasu corridor and its tectonic significance

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Eastern Marmara region consists of three different morphotectonic units: Thrace–Kocaeli Peneplain (TKP) and Çamdağ–Akçakoca Highland (ÇAH) in the north, and Armutlu–Almacık Highland in the south of the North Anatolian Fault Zone (NAFZ). The geologic-morphologic data and seismic profiles from the Sakarya River offshore indicate that the boundary between the TKP in the west and ÇAH in the east is a previously unrecognized major NNE–SSW-trending strike-slip fault zone with reverse component. The fault zone is a distinct morphotectonic corridor herein named the Adapazarı–Karasu corridor (AKC) that runs along the Sakarya River Valley and extends to its submarine canyon along the southern margin of the Black Sea in the north. It formed as a transfer fault zone between the TKP and ÇAH during the Late Miocene; the former has been experiencing extensional forces and the latter compressional forces since then. East–West-trending segments of the NAFZ cuts the NE–SW-trending AKC and their activity has resulted in the formation of a distinct fault-bounded morphology, which is characterized by alternating E–W highlands and lowlands in the AKC. Furthermore, this activity has resulted in the downward motion of an ancient delta and submarine canyon of the Sakarya River in the northern block of the NAFZ below sea level so that the waters of the Black Sea invaded them. The NE–SW-trending faults in the AKC were reactivated with the development of the NAFZ in the Late Pliocene, which then caused block motions and microseismic activities throughout the AKC.

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1. INTRODUCTION

The neotectonic history of eastern Marmara region began in post-Miocene time with the development of the North Anatolian Fault Zone (NAFZ) (Figure 1A) which is one of the most important active right-lateral strike-slip faults in the world (e.g. Ketin 1969; Ambraseys 1970; McKenzie 1972; Tatar 1978; Şengör 1979; Woodcock 1986; Şaroğlu 1988; Barka 1992; Bozkurt 2001a, b; Westaway 2003). The fault zone is about 1500 km long and extends from Karlıova in eastern Turkey in the east to the Greek mainland in the west (Figure 1A). The NAFZ is a transform fault forming part of the boundary between the Eurasian and Anatolian plates. The Anatolian Plate, situated between the converging Eurasian and Arabian plates, escapes westwards along the dextral North Anatolian and sinistral East Anatolian fault zones (e.g. McKenzie 1972; Şengör 1979; Şengör *et al.* 1985; Taymaz *et al.* 1991a, b; Bozkurt 2001a; Bozkurt and Mittwede 2001). Earlier studies argued that the NAFZ nucleated in eastern

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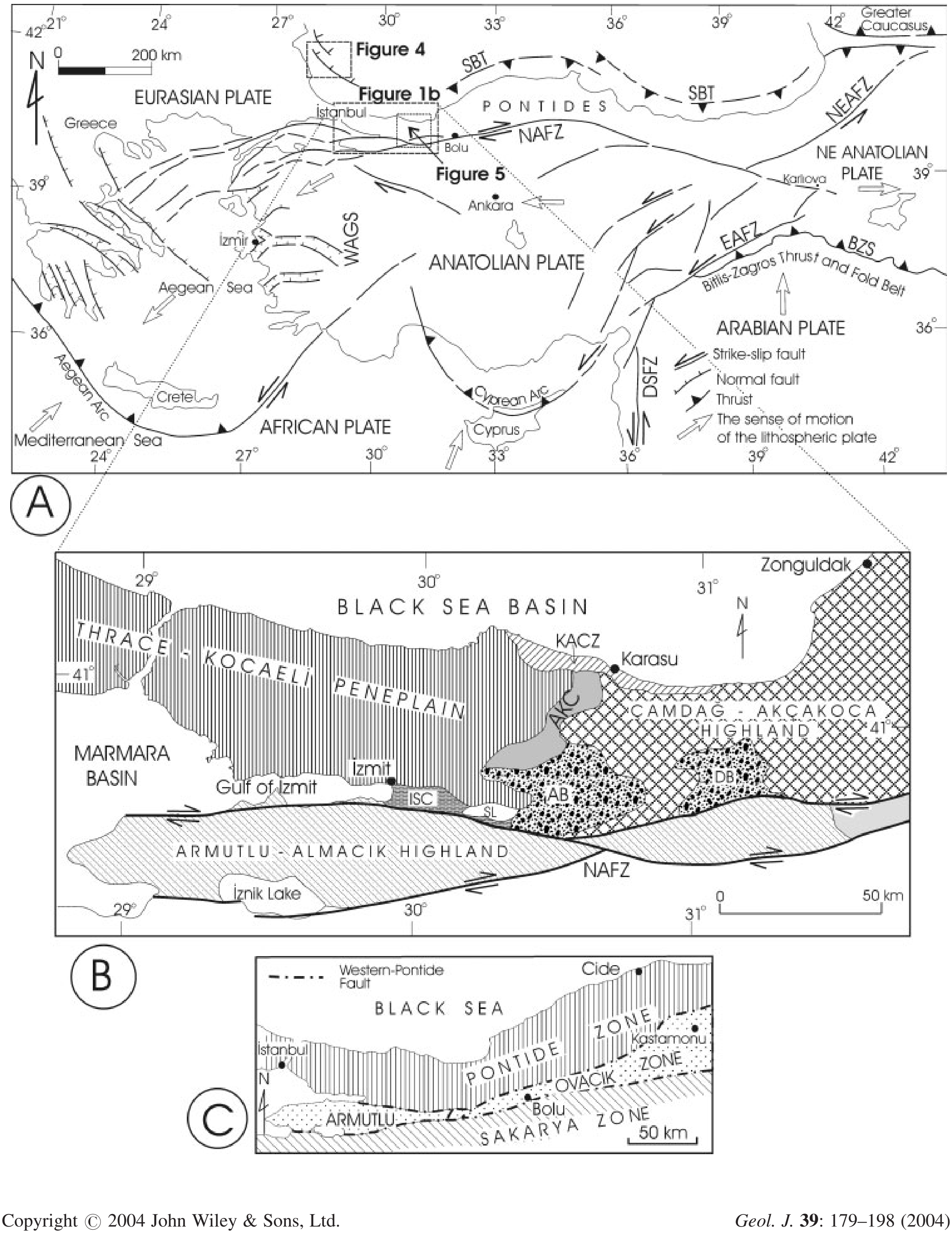
Figure 4
Figure 1b
Figure 5
EURASIAN PLATE
PONTIDES
NAFZ
SBT
NEAFZ
NE ANATOLIAN PLATE
Greater Caucasus
Greece
İstanbul
Bolu
Ankara
Karlıova
İzmir
WAGS
ANATOLIAN PLATE
EAFZ
BZS
Bitlis-Zagros Thrust and Fold Belt
Aegean Sea
ARABIAN PLATE
DSFZ
Crete
Aegean Arc
Cyprean Arc
Cyprus
AFRICAN PLATE
Mediterranean Sea
Strike-slip fault
Normal fault
Thrust
The sense of motion of the lithospheric plate
0 200 km
A
BLACK SEA BASIN
Zonguldak
THRACE - KOCAELI PENEPLAIN
KACZ
Karasu
AKC
ÇAMDAĞ - AKÇAKOCA HIGHLAND
MARMARA BASIN
Gulf of Izmit
Izmit
ISC
SL
AB
DB
ARMUTLU - ALMACIK HIGHLAND
NAFZ
İznik Lake
0 50 km
B
Western-Pontide Fault
Cide
BLACK SEA
İstanbul
PONTIDE ZONE
Kastamonu
OVACIK ZONE
ARMUTLU
Bolu
SAKARYA ZONE
50 km
C

Anatolia after the Late Miocene and propagated westwards reaching northwestern Anatolia during the Pliocene–Pleistocene (e.g. Şengör 1979; Şengör *et al.* 1985; Dewey *et al.* 1986). However, although some details of timing and interpretation differ, it is now agreed that the throughgoing right-lateral faulting along the NAFZ did not begin until the Early Pliocene (5 Ma (Barka and Kadinsky-Cade 1988; Westaway 1994; Tüysüz *et al.* 1998; Armijo *et al.* 1999, 2002; Yaltırak *et al.* 2000; Bozkurt 2001a; Koçyiğit *et al*. 2001) or *c.* 7 Ma (Westaway 2003)). It is known that beginning from 31°E longitude, around Bolu, the NAFZ splays off westward into a number of subfault zones (Ketin 1969; Şengör 1979; Barka and Kadinsky-Cade 1988; Koçyiğit 1988; Okay *et al.* 1999, 2000). Therefore the width of the NAFZ ranges from 10 km to 110 km, in northwestern Turkey (e.g. Koçyiğit 1988; Bozkurt 2001a). According to Şaroğlu (1988), during the period between Late Miocene and Early Pliocene, most probably, the NAFZ did not exist as it does today; instead there were fault segments with no interrelations. Different ages, offsets and strike amounts must be the result of their independent character. Bozkurt (2001b, and references therein) gives a more detailed account of the history of the NAFZ.

