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Morphotectonic development of the Marmara Region

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ABSTRACT

The Marmara Region of northwest Turkey covers the Marmara Sea Basin and the surrounding lands. In the region, morphologically different areas may be distinguished. The Marmara Sea Basin is a structural depression. The land to the north is known as the Thrace-Kocaeli Peneplain, a flatland elevated above a horst. This may be referred to as the Istanbul Horst, bounded by two strike-slip fault zones which define the structural boundaries of two sea basins; the Black Sea in the north and the Marmara Sea in the south. The southern boundary fault is part of the North Anatolian Transform Fault Zone (NAFZ) which cuts through the region in the E–W direction and extends to the Aegean Sea Region.

The land to the south of the Marmara Sea is a plateau about 300 to 800 m high known as the Bursa-Balıkesir Plateau. It has a rather rugged topography represented by NW and NE trending ridges separated by depressions. The ridges and the depressions correspond to horsts and grabens respectively.

The data reveal that the Marmara Region has passed through the following morphotectonic evolution. Together with the surrounding region it suffered a long period of denudation between the Oligocene and the end of the late Miocene, which formed a regionwide peneplain. The N–S extensional regime followed this phase and began to produce a horst-graben system, and thus, fragmented the peneplain. The flat-lying erosional surfaces have been elevated above the horsts. Later, the NAFZ reached the Marmara Region. In the initial stage, it affected NW Anatolia extensively as a wide right-lateral shear regime. This has evolved, and through time the present narrow fault zone has developed.

The major morphological difference between the regions to the north and the south of the Marmara Sea Basin is mainly related to the NAFZ. As a plate boundary, it formed a barrier to the N–S extension, saving the northern sector from the effect of the extension. The southern region has gradually elevated to much higher altitudes.

1. Introduction

The Marmara Region refers to northwestern Turkey. It is situated between the Aegean, Balkan, Black Sea, and Anatolian regions (Fig. 1). Tectonically the region is complex and critical, because the N–S extensional regime of the Aegean Region and the North Anatolian Transform Fault Zone (NAFZ) as the northern plate boundary of the Anatolian Plate intersect. Structural and morphological analyses of the interactions of these two different tectonic regimes have not yet been attempted. The previous geological efforts in the area have primarily been focused on the NAFZ within the Marmara Sea because of the devastating 1999 earthquakes. This study is a pioneering work in this region, examining the major morphological features in light of multidisciplinary geological and geophysical data, because it is known that the active tectonics of the region are best expressed in the morphology.

The Marmara Region of NW Anatolia consists essentially of the Marmara Sea and the surrounding areas (Fig. 1). In this region, the most prominent morphotectonic entity is the Marmara Sea, which is located between two larger seas, the Black Sea and the Aegean Sea. These three seas are connected to one another by two narrow straits, the Çanakkale Strait (the Dardanelles) and the Istanbul Strait (the Bosporus) in the southwest and the northeast, respectively (Fig. 1).

The land area to the north of the Marmara Sea may be divided into two sectors with respect to the Istanbul Strait (Fig. 1). The western sector is known as the Thrace Region. The eastern sector is called the Kocaeli Peninsula. The southern part of the Marmara Sea is northwestern Anatolia.

The major morphotectonic components of the region are the following (Fig. 1).

a- The Thrace-Kocaeli Peneplain
b- The Marmara Sea Basin
c- The Istanbul and Bursa-Balıkesir Plateaus
d- The North Anatolian Fault Zone (NAFZ)
e- The Ganos High and the Armutlu High.

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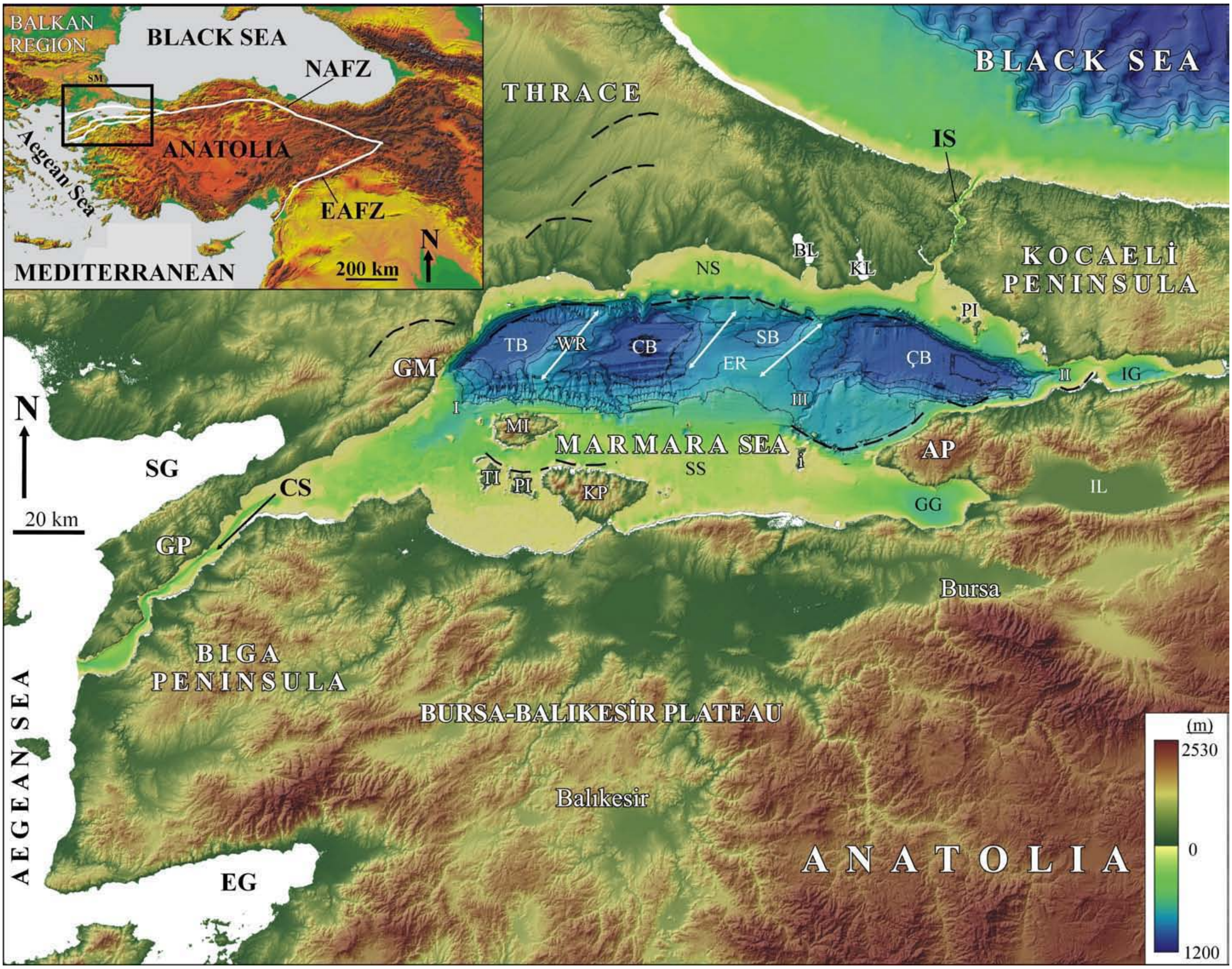


Fig. 1. The location map. SG = Saros Gulf, GG = Gemlik Gulf, IG = Izmit Gulf, EG = Edremit Gulf, GP = Gelibolu (Gallipoli) Peninsula, AP = Armutlu Peninsula, CS = Canakkale Strait (Dardanelles), IS = Istanbul Strait (Bosporus), SS = Southern shelf, NS = Northern shelf, TB = Tekirdag Basin, WR = Western Ridge, CB = Central Basin, ER = Eastern Ridge, SB = Silivri Basin, ÇB = Çınarcık Basin, IL = Iznik Lake, GM = Ganos Mountain, SM = Strandja Mountain, TI = Türkeli Island, PI = Paşalimanı Island, MI = Marmara Island, KP = Kapıdağ Peninsula, i = Imrali Island, PI = Princess Islands, BL = Büyükçekmece Lagoon, KL = Küçükçekmece Lagoon. I, II, III indicate major canyons in the Marmara Sea. Broken lines are major normal faults. Colour bar displays elevation. Inset shows the location of the study area in Turkey. NAFZ = The North Anatolian Transform Zone, EAFZ = The East Anatolian Transform Fault Zone.

The most prominent active tectonic entity in the region is the NAFZ. It cuts across the Anatolian Peninsula in the E–W direction, entering into the Marmara Region and extending to the Aegean Sea (Fig. 1). As an active tectonic element, it has significant morphological control in the region.

In this paper, these morphological entities are first described and then, in light of the data presented, their development will be discussed. Prior to this, however, a brief history of the tectonic evolution of the region will be given to enable the reader to follow the ensuing narrative more effectively.

The Anatolian Plate is the major, wedge shaped lithospheric entity in Anatolia (Fig. 1). It is bounded by two transform faults. Of these, the NAFZ, represents the northern fault. The Anatolian Plate is escaping westward from the point of convergence in the Karlıova junction along these transform faults. This began following the complete elimination of the Tethyan oceanic realm between the collided Arabian and Laurasian plates during the Pliocene (Şengör and Kidd 1979; Şengör and Yılmaz, 1981; Şaroğlu and Yılmaz, 1991). From eastern Anatolia, the NAFZ stretches to the west for more than 1000 km (Fig. 1). The earthquakes that affect Anatolia today originate primarily along this fault (i.e., the eastern Marmara Earthquake, which occurred on 17 August 1999; Mw = 7.4; Barka, 1999). The Ganos and Armutlu highs are the two mountain ranges located within the NAFZ (Fig. 1).

Before the development of the NAFZ, the tectonic situation of Anatolia may be summarized as follows; in western Anatolia the complete elimination of the oceanic realms and the remnant seas occurred between the Late Cretaceous and Eocene period (Şengör and Yılmaz, 1981; Yılmaz et al., 1995). The post-collisional convergence between the Pontide–Sakarya collided mosaic and the Tauride continued after the Eocene and the region began to be squeezed, shortened and consequently elevated (Şengör and Yılmaz, 1981).