The region south of Marmara, experiencing a N–S continental extensional tectonic regime, is known as the Western Anatolian Graben System (WAGS, Figure 1A). The Marmara Basin is located along the branches of the NAFZ and is interpreted as a pull-apart basin (Barka and Kadinsky-Cade 1988; Smith *et al.* 1995; Okay *et al.* 1999, 2000). The northern block of the NAFZ is considered as a single morphotectonic entity that is bounded by a north-vergent thrust in the southern shelf of the Black Sea (Letouzey *et al.* 1977). The area in the western part of this entity is known as the Thrace–Kocaeli Peneplain (TKP) (Pamir 1938) (Figure 1B). The Sakarya River flows at the eastern edge of the TKP along an asymmetric inconsequent valley between Adapazarı plain in the south and the Black Sea in the north. In this region the Sakarya Valley develops as a morphologically distinct NNE–SSW-trending corridor (Figure 2) that was formed by both fluviatile erosion and tectonic processes. The Adapazarı-Karasu corridor (AKC), as a NNE–SSW-trending morphotectonic element, also shows a contrast to the E–W-trending NAFZ (Figure 1B).

The area between longitudes 30°E and 31°E is critical because it is located on a region where the major morphotectonic elements of the region meet (Figure 1B). The western part of the NAFZ cuts across the different major morphotectonic units of the eastern Marmara region. The understanding of the geology, relations and evolution of these units has a critical importance in addressing the neotectonic problems of the region. The main aims of this paper are to introduce the major and subordinate neotectonic features of the area between the Adapazarı Basin in the south and the Black Sea in the north and to discuss their tectonic significance. First, we present field observations from the different major units. Then, we combine new evidence with existing geological-geophysical data (seismic reflection profiles and seismicity) in order to shed light on the neotectonic evolution of this region.

2. REGIONAL FRAMEWORK

The geological evolution of eastern Marmara region is divided into two major tectonic periods: palaeotectonic and neotectonic. During the palaeotectonic period, three major tectonostratigraphic units developed. These are from north to the south: the Pontide Zone, the Armutlu–Ovacık Zone, and the Sakarya Zone (Figure 1C) (Elmas *et al.* 1997; Yiğitbaş *et al.* 1999).

In the western part of the Pontide zone, pre-Neogene units are represented by a thick Palaeozoic sedimentary succession and its Mesozoic–Tertiary sedimentary cover (Figure 3). The lower parts of the Palaeozoic

Figure 1. (**A**) Tectonic map of the eastern Mediterranean region showing structures developed during the Miocene to Holocene time (compiled from Jackson and McKenzie 1984; Şengör *et al.* 1985; Barka and Kadinsky-Cade 1988; Barka 1992; Elmas and Meriç 1998). The regions marked with rectangles show the locations of the maps displayed in Figures 1B, 4, and 5. Abbreviations: SBT, Southern Black Sea Thrust; NAFZ, North Anatolian Fault Zone; NEAFZ, Northeast Anatolian Fault Zone; EAFZ, Eastern Anatolian Fault Zone; WAGS, Western Anatolian Graben System; DSF, Dead Sea Fault Zone; BZS, Bitlis-Zagros Suture. (**B**) Major morphotectonic elements of the eastern Marmara region. Abbreviations: KACZ, Kefken–Akçakoca Coastal Zone; AKC, Adapazarı–Karasu Corridor; ISC, İzmit–Sapanca corridor; AB, Adapazarı Basin; DB, Düzce Basin; SL, Sapanca Lake. (**C**) Major palaeotectonic zones in the eastern Marmara region (from Yiğitbaş *et al.* 1999).

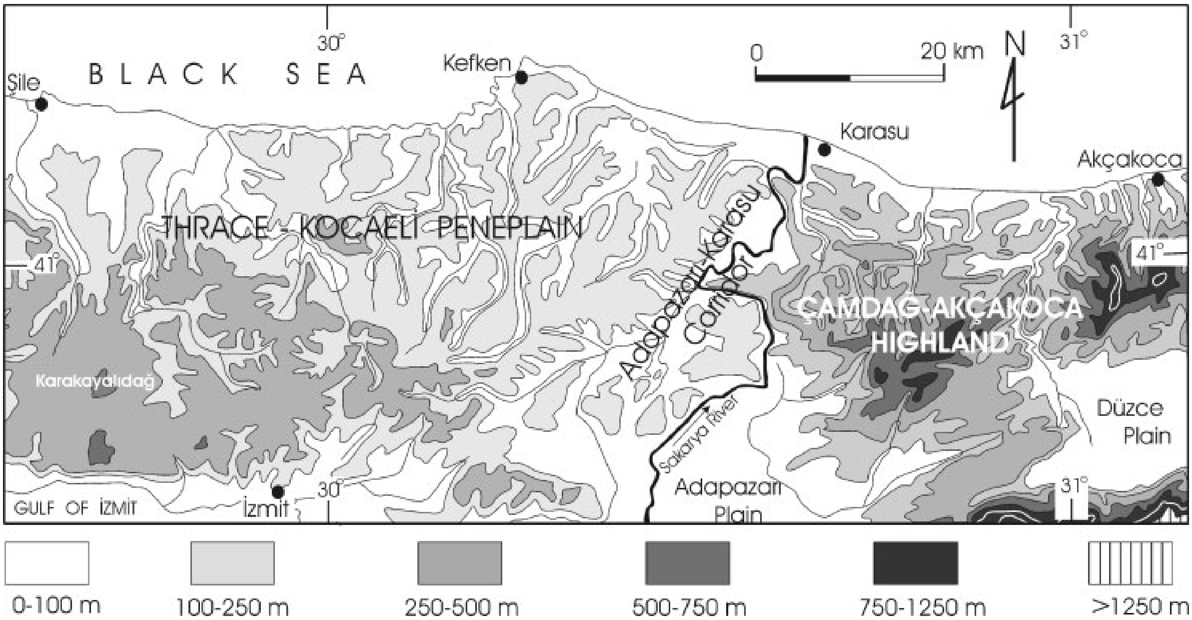

Figure 2. Drainage and topographic map of the Çamdağ–Akçakoca Highland and the eastern part of the Thrace–Kocaeli Peneplain.

succession to the east of the Sakarya River consist of a high-grade metamorphic assemblage of pre-Ordovician age (Figure 3).

The basement of the Sakarya Zone is markedly different from the western Pontide Zone (Yılmaz *et al.* 1981, 1997). This zone contains no *in situ* Palaeozoic sedimentary rocks and underwent strong deformation and metamorphism in the Late Triassic (Yılmaz 1977; Şengör and Yılmaz 1981; Okay 1989). The basement units are overlain by a transgressive sequence of Liassic to Eocene age.

The Armutlu–Ovacık Zone, which is bounded tectonically by the Pontide and the Sakarya zones (Figure 1C), appears to represent a tectonic mixture of both zones. Each tectonic compartment includes the basement units and the metamorphic equivalents of the Jurassic–Upper Cretaceous rocks in the other two neighbouring zones (Yiğitbaş *et al.* 1999; Elmas and Yiğitbaş 2001).

Although both branches of the NAFZ presently bound the three major palaeotectonic units, they were amalgamated by the western Pontide Fault during the Late Cretaceous to Early Eocene period; this structure is interpreted as an ancestral NAFZ (Yiğitbaş *et al.* 1999; Elmas and Yiğitbaş 2001).

Although there are different ideas on the age and total displacement, it is broadly accepted that the development of the NAFZ, as a result of continental collision along the Bitlis–Zagros suture, initiates the neotectonic period in the region (e.g. Şengör and Yılmaz 1981; Şengör *et al.* 1985; Bozkurt and Koçyiğit 1995, 1996; Koçyiğit 1988; Bozkurt 2001a; Koçyiğit *et al.* 2001). To study the structural features of the neotectonic period in the eastern Marmara region, some major morphotectonic units bounded by active fault segments are distinguished (Figure 1B). Of these, the Black Sea Basin, the Thrace–Kocaeli Peneplain (TKP) and the Çamdağ–Akçakoca Highland (ÇAH) are located at the northern block of the NAFZ. The Armutlu–Almacık Highland is placed within the NAFZ. The Marmara Basin further west is on the western prolongation of the NAFZ. There are also secondary morphotectonic units that represent a transition between these major morphotectonic entities: the Kefken–Akçakoca Coastal Zone (KACZ), Adapazarı–Karasu corridor (AKC), Adapazarı Basin (AB), and İzmit–Sapanca corridor (ISC) (Figure 1B). The İzmit–Sapanca corridor is situated between the Armutlu–Almacık Highland in the south and the TKP in the north, and it forms a passage between the Marmara Sea and Adapazarı plain. The Adapazarı–Karasu corridor — 250 m to 5 km wide and a 35 km long NE–SW-trending trough — separates the TKP in the west