During the Oligocene period the whole Aegean Region including Western Anatolia, the Aegean Sea area, and the Balkan Region became a high land (Şengör and Yılmaz, 1981; Görür et al., 1995) and began to be effectively eroded. This elevated domain subsided near sea-level during the Late Miocene period (Yılmaz et al., 2000). This event may be regarded as the collapse of the orogene, which has been previously stated as a much earlier event (Dewey, 1988; Seyitoğlu and Scott, 1991). During this time, following a long absence, the sea incursion

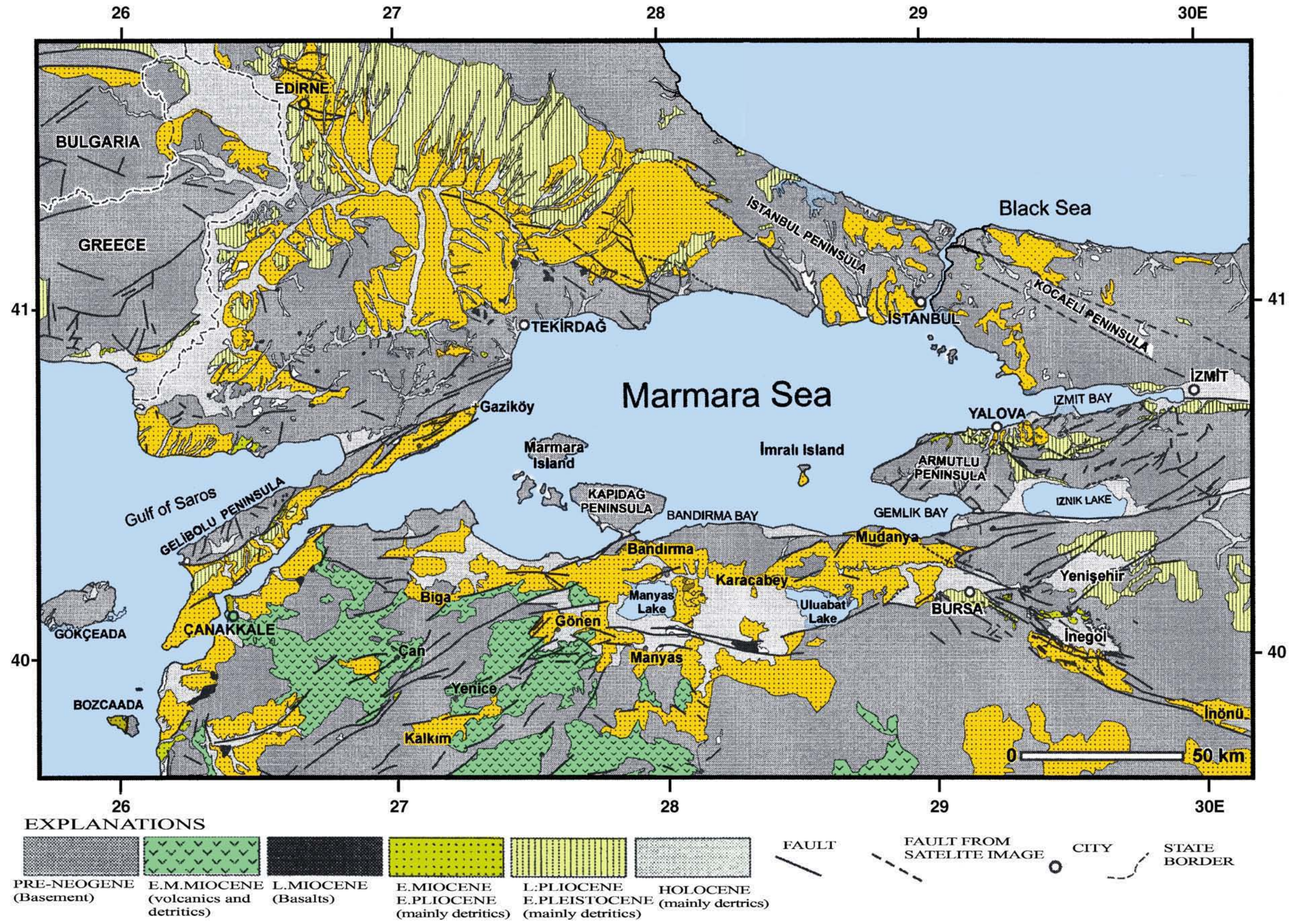


Fig. 2. Simplified geology map of the Marmara Region (modified after Yaltırak, 2002, Fig. 5).

began into the region for the first time from the Central Aegean area. During the period when the region represented a continental environment, the regionwide denudation continued uninterruptedly from the Oligocene to the end of Late Miocene, and generated an extensively developed flat-lying erosional surface, which, being close to the sea level, may be regarded as a peneplain surface. For this the following data may be given; the Upper Miocene-Lower Pliocene successions studied throughout western Anatolia are transitional in nature between shallow marine, lagoon, and lacustrine environments in which mainly low energy sediments were deposited (Yılmaz et al., 2000).

Presently this erosional surface may be used as a key stratigraphic marker to identify the younger and older events, and the consequent morphological features. The entrance of the NAFZ into the north-western Anatolia post-dates the development of this erosional surface, because the NAFZ cuts and displaces this marker.

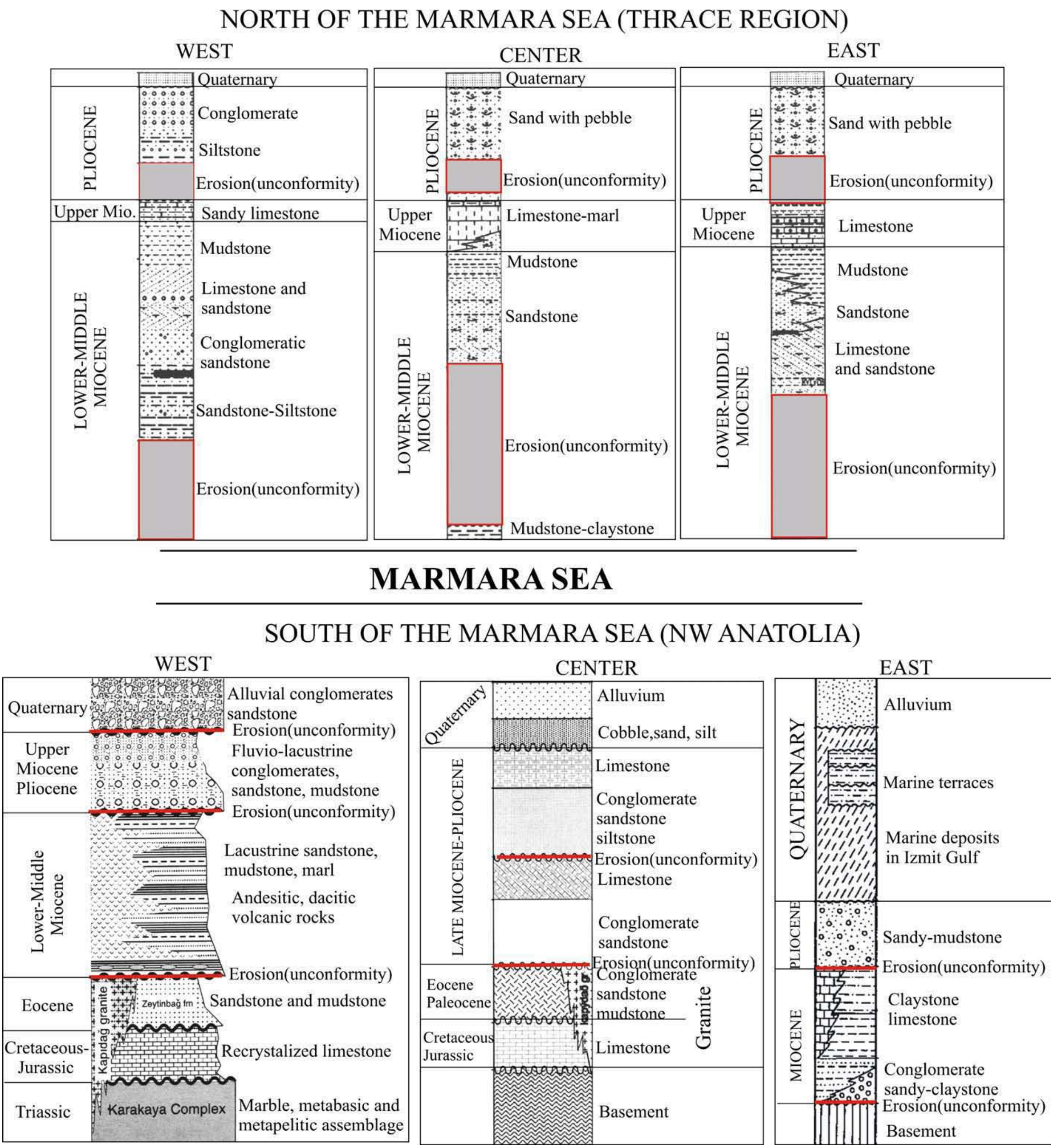


Fig. 3. Stratigraphic columnar sections from the northern (modified after Sakınç et al., 1999, Fig. 4) and southern (modified after Emre et al., 1998, Fig. 4; Gürer et al., 2003, Fig. 5; 2006, Fig. 4) parts of the Marmara Region. The gray zones and red lines indicate the erosional periods, which led to the development of the flat-lying erosional surfaces.

2. Characteristics and development of the major morphotectonic entities of the Marmara Region

2.1. The Thrace-Kocaeli Peneplain

Above all of the land masses in the Marmara Region, and at the top of the horsts separated by the grabens in the western Anatolian region, lie mature erosional surfaces which are easily recognized by the flat-lying horizon. These are the remnants of an extensive peneplain surface. This surface reveals also that the region suffered a relatively calm period during which erosion was the major process. This surface was first recognized by Cvijic (1908) from the Istanbul area, who named it the "Pera Plain". The remains of the peneplain may also be seen on the Thrace and Kocaeli peninsulas. Therefore, Pamir (1938) named this surface the Thrace-Kocaeli Peneplain. The peneplain surface developed above the Paleozoic, Mesozoic, and Cenozoic rocks including the upper Miocene units that crop out as the major rock units of the region (Figs. 2 and 3).

The peneplain is also quite clearly observed on both sides of the Bosporus (Fig. 4) (Yılmaz, 2007). The youngest rock unit, recognized below the peneplain surface, is the upper Miocene–lower Pliocene lacustrine sequence (Fig. 3). Therefore, it may be stated that the erosion in the Marmara Region also lasted till the late Miocene. The remnants of this surface cropping out more extensively in the Thrace and Kocaeli regions are only observed as isolated patches in the Istanbul Region (Fig. 5). This is partly because the younger denudation has eroded the cover succession in the Istanbul Region, down to the Paleozoic basement (Figs. 2 and 3). Above the erosional surface have been deposited Plio-Quaternary sediments (Fig. 3) (Pamir, 1938; Sakınç et al., 1999).

Under the younger cover rocks, the erosional surface has been detected by seismic data, obtained from the land areas as well as from the shelves (Perinçek, 1991; Çağatay et al., 1998; Yaltırak et al., 1998, 2000; Ocakoğlu et al., 2005; Gökaşan et al., 2008). The seismic studies conducted in the Bosporus and the surrounding sea regions also display the presence of an erosional surface at the same stratigraphic level (Alavi et al., 1989; Oktay et al., 1992; Gökaşan et al., 1997; Demirbag et al., 1999; Gökaşan et al., 2002, 2005; Tur, 2007; Dolu et al., 2007).

The opening of the Black Sea Basin began during the Late Jurassic–Early Cretaceous period (Görür, 1988; Yılmaz et al., 1997). This shallow sea became a deep basin in the late Cretaceous (Yılmaz et al., 1997). The Black Sea Basin has remained open since that period. The peneplenation of the Marmara and Thrace regions developed much later on the southern side of the Black Sea. A region-wide erosion developed above the land adjacent to the Black Sea, before the opening of the Marmara Sea Basin.

Presently, the Black Sea fault zone, which defines the southern boundary of the Black Sea, forms the northern border of the peneplain surface. The erosional surface is cut by the branches of this fault zone, and is lowered on the down-thrown blocks below sea-level. The dip-slip component of the fault, which forms the straight shore line (Fig. 1) is more than 500 m, between the flat-lying erosional surface at the top of the hills lying parallel to the shoreline and the similar surface identified by seismic data, in the shelf (Demirbag et al., 1999; Algan et al., 2002). In the shelf, the erosional surface extends northwards to the shelf edge where it is sharply truncated by a set of faults, which define the canyon head.