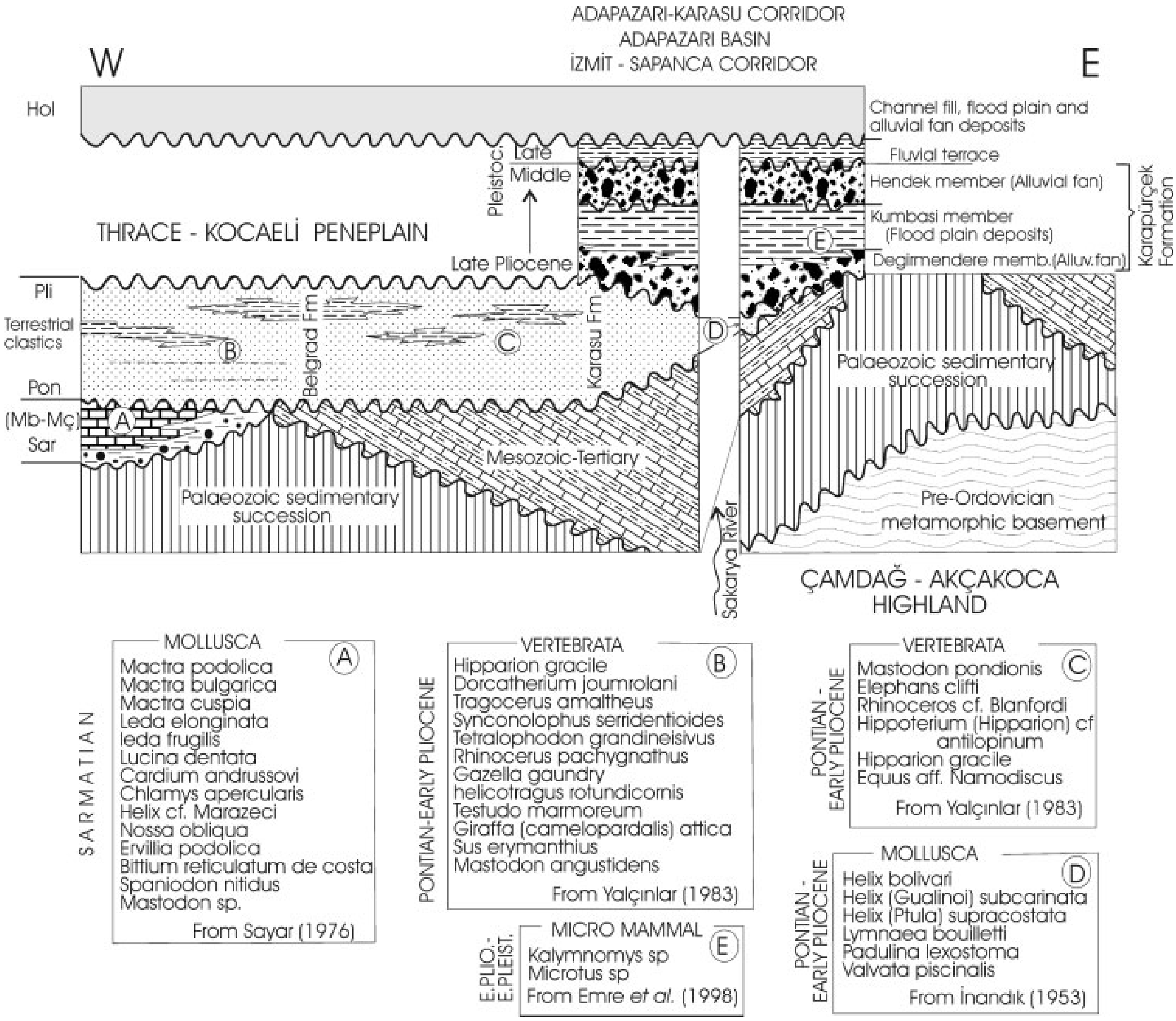

Figure 3. Generalized stratigraphic sections in different morphotectonic zones of the eastern Marmara region (see text for explanation of Neogene to Quaternary units).

from ÇAH in the east. This corridor is a link between the KACZ in the north, and the Adapazarı Basin in the south. The ages of sediments that formed during the neotectonic period within the morphotectonic units vary from Sarmatian to present (Figure 3).

The Marmara Basin—a complex pull-apart or a strike-slip related extensional basin (e.g. Barka and Cadinsky-Cade 1988; Smith *et al.* 1995; Okay *et al.* 1999, 2000)—is a primary morphotectonic unit in the region. Its eastern part, the Gulf of İzmit, is a tectonic corridor that was formed and structurally controlled by the branches of NAFZ (Barka 1992; Emre *et al.* 1998; Koçyiğit *et al.* 1999; Okay *et al.* 1999; Ünay *et al.* 2001). The Late Pliocene–Pleistocene sediments deposited in the Gulf of İzmit are marine equivalents of the continental sediments deposited within the NAFZ along the İzmit–Sapanca corridor (Emre *et al.* 1998; Ünay *et al.* 2001). Following the 17 August 1999 İzmit and 12 November 1999 Düzce earthquakes, the Sea of Marmara and the ruptured segments of the NAFZ formed the subject of intense research (e.g. Hubert-Ferrari *et al.* 2000; King *et al.* 2001; Le Pichon *et al.* 2001; Akyüz *et al.* 2002; Ambraseys 2001; Armijo *et al.* 2002; Ergintav *et al.* 2002; Hartleb *et al.* 2002;

Hearn *et al.* 2002; Özalaybey *et al.* 2002; Çakir *et al.* 2003a, b; England 2003; Hitchcock *et al.* 2003; Lenk *et al.* 2003); detailed information can be found in these papers.

The Armutlu–Almacık High, as a primary morphotectonic unit, forms a complex positive flower structure between the branches of the NAFZ (Figure 1B). In the north, it is bordered by the Marmara Basin, the İzmit–Sapanca corridor and the Adapazarı Basin (Figure 1B). The Neogene sedimentary cover of the Armutlu–Almacık High is Late Miocene (Pontian) to Pliocene in age (Akartuna 1968).

Results of previous studies (Letouzey *et al.* 1977; Finetti *et al.* 1988; Robinson *et al.* 1996) show that the Pontide mountain chain actually thrusts over the oceanic crust of the Black Sea (Figure 1A). The steady rising slopes along the northern part of the Black Sea mountain range, including the ÇAH which is notched with superimposed deep valleys, reflect the thrust-bound uplifting of the onshore area. The young highland morphology in the east of the AKC changed into a wide lowland area, the TKP, in the west. Offshore of the peneplain (TKP) the southern continental margin of the Black Sea Basin has normal faulting, which cuts both older thrust faults and submarine topography (Figure 4), indicating an active extensional tectonic regime (Can 1996). These different morphotectonic elements meet each other in the area between Adapazarı–İzmit–Kefken–Akçakoca, in the eastern Marmara region.

The AKC, the KACZ and the Adapazarı Basin in the east of the northern block of the western part of the NAFZ have critical importance because they border major morphotectonic units of the region. Therefore, in the following sections, morphological, geological and geophysical features of the morphotectonic elements will be described under separate headings.

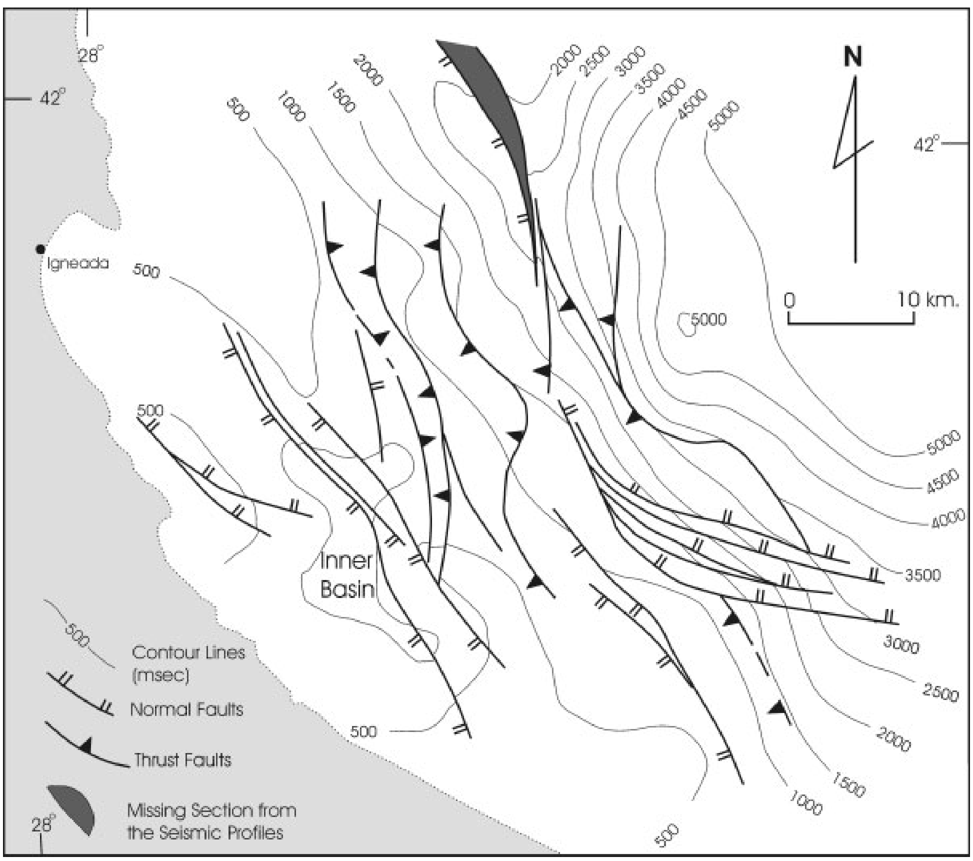

Figure 4. The structural map for the southwestern margin of the Black Sea (from Can 1996). See Figure 1A for location.

3. THRACE–KOCAELI PENEPLAIN (TKP)

The flatland bordered by ÇAH, the Armutlu–Almacık High and the Marmara Basin (Figure 1B) is known as Thrace–Kocaeli Peneplain (TKP; Pamir 1938). The mature erosional surface is at about 120–130 m on the Thrace and the Kocaeli Peninsula where the peneplain rises gradually from the coast of the Sea of Marmara to the north and reaches about 250 m around the east–west-trending water-divide. Except for the Kefken Akçakoca coastal zone, the E–W scarp marks the northern margin of the TKP; the scarp corresponds to post-peneplain morphologic discordance developed due to reactivated faults.

Before the development of the peneplain, the area was under the influence of the Sarmatian Sea (Paratethys) that extended from Vienna in the west to the Caspian Sea in the east (Pamir 1938; Muratov *et al.* 1978). By the beginning of the Pliocene, the Sarmatian Sea retreated, and rivers became active and only some monadnocks (such as Karakayalidağ) remained after the erosion. In the Middle Pliocene, the area was tectonically uplifted and rivers, in many parts of TKP, started to erode their beds and then developed superimposed drainage (Pamir 1938; Ertek 1995).

To the east, the TKP is composed of plateaus 100–250 m high. Some rough areas were developed due to lithologic and structural differences (e.g. the Upper Cretaceous volcanic rocks in the northern part of the Kocaeli Peninsula, the Mesozoic karstic carbonate rocks and the Palaeozoic quartzites in the south). With the exception of small areas that were composed of resistant rocks, the Kocaeli Peninsula is a rather flat plateau (İnandık 1953), where the drainage network is generally dendritic. However, rivers comply with structural trends and towards the Sakarya Valley lithologic boundaries form a rectangular drainage pattern. Some rivers developing on the cover units of the peneplain surface downcut to the basement due to deep erosion, and formed superimposed valleys (Ertek 1995). The vertical movements accelerated the erosional effects of the rivers in the northern parts of the Kocaeli Peninsula. The periods of rapid erosion caused deep incision of riverbeds. Presently, depositional processes are dominating in riverbeds while erosional processes take place in headwater parts of rivers. The information given above thus suggests that, with the commencement of the dextral motion along the NAFZ, morphologic discordance(s) was developed in the region through the development of young morphology subsequent to a regional morphological maturity attained during the so-called palaeotectonic period.

3.1. Neogene–Quaternary sequence in the TKP

The Pre-Neogene stratigraphy in the TKP is given in Figure 3. The Neogene sequence above the Ordovician–Eocene basement rocks of the TKP is represented by the terrestrial–lacustrine deposits (Çukurçeşme Formation: Mç in Figure 3) and *Mactra*-bearing limestones (Bakırköy Limestone; Mb in Figure 3) of Paratethys. The fossil assemblage (Figure 3) of the unit indicates a Sarmatian age (Sayar 1976; Rögl and Steininger 1984).

In the İstanbul region, the Neogene is represented by a horizontal, poorly cemented pebble–sand–clay sequence (Belgrad Formation; Figure 3). The unit has a characteristic red-yellow colour. The lower part of the sequence is composed of clay–silt alternation while the upper part contains conglomerate and sandstone with silt and clay lenses. Cross-bedding is the only synsedimentary structure and occurs only in the middle and upper parts of the unit. The unit is 10–20 m thick but it attains a thickness of 40 m to the north of the region. The pebbly and sandy sediments exposed around Gebze in the Kocaeli Peninsula are regarded as equivalent to the Belgrad Formation. The age of the unit, based on the fossil content, is Pontian–Early Pliocene (Figure 3; Yalçınlar 1983).

The Pontian–Lower Pliocene rocks are not restricted to the TKP, but form widespread exposures (known as the Karasu Formation) in the AKC and in the Adapazarı Basin to the east (Figure 3). The Holocene sediments of the TKP are composed of alluvium and alluvial terrace deposits. Also, old and recent dunes are observed in the northeastern parts of the peneplain.

4. ÇAMDAĞ–AKÇAKOCA HIGHLAND (ÇAH)

The mountainous area to the east of the Sakarya River is named the Çamdağ–Akcakoca Highland (ÇAH; Figure 1B) and has distinct geologic and morphotectonic features with elevations up to 1000 m in places (Figure 2).

Tectonic and eustatic changes have been influential in the area since at least the Late Miocene. The drainage pattern displays no significant orientation (İnandik 1953) and developed as a result of eustatic changes during the Quaternary. In response to eustatic changes, the river terraces that were controlled by Miocene–Pliocene faults are eroded away (Uludağ 1993). As a result, the headward erosion of rivers attained up to 800–850 m high.

Due to eustatic changes, the rivers following the Pliocene units in the northern parts of the region deeply incised their beds and formed buried meandering and hanging valleys. Uludağ (1993) reported the presence of three different erosional surfaces that developed during Early–Middle Miocene, Late Miocene and younger periods.

4.1. Neogene–Quaternary sequence in the ÇAH

The Pre-Neogene basement stratigraphy of the ÇAH is given in Figure 3. The basement is overlain unconformably by the Pontian–Pliocene Karasu Formation in the northwestern part of ÇAH and by the Upper Pliocene–Pleistocene sedimentary sequence of the Adapazarı Basin in the southwestern edge (Figures 3, 5). The documentation of Pontian age from the clastic sediments of the Adapazarı Basin to the east of Sakarya River (Figure 3; İnandık 1953) suggests that the Pontian deposits partially overlapped the ÇAH foothills.

5. ADAPAZARI BASIN

The Adapazarı Basin is a fault-bounded plain that covers more than 650 km^2 (Figures 1B, 5). It has a topographic gradient of about 0.6–0.8% to the north and is characterized by a homogeneous plain surface. The Sakarya River flows in the centre with a gradient of 0.5%; abandoned meanders are found in some parts (İnandık 1953; Bilgin 1984).

The Adapazarı Basin is bounded by the east–west-trending, 1500 m high Armutlu–Almacık Highland in the south (Figures 1B, 5); the boundary is marked by different segments of the NAFZ. The antecedent Geyve strait of the Sakarya River, flowing from south to north, dissects the Armutlu–Almacık Highland (Figure 5). Bilgin (1984) determined the presence of four different terraces at the northern part of Geyve gorge. The northern boundary of the Adapazarı depression is not orderly in comparison to the linear southern boundary. The northern margin is rather irregular and controlled by NE–SW-trending faults that resulted in the formation of sub-plains (or sub-basins), namely the Gökçeeren (Gp) and Söğütlü (Sp), in the northwest of the Adapazarı plain (Figure 5). Bilgin (1984) argued that the Sakarya River flowed firstly throughout these flats.

The Adapazarı Basin is separated from the Düzce Basin in the east (Figures 1B, 2) by a morphologic barrier 250–300 m high, where Eocene aeolian deposits and fluvial pebbles (İnandık 1953) of an old riverbed (Tchihatcheff 1867–1869) are exposed.

The geometry of the Adapazarı plain suggests that it is a basin reworked by intense river erosion (İnandık 1953) and accompanied active tectonism.

5.1. Adapazarı Basin fill

The Adapazarı Basin comprises two contrasting infills separated by an angular unconformity. The lower sequence consists of alluvial fan deposits (Figures 3, 5). The age of these sediments, based on the fossil assemblage (‘D’ in Figure 3), is Pontian–Early Pliocene (İnandik 1953). They are correlated with the terrestrial sediments of the TKP deposited during the same period (Yalçınlar 1983; Emre *et al.* 1998; Ünay *et al.* 2001). The upper sequence is made up of fine- and coarse-grained clastic rocks, namely the Karapürçek Formation (Emre *et al.* 1998; Ünay *et al.* 2001) (Figure 3). The younger sequence (Karapürçek Formation) overlaps the Lower Palaeozoic basement units of the ÇAH along the southern foothills of the highland (Figure 5) and is divided into three members: Değirmendere, Kumbaşı and Hendek members. The first is represented by alluvial fan sediments deposited along different segments of the NAFZ in the south. On the basis of mammals (‘E’ in Figure 3), the age of the unit is Villarian–lower Biharian (latest Pliocene–Early Pleistocene) (Emre *et al.* 1998; Ünay *et al.* 2001). They are interpreted as the