2.2. The Marmara Sea Basin

The Marmara Sea is an oval shaped interior sea located between Asia (Anatolia) and Europe (Thrace) (Fig. 1). The morphological features of the Marmara Sea Basin: the shelves, slopes, and the deeper parts of the basin display different features at different sites (Fig. 1). Toward the east and southwest, the sea narrows. The sea has two well developed shelves in the northern and the southern sides (Fig. 1). They are about −100 m deep, and cover the largest areas (approximately 6077 km^2; Gazioğlu et al., 2002) within the Marmara Sea region. The northern shelf is about 3–5 km wide and is very narrow compared to the southern shelf, which exceeds 30 km in width (Fig. 1). The latter covers an area of 1883 km^2. The northern shelf edge runs sub-parallel to the coastline along the Thracian coast (Fig. 1) and becomes wider towards the east along the Kocaeli Peninsula. Distinct morphological features on the shelf in front of the Kocaeli Peninsula are the Princess Islands (Fig. 1). On the southern shelf, there are bigger islands, i.e. the Marmara, Türkeli, Paşalimanı, and İmralı islands, and the Kapıdağ Peninsula. The latter is connected to the mainland by a tombolo (Fig. 1). The Marmara Sea is delimited in the east and west by two linear mountain ranges: the Armutlu and Ganos Mountains (Fig. 1). They rise steeply in front of the sea, and therefore there are no wide shelves along these highs. The steep slopes extending from

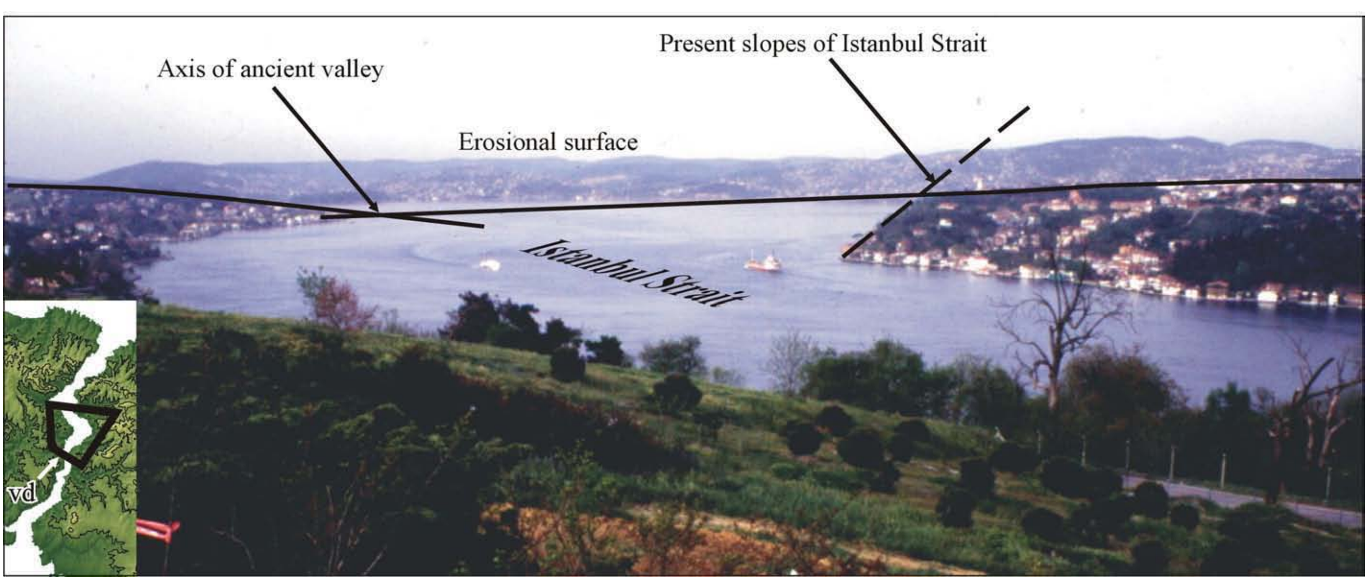


Fig. 4. The photograph showing the northeasterly view of Istanbul Strait (Bosporus) and the surrounding areas (modified after Gökaşan et al., 2005, Fig. 2). The Thrace-Kocaeli Peneplain as a flat-lying erosional surface is seen in the horizon. The slope angles, gently inclined at the higher levels and steeply inclined at the lower levels make sharp angles with one another. vd = view direction.

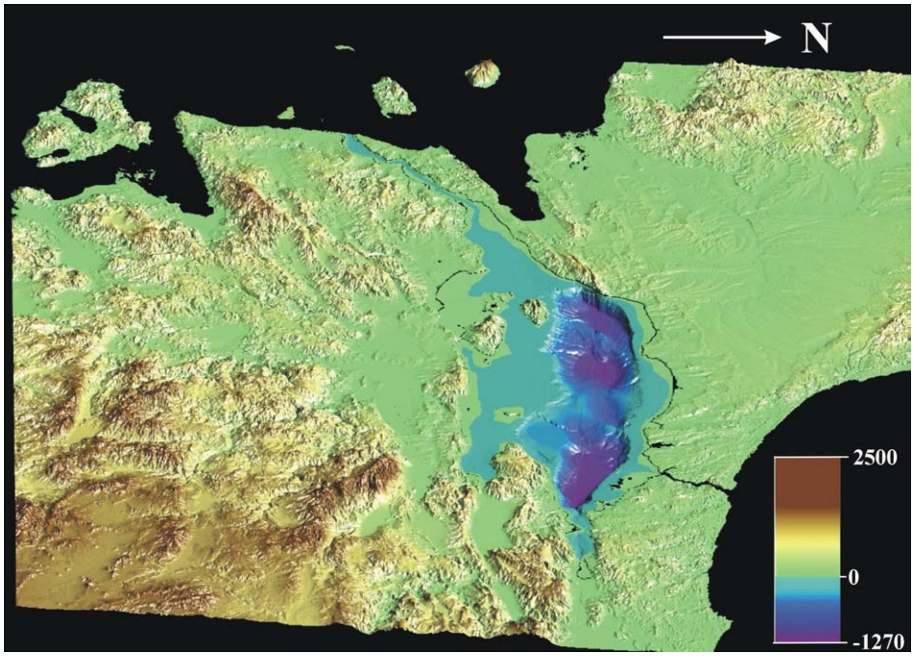


Fig. 5. Pseudo colour 3D, “bird's-eye” view of Marmara Region's digital elevation model and sea surface model. View direction east to west.

the top of the ridges down to the sea bottom stretch more than 2000 m.

The Marmara Sea is a deep trough, which consists of three sub-basins (Figs. 1 and 5). Along the long axis of the sea, the three deep sub-basins are separated by two diagonally NE trending ridges, the eastern and western ridges, which are −570 m and −650 m in depth, respectively (Fig. 1). The sub-basins are known as the Çınarcık, Central, and Tekirdağ basins, from east to west. The eastern sub-basin (Çınarcık), which is −1270 m, is deeper than the others; the Central and Western sub-basins are −1250 m and −1120 m deep, respectively. There is even a fourth sub-basin, which is situated at the top of the eastern ridge. This is known as the Silivri Basin and thus has a much shallower depth (−830 m; Fig. 1).

The Çınarcık Basin, triangular in shape, is the largest sub-basin. It extends eastward to the İzmit Gulf (IG), which is narrow and shallow (−200 m; Fig. 1). The northern and southern slopes of the Çınarcık Basin are linear and steep. The young (Plio-Quaternary) sediments deposited in the Marmara Sea Basin are thickest in the Çınarcık Basin, reaching up to 3 km in thickness (Carton, 2003).

2.2.1 Slopes and major morphological features (i.e. canyons-landslides) of the Marmara Sea Basin

The gradient of the shelves of the Marmara Sea is generally gentle (Fig. 1). They pass to the slopes where the gradient becomes greater than 7° (Gazioğlu et al., 2002). The slopes display two different morphological features: a) straight and steep slopes (most of the northern slopes belong to this category); and b) concave and low angle slopes (Fig. 1). All of the southern slopes belong to this category (Fig. 1). Along the northern border, the slope angles locally reach more than 70° (Gazioğlu et al., 2002).

Secondary morphological features in the form of canyons and landslides have commonly developed on the steep slopes (Figs. 1 and 6). The canyons show great variations in depth and diameter (Fig. 1). Two big canyons have been identified on the westernmost edge of the southern slope of the Marmara Sea near the Dardanelles (I on Fig. 1), and also at the western edge of the Izmit Gulf (II on Fig. 1) (Gazioğlu et al., 2002; Ergin et al., 2007). Another big canyon lies north of Imralı Island adjoining it to the Eastern Ridge (III on Fig. 1). There are also a number of small canyons along the northern as well as the southern slopes (Fig. 1).

The sub-marine landslides are other distinct morphological features that are extensively observed above the slopes (Gazioğlu et al., 2002; Gökaşan et al., 2003; Gazioğlu et al., 2005). Five major sub-marine landslides have been identified (Fig. 6). Two of these are located in the western part of the Marmara Sea (Fig. 6, detail maps A and B). Of these, the westernmost one has been defined as a mud flow (Fig. 6, detail map A) (Gazioğlu et al., 2002). The Western Ridge, dividing the Central and Tekirdağ Basins, has also been interpreted as a giant landslide mass (Fig. 6, detail map B) (Gökaşan et al., 2003). It is claimed that this landslide is coeval with, and was formed during the development of the NAFZ (Gökaşan et al., 2003). In addition to those observed along the slopes of the Marmara Sea, landslides have also been identified on the ridges separating the sub-basins (Fig. 6, detail map C) (Gökaşan et al., 2003). For the origin of the landslides, the following evidence may be listed: the landslides developed along the northern margins of the Marmara Sea are spacely-connected with the faults; the NAFZ (those displayed in Fig. 6 detail maps D and E) and the ridge bounding faults (those displayed in Fig. 6 detail maps B and C). These are placed above the steeply dipping fault planes. Therefore, they are genetically connected with the motions that occurred along these active faults. The enhancing role of the young and small-scale normal and reverse faults, formed in association with the major faults bounding the ridges, may also be stated. A set of external cracks are widely observed along the steep northern slope implying that some new landslides are to develop (Fig. 6, detail map D) (Gökaşan et al., 2002; Gazioğlu et al., 2005). The amphitheater morphology and back-tilted sliding blocks in the landslides that have developed on the steep northern slope of the Çınarcık Basin collectively indicate that this big landslide is rotational in nature, and formed above a concave fault surface (Fig. 6, detail map E). Since the NAFZ is partly responsible for the present morphology of the Marmara Sea Basin, its role in the development and re-activation of the landslides is also evident.

2.3. The Istanbul and Bursa-Balıkesir plateaus

The northern and the southern regions of the Marmara Sea represent two plateaus: the Istanbul and the Bursa-Balıkesir plateaus, respectively. The two plateaus have apparently developed coevally because the two sides of the Marmara Sea were parts of the same land prior to the opening of the Marmara Sea Basin and therefore have