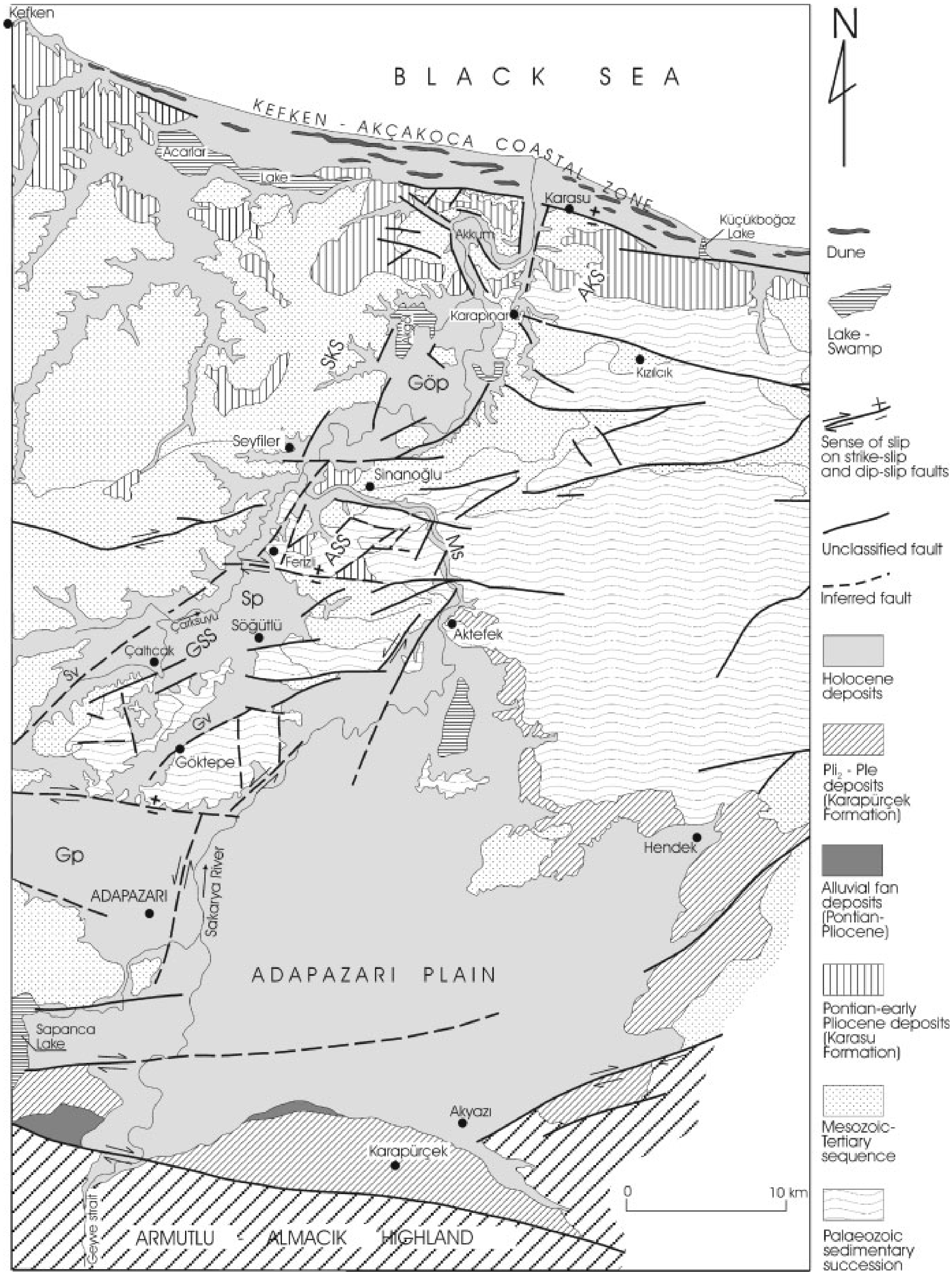

Figure 5. Geological map of the surrounding area of the Sakarya River between Adapazarı and Karasu (see Figure 1A for location). Abbreviations: GSS, Göktepe–Söğütlü Sector; ASS, Aktefek–Sinanoğlu Sector; SKS, Seyfiler–Karapınar Sector; AKS, Akkum–Karasu Sector; Gp, Gökçeeren Plain; Sv, Sarıboğaz Valley; Gv, Göktepe Valley; Sp, Söğütlü Plain; Ms, Mağara Strait; Göp, Gölkent Plain.

terrestrial equivalents to lower lithologies of the Upper Pliocene–Lower Pleistocene sequence (Toker and Şengüler 1995; Çetin *et al.* 1995) on the sea floor in the Gulf of İzmit (Emre *et al.* 1998) to the east of the Marmara Basin. The alluvial fan deposits pass laterally into a sequence of flood plain sediments made up of grey conglomerate, grey-yellow-brown sandstone–siltstone and dark grey-black-green claystone (Kumbaşı Member). The age of this sequence is Early Pleistocene (Emre *et al.* 1998; Ünay *et al.* 2001). The upper part of the Karapürçek Formation comprises alluvial fan deposits (Hendek Member; Emre *et al.* 1998) of red-yellow-brown, poorly compacted, poorly sorted conglomerate–sandstone–mudstone–siltstone. They crop out in the southern and eastern parts of the Adapazarı Basin and also in the western edge of the ÇAH. As they conformably overlie the Villarian–lower Biharian (latest Pliocene–Early Pleistocene) Değirmendere Member and are overlain by the Upper Pleistocene fluvial benches and Holocene sediments of the Sakarya River, the age of the Hendek Member is Middle Pleistocene (Emre *et al.* 1998).

6. ADAPAZARI–KARASU CORRIDOR (AKC)

The area between the Adapazarı Basin in the south and the Black Sea in the north—the Sakarya River Valley and related morphotectonic structures—is named the Adapazarı–Karasu corridor (AKC) (Figure 1B). The Sakarya River flows through the corridor between the ÇAH (up to 1000 m height) in the east and the TKP (about 200 m height) in the west (Figure 2) and forms asymmetric V and/or U-type valleys. The AKC is a relatively low (40 m average), narrow (250 m to 5 km wide), and long (35–40 km) depression trending NNE–SSW between the TKP in the west and the ÇAH in the east; thus, the AKC constitutes a boundary between the two major morphotectonic entities. The corridor connects the Adapazarı Basin in the south to the Black Sea in the north. The Sakarya River drains the Adapazarı Plain to the Black Sea, via the morphologically low corridor. The river has different stream channels through the AKC depending on local structural varieties and morphological contrast. On this basis, the corridor may be divided into four morphotectonic sectors. These are, from south to north, Göktepe–Söğütlü, Aktefek–Sinanoğlu, Seyfiler–Karapinar and Akkum–Karasu sectors (Figure 6).

The Göktepe–Söğütlü sector forms a transition zone between the Adapazarı Basin and the AKC. The northern part of the area is a typical flood plain (Söğütlü Plain; Figures 5, 6) drained by Çarksuyu—a wide meandering branch of the Sakarya River. The southern part of the area is dissected by NE–SW-trending fault-controlled valleys (Sariboğaz and Göktepe valleys; Figures 5, 6). The Göktepe–Söğütlü sector is bordered by E–W-trending strike-slip faults both in the north and south.

The Aktefek–Sinanoğlu sector is an area uplifted along the E–W-trending right-lateral segments of the NAFZ. The Sakarya River flows, from south to north, through a deep narrow valley (Mağara Strait: MS; Figures 5, 6) on the oldest basement units in the region. The valley has a deep asymmetric V-shaped profile and maximum elevation of 250–300 m in the western slope, and 800 m in the eastern slope. Likewise, E–W-trending hanging valleys are developed in this sector (Bilgin 1984).

The Seyfiler–Karapınar sector is a typical flood plain (Gölkent Plain) in which the Sakarya River flows with a wide meandering form (Figures 5, 6). In this area, the changing and widening of the Sakarya River channel caused the development of the abandoned meanders in the form of oxbow lakes—the flat semi-linear valley slopes with steep profiles and a wide flood plain.

The Akkum–Karasu sector is a highland uplifted by E–W-trending northern and southern boundary faults. In the area, the Sakarya River flowing on the basement units is controlled by N–S-trending faults (Figures 5, 6). Based on these characteristics, the area is similar to the Aktefek–Sinanoğlu sector.

The faults in the AKC control the morphology and deposition in front of the fault scarps. According to their strike and relations to each other, these faults can be divided into two groups: (a) NNE–SSW-trending left-lateral strike-slip faults with reverse component and (b) E–W-trending right-lateral strike-slip faults with normal component (Figures 5, 6).

The different sectors represented by plains and uplifted blocks within the AKC are bounded by NNE–SSW-trending faults. Some of the faults are not easily recognized in the field because of dense forest and thick alluvium

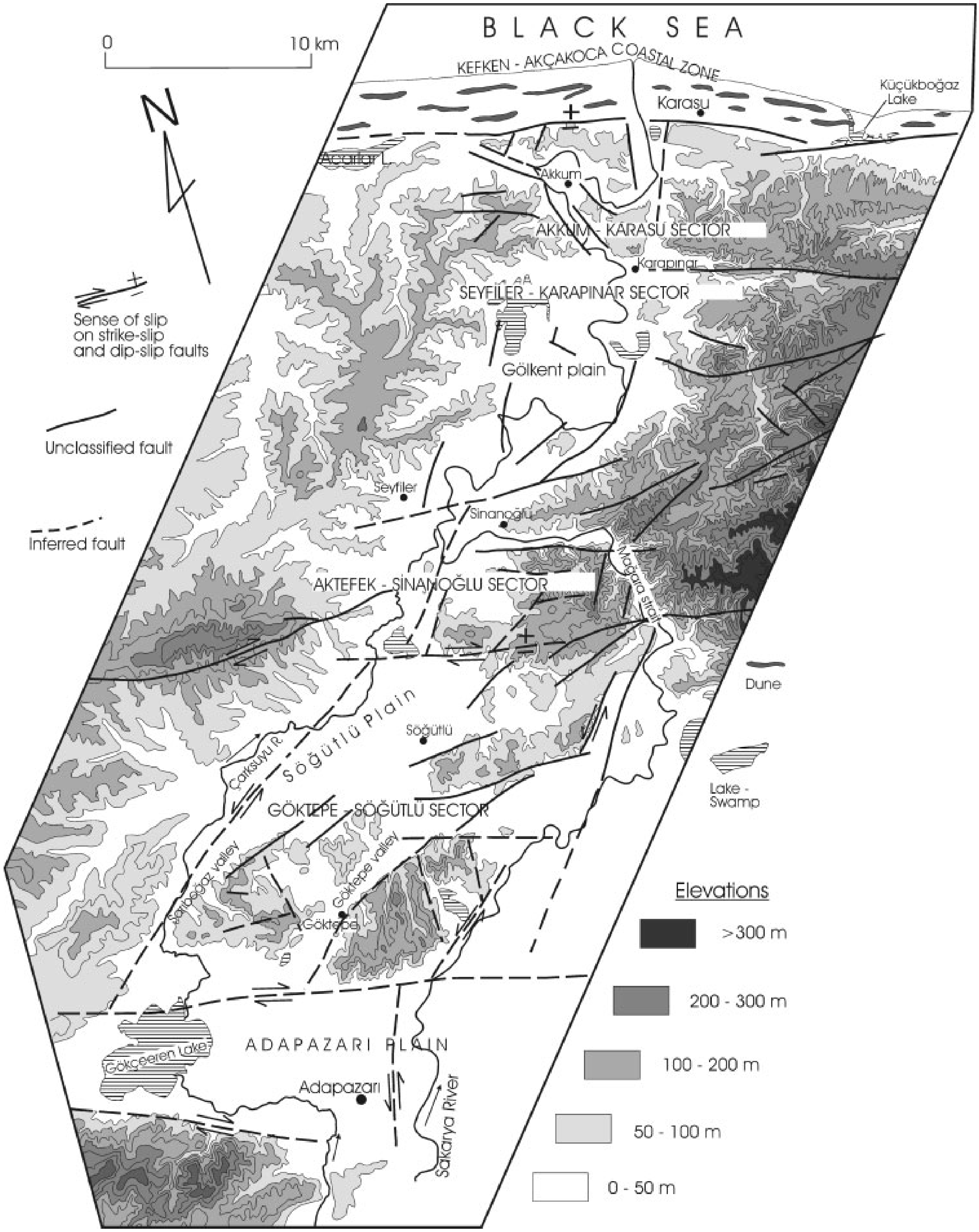

Figure 6. Simplified morphotectonic map of Adapazarı–Karasu corridor.