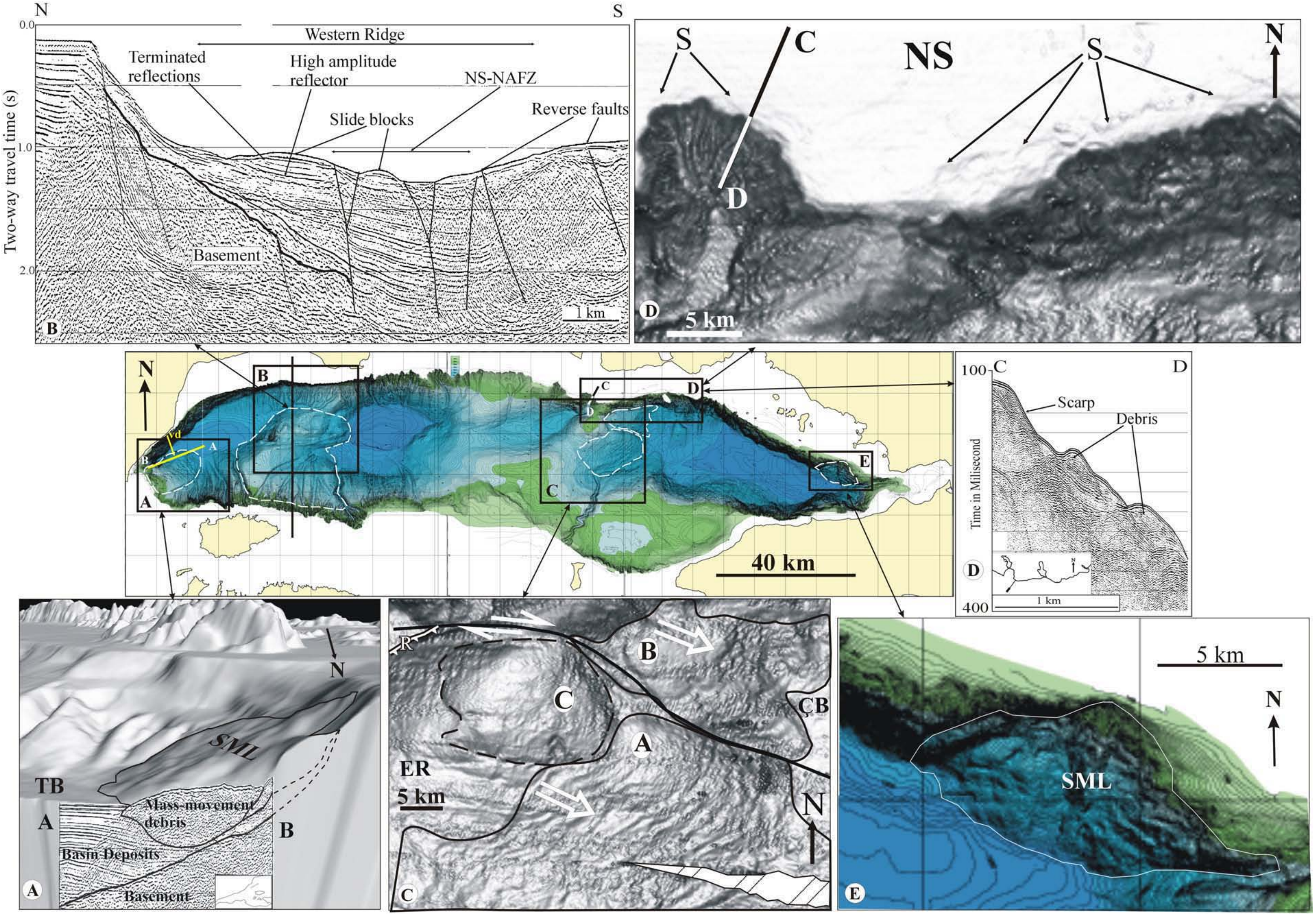


Fig. 6. Major sub-marine landslides in the Marmara Sea (composite figure composed of data from Rangin et al., 2001; Gazioğlu et al., 2002, Fig. 4; 2005; Gökaşan et al., 2002, Fig. 5e; 2003; Figs. 6, 7). A and B = Slides, C = Stable area on the Eartern Ridge, S = Scars, R = Reverse fault, SML = Submarine landslides, A–B and CD = Seismic profiles, NS = Northern slope, vd = view direction, ER = Eastern Ridge, ÇB = Çınarcık Basin, TB = Tekirdağ Basin.

undergone a similar history of evolution. This view is based on the fact that the stratigraphic positions of the erosional surfaces on both sides of the Marmara Sea are the same (Fig. 3). Therefore, they are regarded as co-genetical (Yılmaz, 2007). The initial fragmentation of the regional erosional surface began with the development of the Marmara Basin. This event disrupted the continuity of the erosional surface. Later, the erosional surfaces on both sides of the Marmara Sea Basin apparently were elevated at different rates. The height of the Istanbul Plateau varies between 40 and 300 m (Fig. 7). The Bursa-Balıkesir Plateau has an average altitude of 500 m reaching over 1000 m in the east. Examples of this may be taken from Uludağ Mountain; the upper Miocene–lower Pliocene lacustrine limestone sequence and the erosional surface above it have been elevated on these mountains more than 500 m (Fig. 8). This is clearly observed on the western plunge of the Uludağ High.

The name of the Istanbul Plateau refers to the extensive flat land around the Istanbul Strait (Figs. 4 and 5). This region represents a horst developed between two fault systems (Fig. 9). They run sub-parallel to the coastlines of the Marmara and Black Seas. Although it is simply defined as a horst, this block has apparently been displaced obliquely; elevated as a horst block, and rotated under a dextral shear stress between the two right-lateral strike-slip faults, which are the boundary faults of two adjacent sea basins (Fig. 9). The northern boundary fault seismically is not as active a fault zone as the NAFZ. Thus, it resists the motion of the horst along the NAFZ, and causes the generation of a dextral shear in the horst (Fig. 9). This shear system has forced the horst to rotate anti-clockwise, which has produced NW and NE trending conjugated pair of structural and morphological features (Figs. 7 and 9).

For the elevation of the Istanbul Plateau the following data may be referred to: a) the presence of elevated ancient terraces at different heights on both sides of the Bosporus Channel; b) the stream valleys on both slopes of the Bosporus which are in their incipient stages (Fig. 4). This means that the headward erosion along these valleys has not yet reached the top of the plateau to drain it toward the Bosporus in the shortest distance possible; and c) three different angular gradient surfaces are recognized along the slopes of Bosporus, from the top of the plateau down to the sea level (Fig. 4); towards the Bosporus the flat-lying erosional surface becomes gently inclined. This gentle surface is sharply replaced by a steep slope (>50°) in the middle part. Before sea level is reached, the steep slope is replaced by a sub-vertical slope (Fig. 4). These morphological angular unconformities reveal that only a short period of time has elapsed since the region began to rise so that the slopes of different angles have not yet been obliterated to form one transitional slope angle.

The altitudes of the peneplain around the Istanbul Plateau varies from 40 m along the coastal zone of the Marmara Sea in the south, gradually rising up to 300 m in the north, along the coastal zone of the Black Sea, the highest elevations lie sub-parallel to the Black Sea coast (Fig. 7), and are observable as slightly southward-tilted surfaces. This suggests that the horst while elevated, tilted southward as well. A water-divide has developed along this zone (Fig. 7), which separates the drainage flowing to the Marmara Sea from the drainage to the Black Sea. The lengths of streams flowing to the Black Sea are short in the Thrace Region (Fig. 7). This northerly draining, thin strip of land enlarges eastward toward the Kocaeli Peninsula (Fig. 7). The water-divide displays a sinusoidal pattern which is also the morphological response of the dextral shear stress on the Istanbul Horst. With the development of the Bosporus, the major drainage pattern was modified slightly; a rather narrow strip of land on both sides of the Bosporus began to drain into the Bosporus (Fig. 7). The main water-divide may still be traced across the Bosporus by morphological and bathymetrical data (Gökaşan et al., 1997, 2005).

The dextral shear regime and the consequent major trends of structural lineaments on the different parts of the Istanbul Plateau, as displayed in Fig. 7, apparently control the major drainage system. In the SW of the Thracian Peninsula and in the central part of the Kocaeli Peninsula, NE–SW lineaments dominate (zones A and C in the inset to Fig. 7), and extend into the Marmara Sea.

The rivers and streams flowing to the Marmara Sea, between Büyükçekmece Lagoon and the Bosporus, clearly display a NW–SE trending drainage system (Fig. 7). This changes gradually to a NE–SW

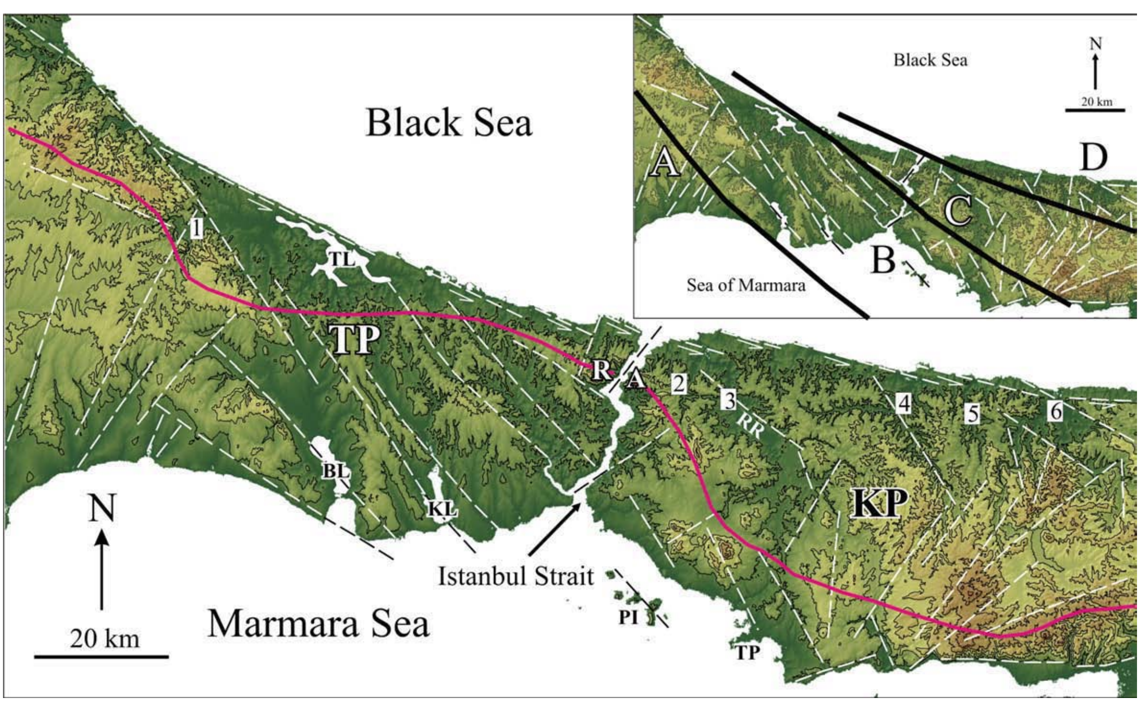


Fig. 7. Major morphological features of the Istanbul Region. The red line indicates water divide. The white broken lines represent lineaments. Streams and rivers 1 to 6 draining the central part of the İstanbul and Kocaeli peninsulas to the Black Sea, and cut and extend beyond the water divide. Contours at 100 m intervals. TP = Thrace Peninsula, KP = Kocaeli Peninsula, TL = Terkos Lake, BL = Büyükçekmece Lake, KL = Küçükçekmece Lake, PI = Princess Islands, TP = Tuzla Peninsula, A = Anadolukavagı, R = Rumelikavagı. Inset displays major trend groups and their approximate boundaries.