of the Sakarya River, but they are readily distinguished on aerial photographs with the aid of deflected and offset streams, sag ponds, linear benches in the alluvium and fault slopes along the edges of the valleys. This suggests that the faults may be continuous under the thick alluvium cover. The NNE–SSW-trending faults, reactivated in the later period, affected alluvial sediments of the Sakarya River, as is the case in the Seyfiler–Karapınar sector. They generally have high-angle dips and are typical oblique-slip faults with left-lateral and reverse components. The left-lateral component is more prominent in the northwestern edge of the Adapazarı Basin.

The NNE–SSW-trending faults are cut by E–W-trending faults parallel to the NAFZ. In addition to the right-lateral component, the E–W faults are also characterized by dip-slip component, particularly in the area between Adapazarı and Sinanoğlu (Figures 5, 6). As a result of significant vertical slip components along the E–W faults, while the Aktefek–Sinanoğlu sector is uplifted, the Mağara Strait is developed by the Sakarya River as an antecedent valley.

The E–W-trending morphologic steep slope, which borders the AKC in the north, is a young fault slope developed by oblique faults owing to right-lateral strike-slip faults paralleling the Black Sea coast (Figures 5, 6). In the southern uplifted blocks of the faults, Quaternary marine sands crop out, indicating that the E–W-trending faults are young structures.

6.1. Neogene–Quaternary sequence in the AKC

The Neogene sequence in the northern part of the AKC crops out along the east and west of Sakarya valley and on the ridges extending along the Black Sea coast (Figure 5). The conglomerate–sandstone sequence of the Karasu Formation starts with palaeosoil horizons above the basement rocks. The cross-bedding, imbricated pebbles and red mudstone–grey marl levels are indicative of deposition in coastal, fluvial and flood plain environments. In comparison to the Black Sea coastal area, the Neogene units form small and isolated exposures in the southern part of the AKC; they are composed of red terrestrial clastic rocks above the basement.

The stratigraphic position, facies properties and lithologic features of the Karasu Formation in the AKC indicate that the unit is equivalent to the Pontian–Lower Pliocene sediments of the Adapazarı Basin (İnandik 1953) and around Gebze (Yalçınlar 1983) in the TKP (Figure 3).

Old beach sands in the north and alluvium terrace deposits in the south form the Holocene sediments in the AKC. They crop out along east–west-trending ridges in the west of Karasu town where they consist of red-grey-beige beach sand and weakly compacted sandstone with crude cross-bedding, laminations, plant and quartz fragments. The area in the north of the fault scarp paralleling the Black Sea coast and bordering the AKC from the north, has different geologic and morphologic features; it is named the Kefken–Akçakoca Coastal Zone.

7. KEFKEN–AKÇAKOCA COASTAL ZONE (KACZ)

The Kefken–Akçakoca Coastal Zone (Figures 1B, 5, 6) is separated from the TKP and ÇAH in the south by a fault scarp 75–80 m high, and extends parallel to the Black sea coast. It contains old and recent sand dunes and lake swamps. This zone is one of the largest coastal plains of southwestern Black Sea, and is divided, by the Sakarya River, into two parts. The coastal zone extends in an east–west direction with a length of 50 km along both sides of the Sakarya River (Figure 5). It is about 4 km wide around the Acarlar Lake in the west and 2.5 km wide in the east of the Sakarya River.

Beach-dune bands up to 50 km long constitute the most important morphologic elements of the KACZ. There is a beach with a width of 100 m in the east and 0–40 m in the west in the coastal part of the zone. Beach deposits are composed generally of well-sorted sand and fine sand. There are coastal dunes extending along the coast behind the beach. They form E–W-trending dune series with heights exceeding 10 m in the western side of the Sakarya River. Dune series can be recognized continuously in front of the slope, which forms the southern boundary of the KACZ. The dunes form morphologic barriers in front of some small creeks, which flow via the plateau in the south. The creeks therefore do not reach the sea and changed their flow directions to E–W. Thus, a lot of barrier lakes and swamps (Acarlar, Kanlıgöl and Küçükboğaz lakes) were developed in the KACZ (Figure 5).

The general trend of old and recent sand dunes, and offset creeks on the slope bordering the KACZ in the south suggest that this E–W-trending border may represent a fault scarp. The areas to the south of the scarp appear as a flat plateau and constitute the northern parts of the AKC.

The Kefken–Akçakoca Coastal Zone may be evaluated as a flooded delta plain of the Sakarya River that was invaded by the Black Sea. There is a submarine canyon that extends to 1500–2000 m depth in the Black Sea in front of the Sakarya River. This canyon cuts the shelf deeply and has steep walls (Erinç 1958; Algan *et al.* 2002). Multichannel seismic reflection data are utilized to see if the faults extend under the water of the Black Sea in the Sakarya River offshore. The seismic lines are 250 km long and trend SW to NE (line A and line B, Figure 7) and NW to SE (line C and line D, Figure 7).

The seismic profiles all indicate that the seafloor is affected by the young faults (Figure 8). A fault map prepared from the seismic profiles (Figure 7) shows the NNE–SSW-trending faults in the AKC extend to the Sakarya River offshore area. Similarly, Avcı (1988) suggested, based on an E–W-trending seismic profile, that the submarine canyon under the Black Sea is controlled by active faults. More recently, Algan *et al.* (2002) argued that the canyon developed by both tectonic and submarine processes is cut by recently active faults. In Figure 7, the faults have variable dip directions and both normal and reverse components in different profiles (e.g. faults 2 and 13; 6 and 14). The variation in dip directions and the tilting of strata across the faults represent the strike-slip nature of these faults. In addition, the faults 5, 12 and 15 might have been E–W-trending oblique-slip dextral faults with normal

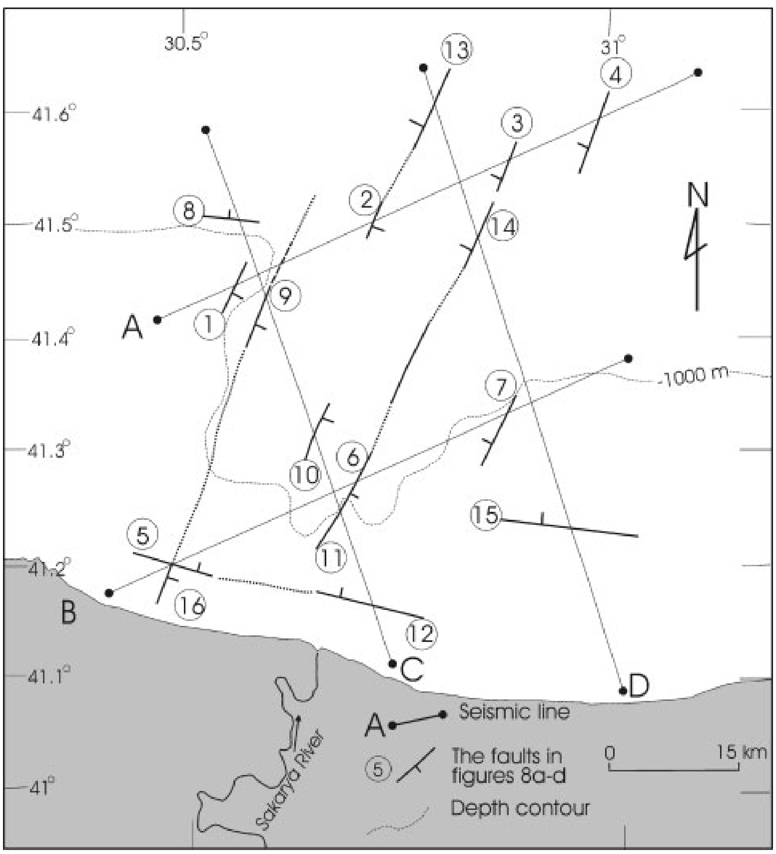

Figure 7. The fault map for Karasu and Sakarya River offshore. It was produced on the basis of the seismic profiles in Figure 8. The faults marked with numbers are seen in seismic profiles. Ticks on the fault show the dip sense of the fault plane. The lines marked with capital letters A to D show the location of the Turkish Petroleum Company (TPAO) multichannel seismic reflection profiles included as Figure 8.