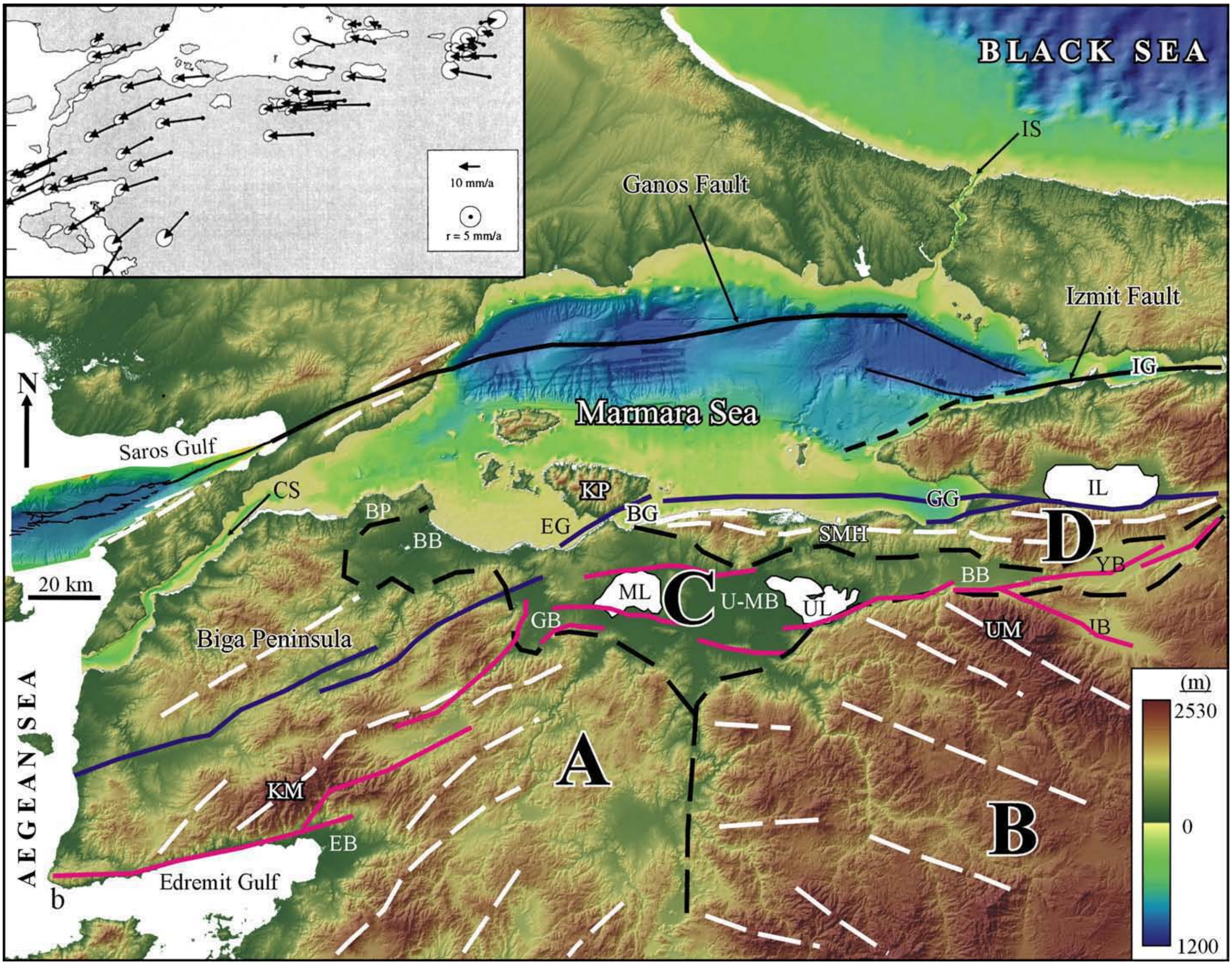


Fig. 8. The branches of the NAFZ in the Marmara Sea and its surrounding areas, and major morphologic features above the Bursa-Balıkesir Plateau. Broken white lines are the trend lines of the hills and mountain ranges. Data compiled from Barka and Kadinsky-Cade (1988), Armijo et al. (2002), Kurtuluş and Canbay (2007), and Ustaömer et al. (2008). The black, blue, and red lines correspond to the northern, central, and southern branches of the NAFZ respectively. A, B, C, and D, indicate different morpho-tectonic sub-areas of the Bursa-Balıkesir Plateau. The N–S broken line between A and B divides eastern and western areas, and corresponds to a hinge line, where presently is a major river valley. Inset shows GPS vectors of northwestern Anatolia after Straub (1996, Fig. 3-22). KM = Kazdağ Mountain, EB = Edremit Basin, BB = Biga Basin, GB = Gönen Basin, ML = Manyas Lake, UL = Uluabat Lake, U-MB = Uluabat-Manyas Basin, KP = Kapıdağ Penninsula, BB = Bursa Basin, UM = Uludağ Mountain, IB = Inegol Basin, YB = Yenişehir Basin, IL = Iznik Lake, BP = Biga Peninsula, SMH = South Marmara Highland.

trending system to the west of Büyükçekmece Lagoon (Fig. 7). The drainage on the Kocaeli Peninsula, on the other hand, displays two different trends: NW–SE and NE–SW (Fig. 7). The conjugated pair of structural lineaments are clearly observed in the zigzagging nature of the Bosporus.

Along the northern part of the Çınarcık Basin, the NW–SE trend becomes dominant (zone B in the inset to Fig. 7). A similar trend is also seen around the Princess Islands. In the area of the Kocaeli Peninsula facing the Black Sea coast, NW–SE lineaments dominate (zone D in the inset to Fig. 7). They control the drainage of the tributary valleys (rivers 2–6 in Fig. 7).

The Bursa-Balıkesir Plateau displays a distinctly different morphology compared to the Istanbul Plateau (Figs. 5 and 8). It has a rugged topography represented by hills and mountain ranges separated by lowlands. The trends of these highs are NE and NW in the western and eastern parts of the region, respectively (Fig. 8). The northern front of the mountainous terrain is a wide flat land, which surrounds the Marmara Sea in the south.

Two different morphological features are recognized on the Bursa-Balıkesir Plateau: a) flat-lying erosional surfaces, and b) narrow and long ridges (Fig. 8).

The narrow ridges correspond commonly to closely developed horsts; they have steep, normal-fault-bounded slopes. The remnants of the erosional surfaces have been elevated above these horsts, therefore, commonly they have flat tops.

Altitudes of the morphological features in the western and eastern parts of the Bursa-Balıkesir plateau also are different. The average height of the plateau in the west is about 300–350 m high. The exception to this is Kazdağ Mountain rising steeply to a height of 1750 m due to the oblique fault systems, which opened the Edremit Gulf (Fig. 8) (Yılmaz et al., 2000). In the eastern areas, however, the average elevation is about 800 m (Fig. 8). The division between the two sectors corresponds to a major structural axis, a hinge line, a tectonic bend, which formed as a result of the westerly motion of the Anatolian Plate. This induced an E–W shortening deformation when it met resistance in the Greece–Balkan Domain (Şengör, 1979). This

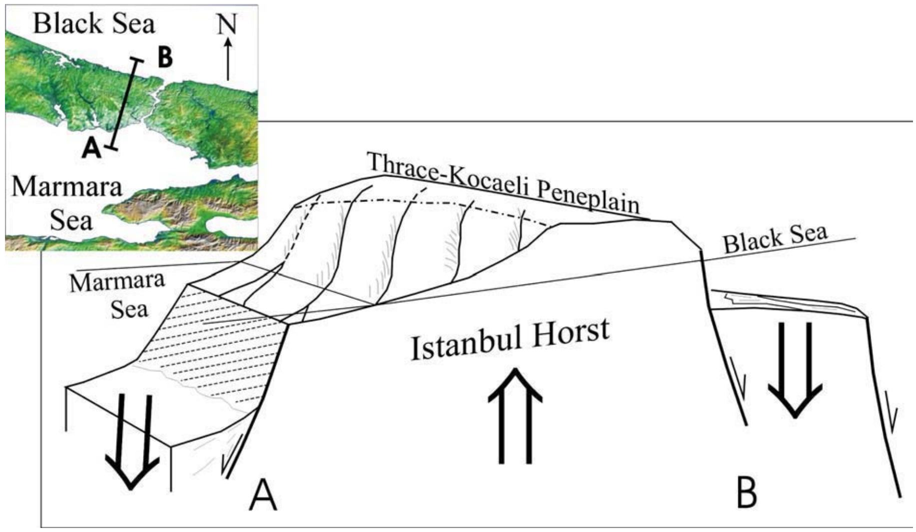


Fig. 9. Cartoon showing schematic block diagram view of the structural nature of the Istanbul Region, which is presently deformed between two oblique slip faults acting as a boundary faults to the two surrounding seas, the Black Sea and the Marmara Sea. This block has been elevated as a horst and forced to rotate in anti-clockwise sense. The remnants of the peneplain on the horst, and major trends of drainage pattern, formed as a result of the anti-clock-wise rotation of the block are displayed. Full arrows indicate vertical component of the displacements (after Yılmaz, 2007, Fig. 10).

obstacle prohibited its further westerly advance, and caused its anti-clockwise rotation to move in a southwesterly direction above the Hellenic Trench (Şengör and Yılmaz, 1981). The anti-clockwise rotation is a relatively young event, confined to the last 2–3 ma periods, according to the paleomagnetic data (Piper et al., 2010).

The GPS vectors display different directions and rates of motion in the eastern and western parts of the plateau (inset of Fig. 8). The eastern part of the plateau (Fig. 8, zone B) moves east to west, while the western part (Fig. 8, zone A) moves northeast to southwest. These are reflected also in the trends of the changes in the strikes of the faults that are clearly linked with the anticlockwise rotation of the Anatolian Plate in the Aegean Region, and the related stress regime that such changes have generated (Straub, 1996; McClusky et al., 2000). In the eastern sector, located at the tip of central-western Anatolia, Barka and Kadinsky-Cade (1988) and Yaltırak (2002) have stressed the presence of major NW–SE trending faults. The lineaments reflecting linear topographic features of regional extent; i.e. the crest lines, valleys etc. that are also aligned NW–SE. These trends correspond to the major structural features such as folds and faults and control the drainage of the eastern part of the Bursa-Balıkesir Plateau (Fig. 8).

The coastlines along the southern Marmara Sea correspond to the northern part of the Bursa-Balıkesir Plateau where there are two distinctly different morphological features: a) in the east, a high coast morphology dominates. It is characterized by steep slopes running parallel to the coast (Fig. 8, zone D). The streams also run sub-parallel to this high coast, and flow in an E–W direction a long way before reaching the Marmara Sea. b) In the west, there is a low coast where the stream valleys reach the Marmara Sea in the shortest distance possible (Fig. 8). The geometry of the Gönen and Biga basins, situated in the west of the Bursa-Balıkesir Plateau, displays an en-echelon pattern. They both elongate in a NE–SW direction. A ridge extending in the same direction divides the two depressions. Such trends and the geometrical pattern that they formed are reminiscent of the depressions and the ridges seen in the Marmara Sea. The Manyas and Ulubat lakes are situated within the flatland bounded by two structural highs; the Southern Marmara High in the north and the major regional elevated terrain in the south. The thin and long fault-elevated northern high has dissected the direct connection of the flatland with the Marmara Sea. Within the flatland the erosion has further carved and obliterated the marker erosional surface.