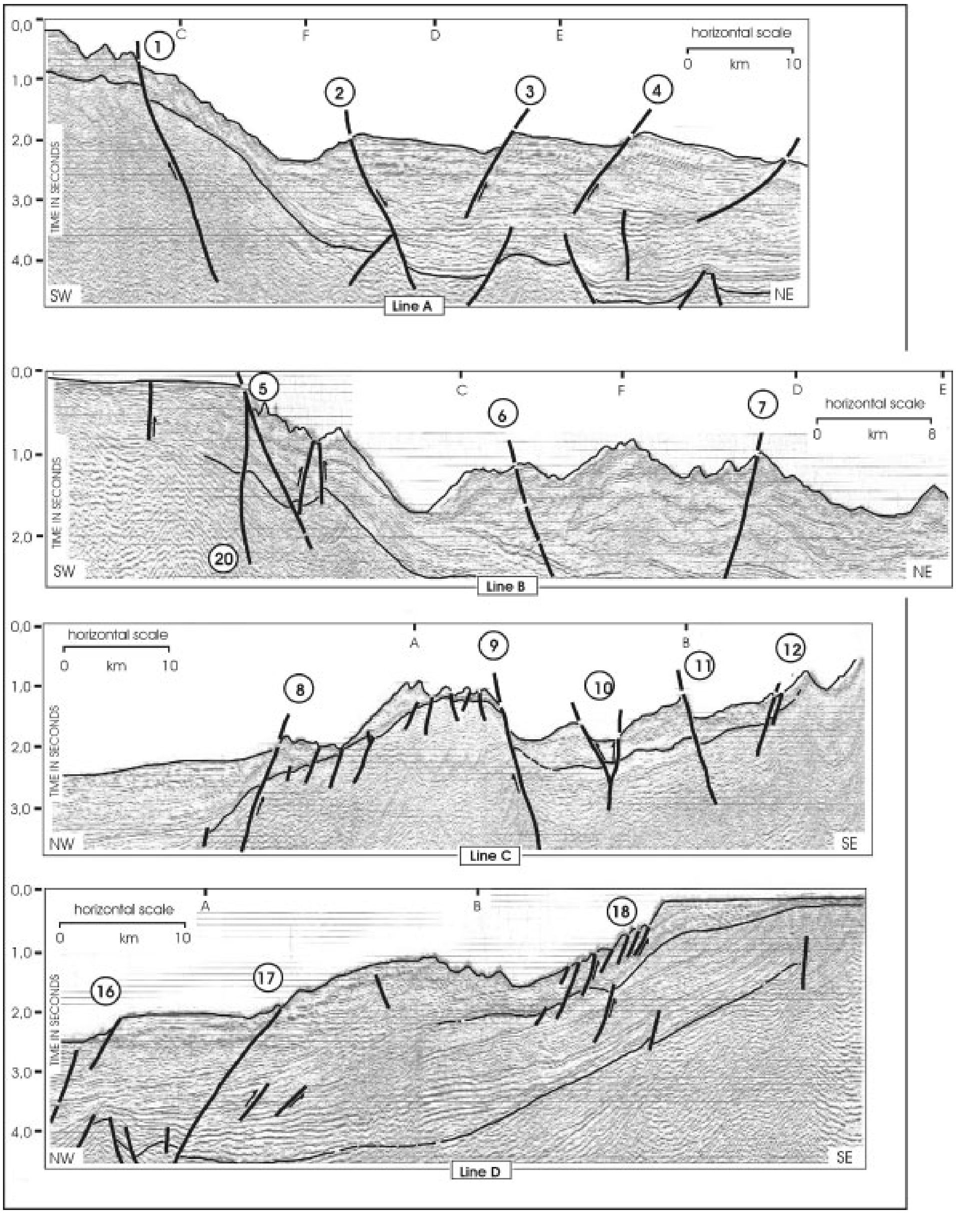

Figure 8. Seismic profiles across the Sakarya submarine canyon. Locations of profiles are shown in Figure 7 with capital letters A to D.

components that caused the subsidence of the northern block of the Kefken–Akçakoca Coastal Zone and the lateral displacement of the submarine canyon axis (Algan *et al.* 2002).

8. EVALUATION OF GEOLOGIC-MORPHOLOGIC AND GEOPHYSICAL DATA

Based on the morphology and structural elements of the neotectonic period, there are five morphotectonic entities distinguished in the eastern Marmara region: Black Sea Basin, Thrace–Kocaeli Peneplain (TKP), Çamdağ–Akçakoca Highland (ÇAH), Armutlu–Almacık Highland and Marmara Basin (Figure 1B). There are also subordinate morphotectonic entities—Kefken–Akçakoca Coastal Zone, Adapazarı-Karasu corridor (AKC), Adapazarı Basin and İzmit–Sapanca corridor—that form the transition between the major tectonic entities.

Based on the Early Palaeozoic to Neogene stratigraphy (palaeotectonic units), the TKP can be correlated with the ÇAH; thus they represent lateral continuations (Figure 3). In contrast, their post-Eocene evolutionary histories differ such that while in the eastern part of the TKP pre-Neogene rocks (up to Eocene) were protected from erosion; they were eroded extensively to the lowermost levels of the Palaeozoic succession in the ÇAH (Figure 5). Therefore, the ÇAH forms a region where the oldest units of the Pontides are exposed. In addition, there is an altitude difference of about 1000 m between the ÇAH and the TKP (Figures 2, 5). It is now agreed that the peneplain topography on the Kocaeli Peninsula developed during the Late Miocene–Pliocene period, but the ÇAH did not form a part of this peneplain. This, in turn, suggests that as the whole history of uplift and erosion in the ÇAH cannot be attributed to the processes since the commencement of dextral motion along the NAFZ, the differences between the TKP and ÇAH must have begun before the NAFZ. This further suggests that the TKP must have extended to the western edge of the ÇAH in the east. The boundary between the two different morphotectonic entities is represented by the AKC.

The morphological, geological and geophysical data indicate that the boundary between the TKP and ÇAH is a NNE–SSW-trending fault zone, named in the present paper as the Adapazarı–Karasu Fault Zone. The distribution of epicentres of the microseismic activities in the Adapazarı Plain and AKC shows a close parallelism to the NE–SW-trending faults (Figure 9A). A similar analogy can be made for the distribution of aftershocks of the 17 August 1999 İzmit earthquakes in the east of the AKC (Figure 9B; Polat *et al.* 2002). Furthermore, epicentral distribution of the earthquakes between 1985–1997 (recorded by the stations of the Earthquake Research Institute) in the area between Adapazarı and Karasu indicates the presence of NE–SW-trending lineaments reaching to the Black Sea (Figure 9A). The presence of NNE–SSW-trending faults, which cut the Black Sea shelf at a high angle, is also supported by offshore seismic profiles (Figures 8, 9) (also see Algan *et al.* 2002).

The Upper Miocene–Lower Pliocene sediments deposited on the peneplain (Belgrad Formation; Figure 3) are widely exposed in the TKP and partly overlie the northern and eastern edges of the ÇAH (Karasu Formation; Figure 5). This suggests that the Adapazarı-Karasu Fault Zone formed the eastern boundary of the TKP in the pre-Late Miocene and controlled the uplift of the ÇAH.

There are two distinct, differently trending, seismically active fault zones in north Anatolia (Figure 10) (e.g. Şengör *et al.* 1985; Barka and Reilinger 1997; Bozkurt 2001a): (1) the dextral NAFZ; and (2) the Northeast Anatolian Fault (NEAF; Tatar 1975, 1978), which extends from the Erzincan Basin to the Caucasus and accommodates about 8 ± 5 mm/yr of left-lateral motion (Barka and Reilinger 1997). In addition to the strike-slip faulting, the seismic activity observed along the southern margin of the Black Sea (Figure 10) indicates that the margin is seismically active and generates destructive earthquakes (e.g. $M = 6.8$ 1968 Bartın earthquake; Alptekin *et al.* 1986). The source mechanism of the Bartın earthquake indicates thrust faulting (Alptekin *et al.* 1986). The available data clearly indicate that the Black Sea region has been experiencing two distinct geodynamic processes since the beginning of the neotectonic period in the region (cf. Finetti *et al.* 1988). The region experienced extensional tectonics with regional-scale normal faults during the Late Cretaceous to Palaeocene. Starting from early Middle Eocene, compressional tectonics began to shape both offshore (Finetti *et al.* 1988) and onshore (Yiğitbaş and Elmas 1997). It is also clear from the seismic profiles that compressional deformation along overthrusts continued on the offshore Eastern Pontides until the present (Gökaşan 1996). The available data are therefore consistent with the interpretation that the southern coast of the Black Sea in the area between Bartın in the west and Caucasus in the east is marked by active thrust faulting known as the South Black Sea Thrust Fault (cf. Letouzey *et al.* 1977; Figure 10). The seismic profile from Sinop offshore and fault plane solution of a moderate earthquake that occurred in the Caucasus (Shirokova 1967) indicate the recent activity of the South Black Sea Thrust Fault.

Thus, the above-mentioned structures, the South Black Sea Thrust Fault in the north, the NAFZ in the south, the NEAF in the east and the Adapazarı–Karasu Fault Zone in the west, define a seismically active block named the North Anatolian Block. In this regard, this paper, for the first time, provides evidence for the existence of the Adapazarı–Karasu Fault Zone and states that the fault zone forms the western boundary of the North Anatolian Block. The ÇAH constitutes the western part of this block (Figure 10).