2.4. The North Anatolian Fault Zone

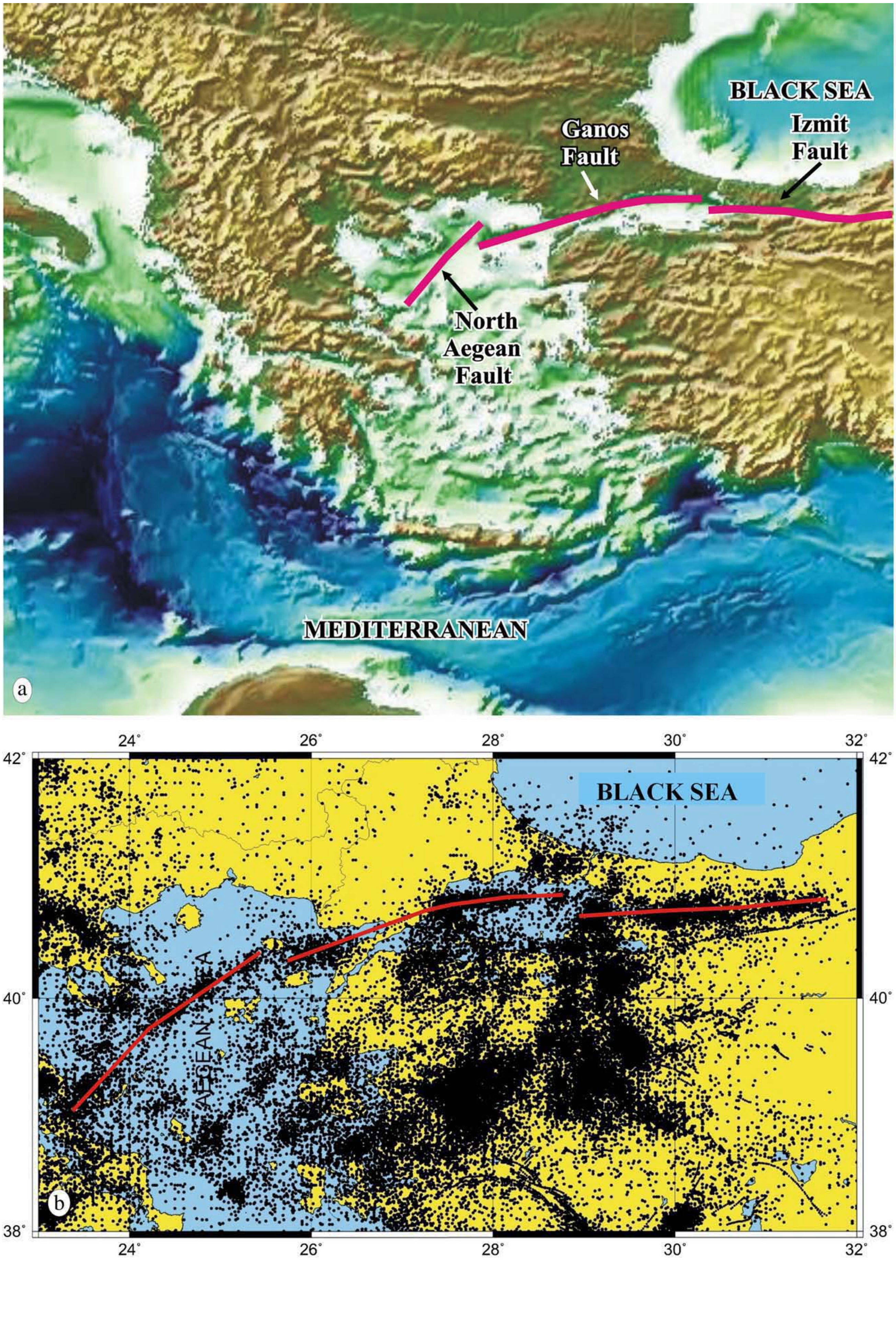
The NAFZ is the major structural element of the Marmara Region. In the eastern part of the region, the NAFZ splits into two major branches (inset of Fig. 1). The northern branch follows a trend along Sapanca Lake. Entering into the Izmit Gulf (Fig. 1), it is buried under the waters of the Marmara Sea (Fig. 8). The southern branch extends along the Dokurcun valley, and the southern side of Iznik Lake as one segment (inset of Fig. 1) before entering the Marmara Sea through the Gulf of Gemlik (Fig. 8). In the southern part of Iznik Lake, the southern branch splits to form a third segment (Figs. 1 and 8). Further west there is not one continuous strike-slip fault. Instead, there are a number of short segments (<20 km) dispersed throughout the Biga Peninsula (Fig. 8). These may be interpreted as the fanning of the NAFZ in the region. Of the three branches, the presently more active branch is the northern branch, cutting across the basins E–W (Fig. 8).

2.4.1. The northern branch of the NAFZ

Before entering the Marmara Sea, the northern branch of the NAFZ is observed as one continuous fault segment. Under the sea, the continuation of the NAFZ may be traced clearly by the seismic and bathymetric data, which collectively reveal that it extends along the steep northern slope delimiting the northern shelf (Fig. 8). Such a steep and deep (>1000 m) slope corresponds to the fault plane.

Along its length, the NAFZ has generated a number of thin and long depressions on land as well as in the sea, such as the Bolu Depression, the Izmit Gulf, and the sub-basins in the Marmara Sea Basin. It cuts across Ganos Mountain in the Gelibolu Peninsula and reaches the Saros Gulf in the Aegean Sea (Fig. 8) (e.g. Şengör, 1979; Şengör et al., 1982a,b; Okay et al., 1999; Yaltırak and Alpar, 2002; Şengör et al., 2005; Ustaömer et al., 2008). Within the Saros Gulf, the southwesterly elongation of the NAFZ is revealed also by the seismic and bathymetric data (Ustaömer et al., 2008). The fault zone known as the North Aegean Fault Zone, defining the northeasterly trending sharp boundary of the northern Aegean Basin, is located along the same trend as the NAFZ (Fig. 10a) (Papanikolaou et al., 2002).

Fig. 10. a) Major segments of the northern branch of the NAFZ in northwestern Anatolia, in the Marmara and the Aegean Seas. b) Seismicity map of the Marmara Region (modified after Ustaömer et al., 2008).


BLACK SEA
Ganos Fault
Izmit Fault
North Aegean Fault
MEDITERRANEAN
a
24° 26° 28° 30° 32°
42° 40° 38°
BLACK SEA
b

2.5. The middle and southern branches of the NAFZ

There is comparatively little data on the middle and southern parts of the Marmara Sea and on the branches of the NAFZ in these areas. In the offshore region of the southern part of the Marmara Region, Kurtuluş and Canbay (2007) have used seismic data to demonstrate that the middle branch of the NAFZ is also an active fault branch (Fig. 8). This fault is observable on the adjacent land areas due to the clear morphological and structural evidence (Fig. 8). Entering the sea along the Gemlik Gulf (Fig. 8), it extends sub-parallel to the southern shore line. Before reaching the Bandırma Gulf the strike of this fault changes to NE–SW. Kavukçu (1990) has shown, using seismic data, the presence of a set of sub-parallel NE–SW trending faults, bounded by two NW–SE trending major strike-slip faults in the Bandırma Gulf. Barka and Kuşçu (1996), in analyzing the data available prior to the 1999 earthquake from the Gemlik and Bandırma gulf areas, reached the conclusion, which is similar to that of the northern branch of the NAFZ, that the fault zone displays an en-echelon geometry, and has formed a set of small pull-apart basins.

The role of the middle and southern branches of the NAFZ on the morphology of the southern shore region and on the surrounding land areas has been analyzed recently by Gürer et al. (2003, 2006). They demonstrated that the NE–SW trending faults, related to the NAFZ, control the regional morphology (Fig. 8). Of these faults, the NE–SW trending ones are right-lateral strike-slip in character. The E–W trending faults, on the other hand, form two groups: the big, listric faults are older, and are cut by the strike-slip faults (Fig. 1). The other group is small in extent, connecting the strike-slip faults, and has been formed coevally along with the associated strike-slip faults (Barka and Kadinsky-Cade, 1988).

There is no decisive age data for the development of the NAFZ in the Marmara Region. Therefore a wide spectrum of age estimates has been previously proposed. They vary from the late Miocene (Armijo et al., 1999) to early Pliocene (Barka and Kadinsky-Cade, 1988). However studies after the August 17, 1999 earthquake using new data have led to proposals of much younger ages, i.e. 200 ka (İmren et al., 2001; Le Pichon et al., 2001; Gökaşan et al., 2001; 2003; Dolu et al., 2007).

2.6. The Armutlu and Ganos highs

The Marmara Sea is delimited along both ends of its long axis by two linear mountain ranges: the Armutlu and Ganos highs (Fig. 1). They are situated within the NAFZ and bounded and cut by the fault branches (Fig. 8). Therefore, both highs have clearly undergone a coeval evolution with the NAFZ.

The Armutlu High, between the northern and southern branches of the NAFZ, is partly separated from the land and forms a peninsula known as the Armutlu Peninsula (Figs. 1 and 8). The northern slope is steep along an oblique slip fault with a significant vertical component (Fig. 8). The southern slope is gently inclined and flattened at the top of the mountain. Between the two major branches of the NAFZ, the Armutlu Peninsula may be regarded as an elevated and southward-tilted fault block. The stratigraphic records on the rise of the Armutlu Peninsula as a fault-bounded “pressure ridge” are also confirmed by the seismo-stratigraphic data, which reveals that the faults having reverse slip components post-date the early Pliocene (Yılmaz et al., 1989). This is because the upper Miocene–lower Pliocene transitional limestone sequence and the erosional surface that lies above this have been cut and offset by the oblique-slip faults. The Armutlu High is surrounded along both sides by two structural depressions in which are placed the Izmit Gulf to the north and Iznik Lake and the Gemlik Gulf to the south (Fig. 8).

The Ganos High of the Gallipoli Peninsula (Fig. 1) is a long and narrow ridge, located on the western end of the Marmara Sea extending along the northern branch of the NAFZ in the NE–SW direction (Figs. 1 and 8). The narrow peninsula rises steeply to over 900 m in the west and 1200 m in the east. The GPS vectors are parallel to the trend of the Gallipoli Peninsula (inset of Fig. 8). This reveals that the extent and elongation of the morphological features are in close harmony with the motion of the Anatolian Plate. The Ganos High is viewed as corresponding to the restraining bend of the plate formed in response to its southwesterly rotation (Şengör, 1979; Şengör et al., 1985).

3. Discussion and conclusions

3.1. The morphotectonic development of the region

The early phase of the morphotectonic evolution of the Marmara Sea region is similar to the evolution of western Anatolia. In essence it incorporates the period of the erosion, which initially formed the peneplain first. This was followed by the fragmentation of this erosional surface. Emre et al. (1998) state that western Anatolia suffered a hot and humid climate during the middle-late Miocene period. Therefore, they claim that the age of the erosional surface corresponds to this era. This view is only partly correct according to the data obtained from the extensive field works covering the Aegean and the Marmara regions (Yılmaz et al., 2000). According to the data, the erosion took place over a long period: from the late Oligocene till the end of the late Miocene. During this period, a number of erosional surfaces were developed, and they have been superimposed one upon the other (Yılmaz, 2007, 2008). The denudation has affected all of western and northwestern Anatolia (Gökaşan et al., 1997; Emre et al., 1998; Demirbag et al., 1999; Yılmaz et al., 2000; Elmas, 2003; Yiğitbaş et al., 2004; Gökaşan et al., 2005; Yılmaz, 2007; Tur, 2007; Dolu et al., 2007; Gökaşan et al., 2008).

Following the establishment of the peneplain two major events occurred:

a- The N–S extension
b- The NAFZ.

The N–S extension began effectively from the end of the late Miocene and continued to the present (Şengör and Yılmaz, 1981; Yılmaz et al., 2000). The products of the extension are seen from the Balkan Region in the north (Burchfield et al., 2000) down to the Mediterranean in the south (Yılmaz et al., 2000). Under the N–S extension, western Turkey and the Aegean Region began stretching N–S. This created a number of grabens intervened by thin and long horsts (Fig. 8). These are also extensively observed on the Bursa-Balıkesir Plateau (Fig. 8). The horsts are tightly developed as the long ridges or the mountain ranges separated by lowlands (Fig. 8). The boundaries of the horsts are commonly normal faults. These horsts have flat-tops. The fragments of the peneplain have been elevated on the horsts.

The opening of the Marmara Sea Basin also began during this phase. The sedimentological evidence for this is the following: the upper Miocene–lower Pliocene low energy lacustrine sequences pass laterally and transitionally to marine sediments in and around the Marmara Sea. This indicates that the Marmara Sea region subsided gradually with respect to the surrounding land. The fossil assemblages, obtained from marine sediments, reveal that water connection occurred between the Black Sea and Aegean Sea realms for the first time during this period, following a long period of cessation (Elmas and Meriç, 1998). The detailed sedimentological studies across the region have displayed that a narrow sea connection occurred along the present axis of the Marmara Sea at this period (Görür et al., 1997; Elmas and Meriç, 1998; Dolu et al., 2007).

The major, approximately E–W striking normal faults are extensively observed on both sides of the Marmara Sea on the land (Yılmaz et al., 2000) as well as in the sea areas (Figs. 1 and 8)(İmren et al., 2001; Le Pichon et al., 2001; Gökaşan et al., 2003). They display curvilinear map patterns (Figs. 1 and 5) which reveal their listric nature. Seismically these faults are not as active today as the strike-slip faults (Fig. 10b). The structural and stratigraphical data reveal that while the center of the Marmara Basin was subsiding, the surrounding areas have gradually elevated to form plateaus. The subsidence of the central part of the basin and the elevation of the two surrounding regions have continuously evolved during the progression of the N–S extensional regime. This formed the initial morphological pattern of the region. This phase lasted uninterruptedly until the effects of the North Anatolian Fault Zone began.

The Marmara Sea itself has long been known to be a structural depression (Fig. 11a; Ketin, 1968; Şengör, 1979; Barka and Kadinsky-Cade, 1988; Wong et al., 1995; Smith et al., 1995; Armijo et al., 1999; Aksu et al., 2000). Development of the Marmara Basin followed two different phases under different tectonic regimes. During the early phase under the N–S extension a normal fault controlled wide basin was formed. This basin covered much larger areas than the present limits of the Marmara Sea, extending from the present Thrace Basin in the north down to the Bursa-Balıkesir Plateau in the south. The basin was fairly shallow with the exception of the central part as evidenced by the deposition of shallow marine sediments (Fig. 3). This phase was followed by a right-lateral shear regime, which initiated in eastern Anatolia and began gradually penetrating into the northwestern Anatolia (Şengör et al., 1985). This is intimately related to the initial phase of development of the NAFZ. Some of the normal faults that had already formed were captured by strike-slip faults which were generated during this period. A new set of right-lateral strike-slip faults also began to develop at this period. They led to the development of a number of small pull-apart sub-basins within the Marmara Basin (Barka and Kadinsky-Cade, 1988). They were gradually enlarged and rotated in clockwise sense, during the progression of the shear regime. These sub-basins and the intervening ridges have collectively been oriented NE. As a result of such an arrangement, a tectonically controlled large basin and a number of smaller and deeper sub-basins developed. Prior to the 17 August earthquake, this view was commonly adopted by geoscientists, and it is still viewed by some as a more plausible model. The 17 August 1999 earthquake and consequent studies have provided rich data enabling the analysis of its kinematic development (Okay et al., 1999, 2000; Emre and Awata 2003). Therefore, some other models have been proposed in light of newly-derived data (Fig. 11b–h). The Turkish Navy Department of Navigation, Hydrography, and Oceanography, MTA SİSMİK-I research vessel and the French Oceanography Institute “IFREMER” carrying out seismologic, seismic and multi-beam bathymetric studies illuminated the sea bottom geometry and crustal properties considerably, and thus have contributed to a better evaluation of the previously proposed models. For example, the bathymetric data have demonstrated clearly that along the extension of the NAFZ there is one continuous lineament stretching ENE–WSW from the Ganos Mountain in the west to Büyükçekmece in the east (Fig. 11c–h) (Okay et al., 1999, 2000; İmren et al., 2001; Le Pichon et al., 2001; Gazioğlu et al., 2002; Armijo et al., 2002; Yaltırak, 2002; Carton, 2003; Demirbag et al., 2003; Gökaşan et al., 2003; Rangin et al., 2004; Sato et al., 2004; Armijo et al., 2005; Şengör et al., 2005; Carton et al., 2007; Bécel et al., 2009; Laigle et al., 2008).

The results of bathymetric and seismic studies together with the distributions of the earthquake epicenters reveal that the active tectonics of the Marmara Sea are primarily controlled by the fault zone of the NAFZ (Gürbüz et al., 2000; İmren et al., 2001; Gazioğlu et al., 2002; Gökaşan et al., 2003; Şengör et al., 2005). Other faults, which define the northern and southern boundaries of the sub-basins of the Marmara deep basin, display little seismic activities compared to the NAFZ. The data also display that the NAFZ cuts and offsets the other faults and is thus younger (İmren et al., 2001; Gökaşan et al., 2001; Le Pichon et al., 2001; Gökaşan et al., 2002; Gazioğlu et al., 2002; Gökaşan et al., 2003; Rangin et al., 2004; Şengör et al., 2005; Ustaömer et al., 2008). The studies carried out on the eastern and western edges of the Marmara Sea clearly demonstrate that the NAFZ extends to these margins. In the eastern part of the Marmara Sea the combination of field, seismic, and bathymetric data have also demonstrated collectively that the NAFZ extends continuously within the Izmit Gulf as a single fault zone (Gökaşan et al., 2001; Emre and Awata, 2003; Dolu et al., 2007). It cuts across the NW and NE trending oblique faults before reaching the Çınarcık Basin. From there on, the question remains: a) whether the NAFZ extends along the southern slope of the Çınarcık Basin (Fig. 11e) (Armijo et al., 2002; Carton, 2003; Armijo et al., 2005; Carton et al., 2007) or b) along the axis of the basin (Fig. 11c, f–h) (İmren et al., 2001; Gökaşan et al., 2002; Yaltırak, 2002; Gökaşan et al., 2003; Ateş et al., 2003). Some also claim that c) the NAFZ follows the northern slope of the Çınarcık Basin (Fig. 11b,d) (Okay et al., 2000; Le Pichon et al., 2001; Rangin et al., 2004; Şengör et al., 2005). On the other hand, Barka and Kadinsky-Cade (1988), Yaltırak (2002), Armijo et al. (2002, 2005) and Ateş et al. (2003) think that d) the northern slope of the Çınarcık Basin is more like a normal fault rather than a strike-slip fault (Fig. 11a, e, f, h).

There is no precise age data for the first appearance of the NAFZ in NW Turkey. It is known that in the western Anatolian and the Aegean regions it post-dates the initiation of the N–S extension, and therefore is younger than the early Pliocene (Yılmaz et al., 2000). However, this subject remains controversial today only for the Marmara Region for the following reason: after its entrance, the development of the NAFZ has passed through different stages. According to Şengör et al. (2005), it is the NAFZ which is solely responsible for the development of the Marmara Sea Basin. The NAFZ, when it first reached the Marmara Region, began affecting very extensive areas as a wide shear zone. This zone, fanning westward, covered all of NW Anatolia. The faults of this period were characterized as oblique slip faults having strike-slip and dip-slip components. Therefore, the faults of this period are not easy to distinguish from the normal faults formed under the N–S extensional regime of the previous phase. Şengör et al. (2005) claimed that the Marmara Sea Basin began to form during this period. Following the phases of development, the right-lateral shear zone of the NAFZ has gradually narrowed and the strike-slip components of the younger faults have become more prominent. The shear zone finally generated one single major strike-slip fault zone, extending approximately in an E–W trend. It cuts across the previously formed faults. The various stages of fault development that are described above may be seen as analogous to the evolution of a shear system as described in the literature (Tchalenko, 1970).

As seen from the alternative views summarized above, the northern steep and deep boundary fault of the Marmara Sea Basin has been interpreted as a) the dip-slip component of the NAFZ, or b) the NAFZ has taken up the previously-formed normal fault and reactivated this fault as a strike-slip fault.

As a very narrow fault zone, the NAFZ began acting as a plate boundary and therefore separated the region into two different sectors: the northern and southern sectors. As a plate boundary, the NAFZ formed a barrier to the N–S extension, saving the northern sector from the effect of the extension. Therefore, under the influence of the NAFZ the two regions, the northern sector, the Istanbul Region and the southern sector the Bursa-Balıkesir Plateau; have suffered different kinds of deformation and consequent morphological evolution. In the southern sector, the westward escape of the Anatolian Plate met with resistance in the Western Aegean-Balkan Region, where the old and stabilized crustal blocks prohibited its further westerly motion creating E–W compression in the northern Aegean Region. Therefore the Anatolian Plate is forced to rotate southwesterly to move above the Hellenic Trench, which easily accommodates such movement (Şengör, 1979). As a result of this, although the rate of subduction of the eastern Mediterranean Ocean floor along the Hellenic Trench is only about 1 cm/year, the rate of total convergence is about 5 cm/year.

The E–W compression in the Bursa-Balıkesir Plateau has generated a regionwide E–W shortening deformation. This, in turn, has produced an “angle”; two convergent sets of lineaments that are clearly

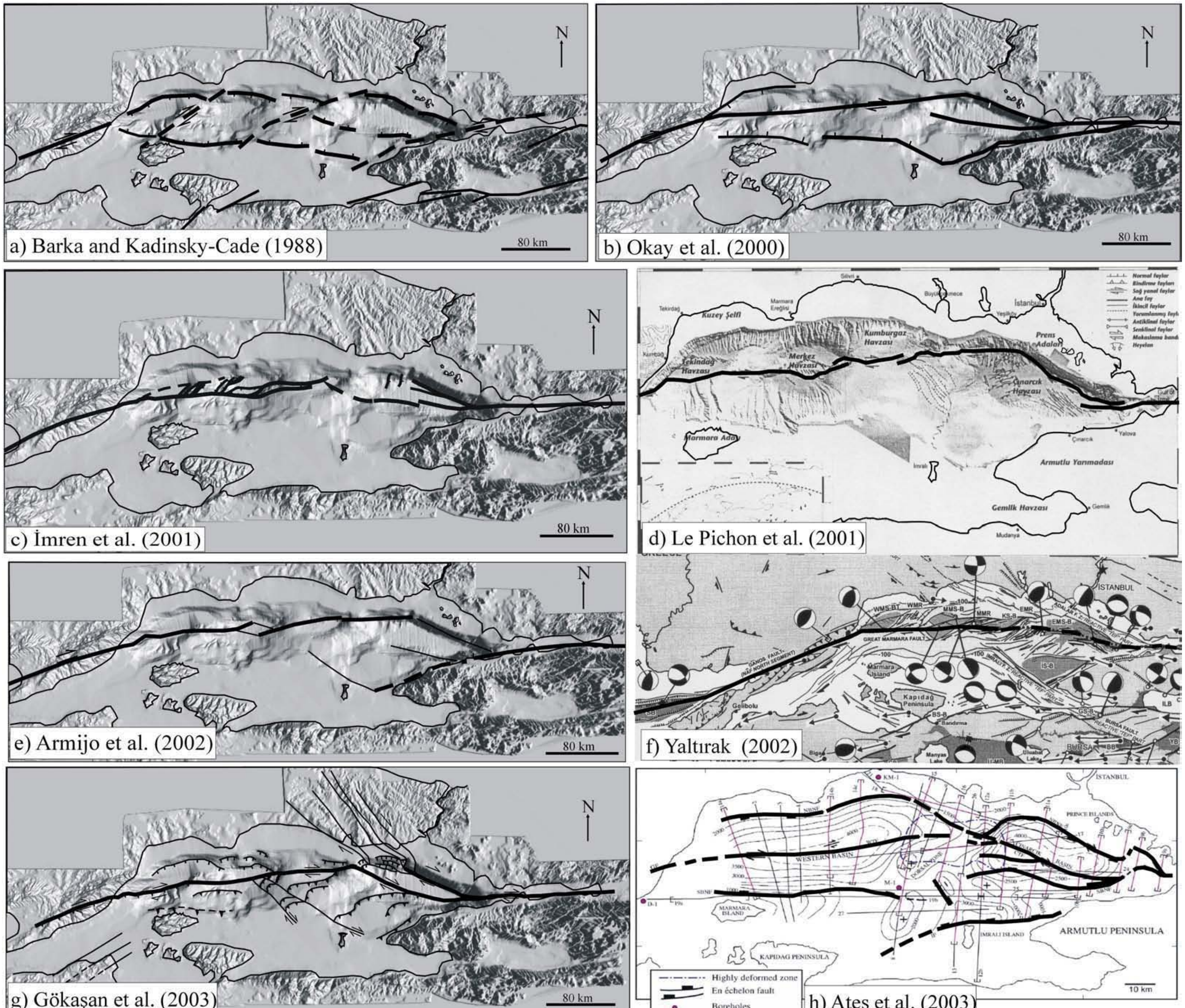


Fig. 11. a–h) Different tectonic-kinematic models, proposed on the location, extension, and development of the NAFZ in the Marmara Sea Basin.