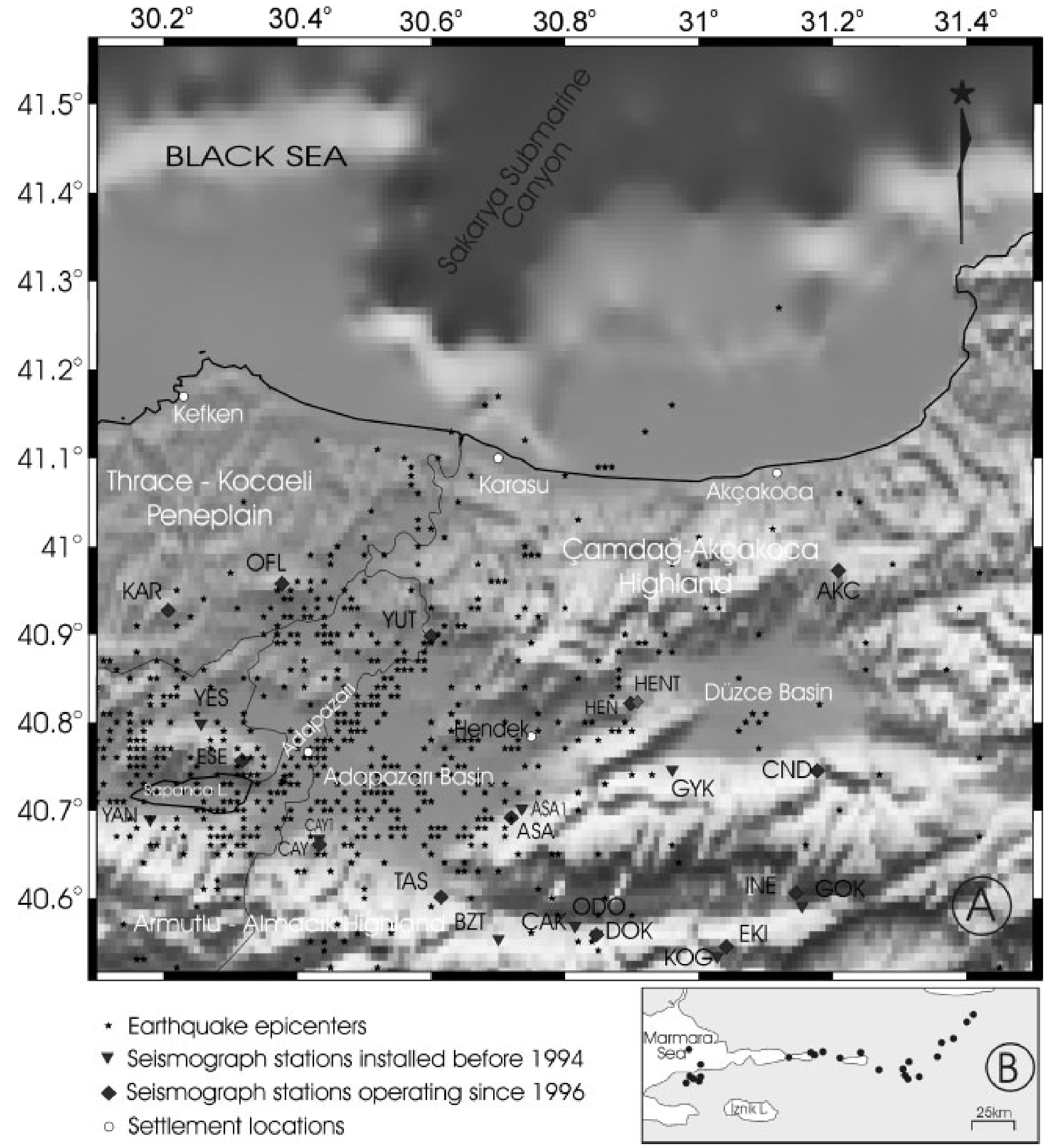

Figure 9. (**A**) Map showing relief and epicentre distributions in and around the AKC. Data provided by the local network deployed in the framework of the Turkish–German Joint Earthquake Research Project. The base-map was prepared using GMT (Wessel and Smith 1995). **(B)** Distribution of aftershocks (Md > 4) of the 1999 İzmit earthquakes (August 17–October 23) (taken from Polat *et al.* 2002).

The existence of the correlative Pontian–Lower Pliocene sediments in the Armutlu Highland, the TKP and the Adapazarı Basin indicate that the activity of the NAFZ in the region and Adapazarı Basin commenced sometime after the Early Pliocene. During this time the alluvial fan and fluvial flood plain sediments (Upper Pliocene–Pleistocene Karapürçek Formation) were deposited commonly in the İzmit–Sapanca corridor and Adapazarı Basin. They extend towards the AKC in the north and are overlain by the Holocene sediments (Figure 5). Alluvial fans commonly developed along the southern margin of both the İzmit–Sapanca corridor and the Adapazarı Basin. This suggests that the branch of the NAFZ in the south of the Adapazarı Basin developed since the Late Pliocene.

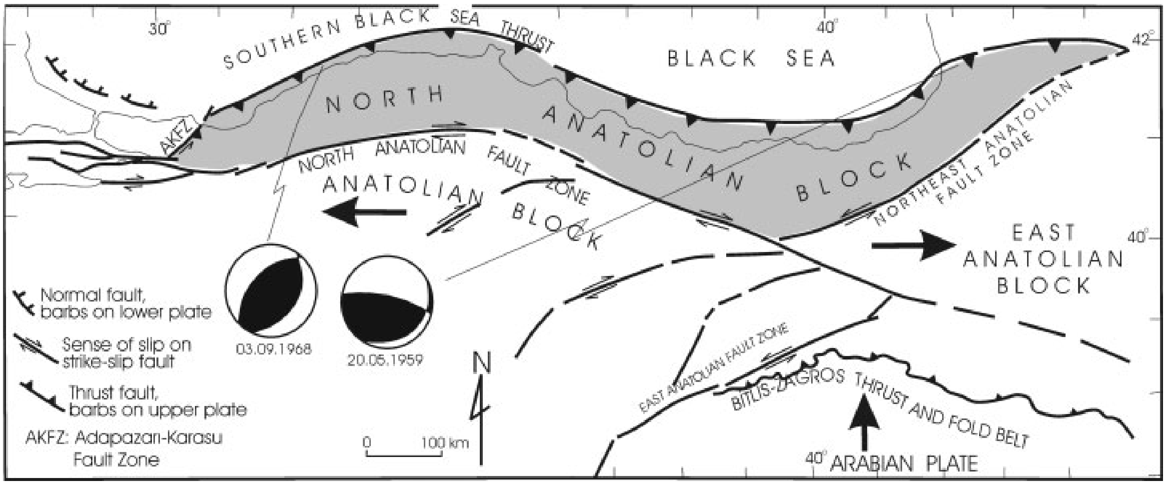

Figure 10. Simplified tectonic map of the north and east Anatolian region showing the setting of the North Anatolian Block (modified from Letouzey *et al.* 1977; Barka 1992). Available fault plane solutions for moderate earthquakes that occurred at the northern margin of the North Anatolian Block are shown. Solutions for 20 May 1959 and 3 September 1968 earthquakes are from Shirokova (1967) and Alptekin *et al.* (1986), respectively.

The result of this paper is consistent with that of Ünay *et al.* (2001) who suggested that latest Pliocene time corresponds to the formation of the Adapazarı pull-apart basin and to the commencement of dextral motion along the northern strand of the NAFZ.

The NNE–SSW-trending Adapazarı–Karasu Fault Zone is cut by the E–W-trending faults paralleling the different segments of the NAFZ (Figures 5, 6), suggesting that the latter is younger. Likewise, E–W-trending faults cut and displace the Upper Miocene–Lower Pliocene sediments, but control the deposition of Quaternary sediments.

As a result of younger E–W faulting, the area between the Adapazarı Basin in the south and the Black Sea in the north (i.e. the AKC) is marked by an irregular morphology characterized by alternating E–W fault-bounded highs and lows (or sectors such as Söğütlü Plain, Göktepe and Sariboğaz valleys) where low areas became the sides of localized Quaternary to Recent sedimentation. On the other hand, the southern boundary of the Adapazarı Basin is marked by a linear high topography with steep slopes, marked by through-going fault segments of the NAFZ (Figures 5, 6).

It is suggested that the Sakarya River or an ancestral river system existed throughout the AKC in the Late Miocene–Early Pliocene period (Bilgin 1984) and its pattern was controlled by the NNE–SSW-trending fault system (Adapazarı–Karasu Fault Zone). Similarly, Erinç (1958) documented, based on bathymetric data, evidence for the presence of a river channel on the Black Sea shelf during the Late Miocene–Early Pliocene time. The northern continuation of this river channel is buried under the waters of the Black Sea after marked subsidence in the northern block of the E–W-trending fault system. This submarine valley and its possible trace onshore indicate that the Sakarya River was flowing into the Black Sea during the pre-Late Pliocene (Bilgin 1984).

It is important to emphasize that the NNE–SSW-trending Adapazarı–Karasu Fault Zone is still active and producing seismic activity, as indicated by the NE–SW lineaments defined by the distribution of aftershocks following the 1999 İzmit earthquakes (Figure 9B; Polat *et al.* 2002). We propose that the activity of the Adapazarı–Karasu Fault Zone is the result of the arcuate shape of the NAFZ in the southwestern boundary of the North Anatolian Block (Figure 10). The active compressional tectonics along the southern coast of the Black Sea in the north and local transtensional/extensional tectonics related to strike-slip faulting in the Adapazarı Basin in the south, suggest that the AKC can be considered as a transfer fault zone (Figure 10) active, at least, since Pontian–Early Pliocene time.

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