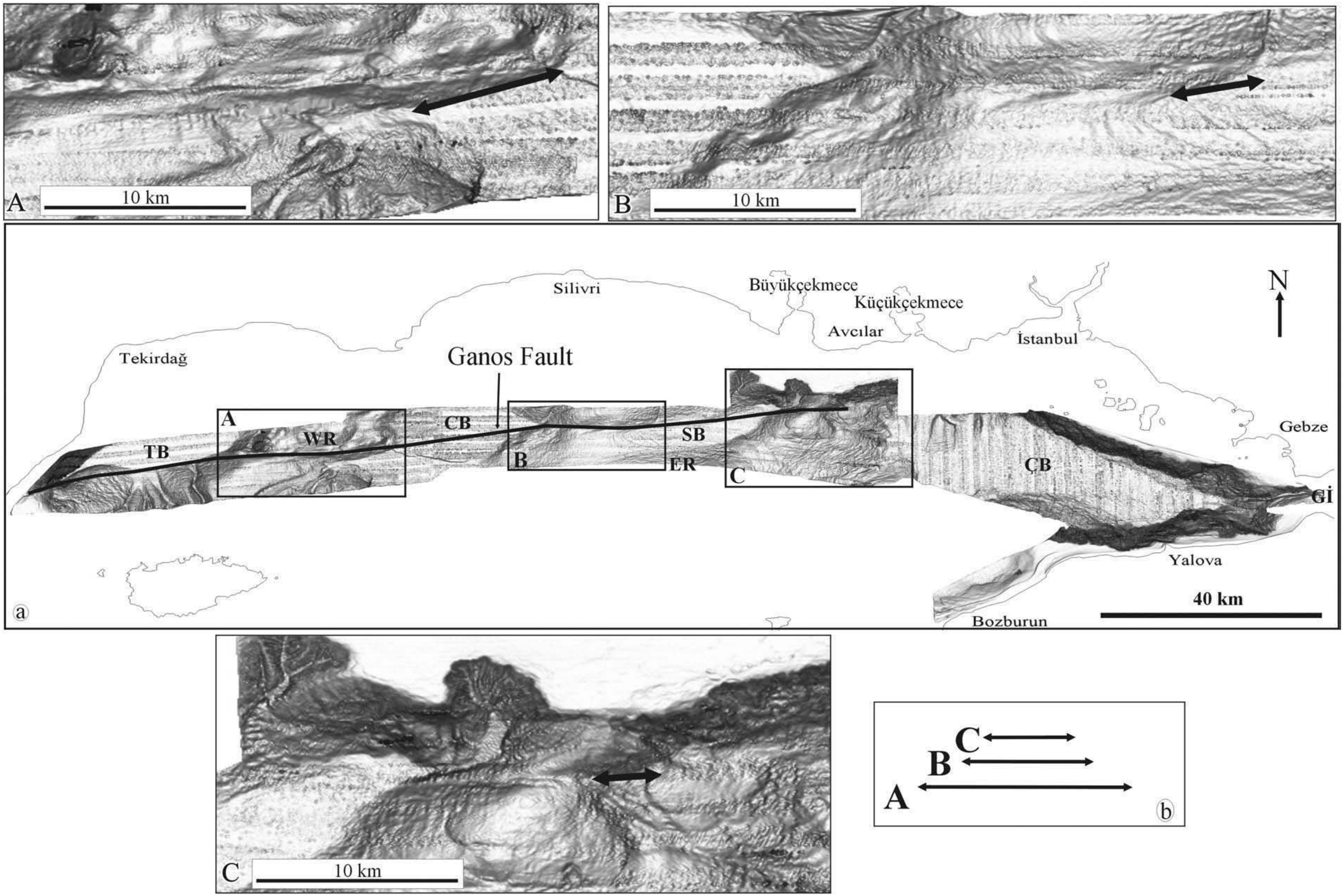


Fig. 12. a–c) Bathymetric map displaying significant decrease of the lateral offsets observed on the Ganos Fault of the NAFZ in the Marmara Sea Basin (see the caption of Fig. 1 for the abbreviations).

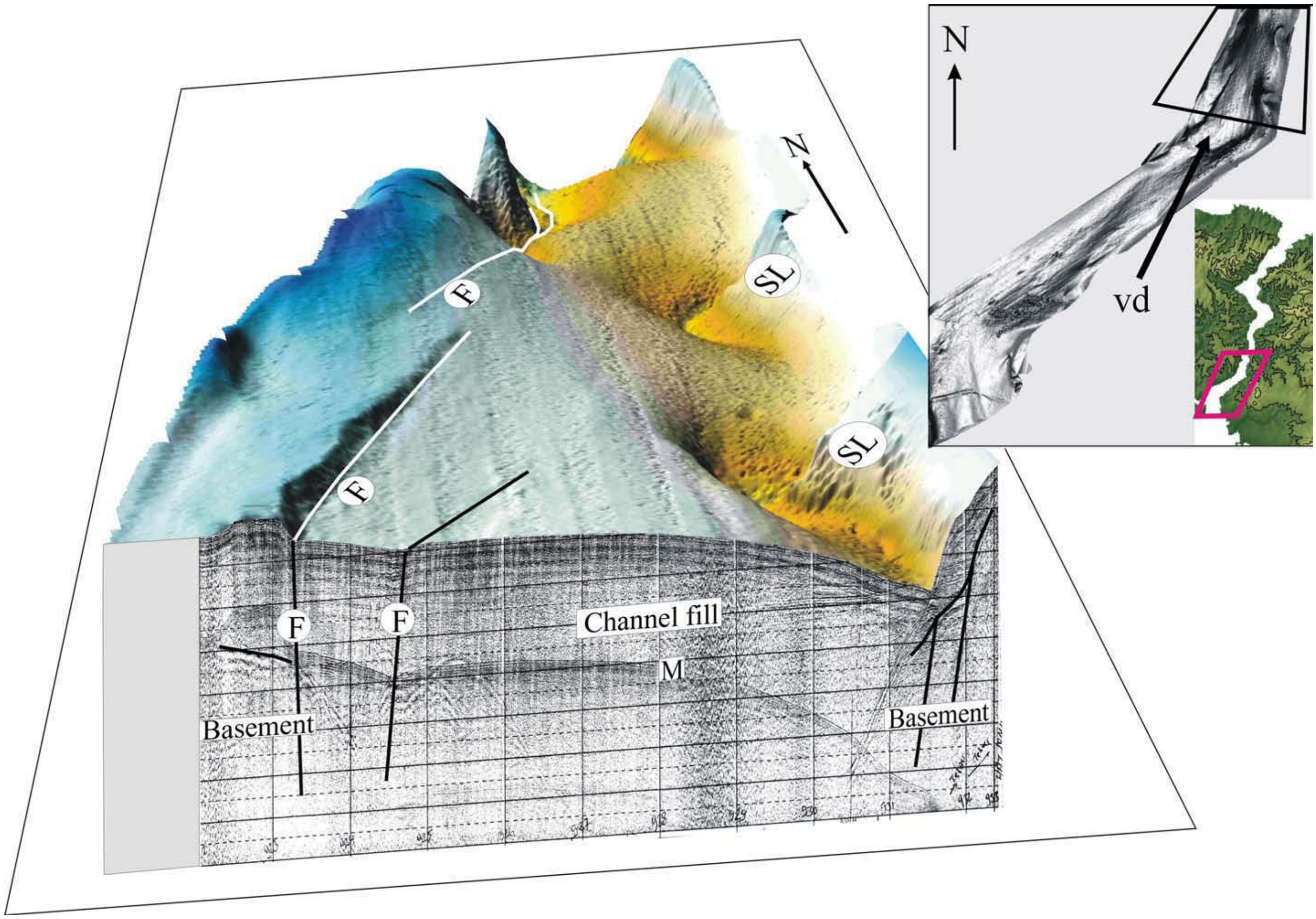


Fig. 13. 3D block diagram view of the southern part of the Bosporus channel, produced using bathymetric and seismic data. The meandering profile of the ancient river valley is seen clearly. The faults apparently modified the initial smooth morphological pattern and have produced the sharply defined presently zigzagging pattern. Inset displays the location of the block diagram (modified after Gökaşan et al., 2006, Fig. 6).

observed in Figs. 5 and 8. These two sets of intersecting lines coincide along a major valley (Figs. 5 and 8) where two different rates of rotations are accommodated by a variety of structural features, wrench faults, folds, shear zones etc. As a result of this, the Bursa-Balıkesir Plateau has risen as a block, while the eastern sector has elevated more than the western sector (see Fig. 5 and the subareas A and B in Fig. 8).

Buried under the water of the Marmara Sea, the continuation of the NAFZ between the two edges is presently widely debated. According to some authors, the NAFZ extends edge to edge as a more than 200 km long single fault (Fig. 11) (İmren et al., 2001, Le Pichon et al., 2001; Gökaşan et al., 2003; Şengör et al., 2005). Others oppose this view and claim that the NAFZ consists of two or more fragments (Fig. 11) (Armijo et al., 2002;Carton 2003; Armijo et al., 2005; Carton et al., 2007). The available data demonstrate that the fault along the westernmost extension of the northern branch of the NAFZ, known as the Ganos Fault, extends to offshore of Küçükçekmece in the east as a single fault (Figs. 8 and 12). The amount of displacement along this fault decreases from the west to the east (Fig. 12a, b). This is seen clearly from the offsets observed in the ridges separating the sub-basins along the fault (Fig. 12a, b). Along the westernmost edge of the Çınarcık Basin, the offset is the smallest (compare detail maps A, B, and C in Fig. 12a). This location corresponds to the seismic gap observed in the earthquake epicenter map (Fig. 10b). This may lead to the interpretation that the Ganos Fault and the Izmit Fault, both sides of the NAFZ in the Marmara Sea region (Fig. 10a) do not adjoin as one continuous fault; they are not attached to one another as stated by Armijo et al. (2002, 2005). If this view is correct, then the northern branch of the NAFZ is composed of different fault segments, such as the Izmit Fault, the Ganos Fault, and the Northern Aegean Fault from the east to the west (Fig. 10a). This diminishing of the right lateral movement on the fault was alternatively explained by Yaltırak (2002) and Gökaşan et al. (2003) as transference of the dextral slip into compression along the eastern ridge.

3.2. Morphotectonic development of the Istanbul Strait (Bosporus)

On the development of the Bosporus different views have been proposed throughout the last century (see Yılmaz, 2007 for a review of the views). Most of the models proposed agree to some extent on the role of tectonics in the development of the Bosporus (Fig. 13) (Hochstatter, 1870; Sholten, 1974; Alavi et al., 1989; Yılmaz and Sakınç, 1990; Oktay and Sakınç, 1991; Yıldırım et al., 1992; Gökaşan et al., 1997; Demirbag et al., 1999; Oktay et al., 2002; Gökaşan et al., 2002, 2005, 2006; Yılmaz, 2007). For example, Oktay et al. (2002) suggested a block rotation mechanism for the structural development of the Istanbul Region and the Bosporus Strait. This is similar to the mechanism proposed for the pattern of deformation in the areas located between the two main faults of the San-Andreas Fault Zone by Dibblee (1977). According to this model, the Istanbul Horst has been tectonically squeezed between the NAFZ and the northern boundary fault; thus, it has been forced to rotate clockwise. Consequently, the Istanbul Plateau has been structurally divided into smaller blocks. The joining together of the NE–SW trending

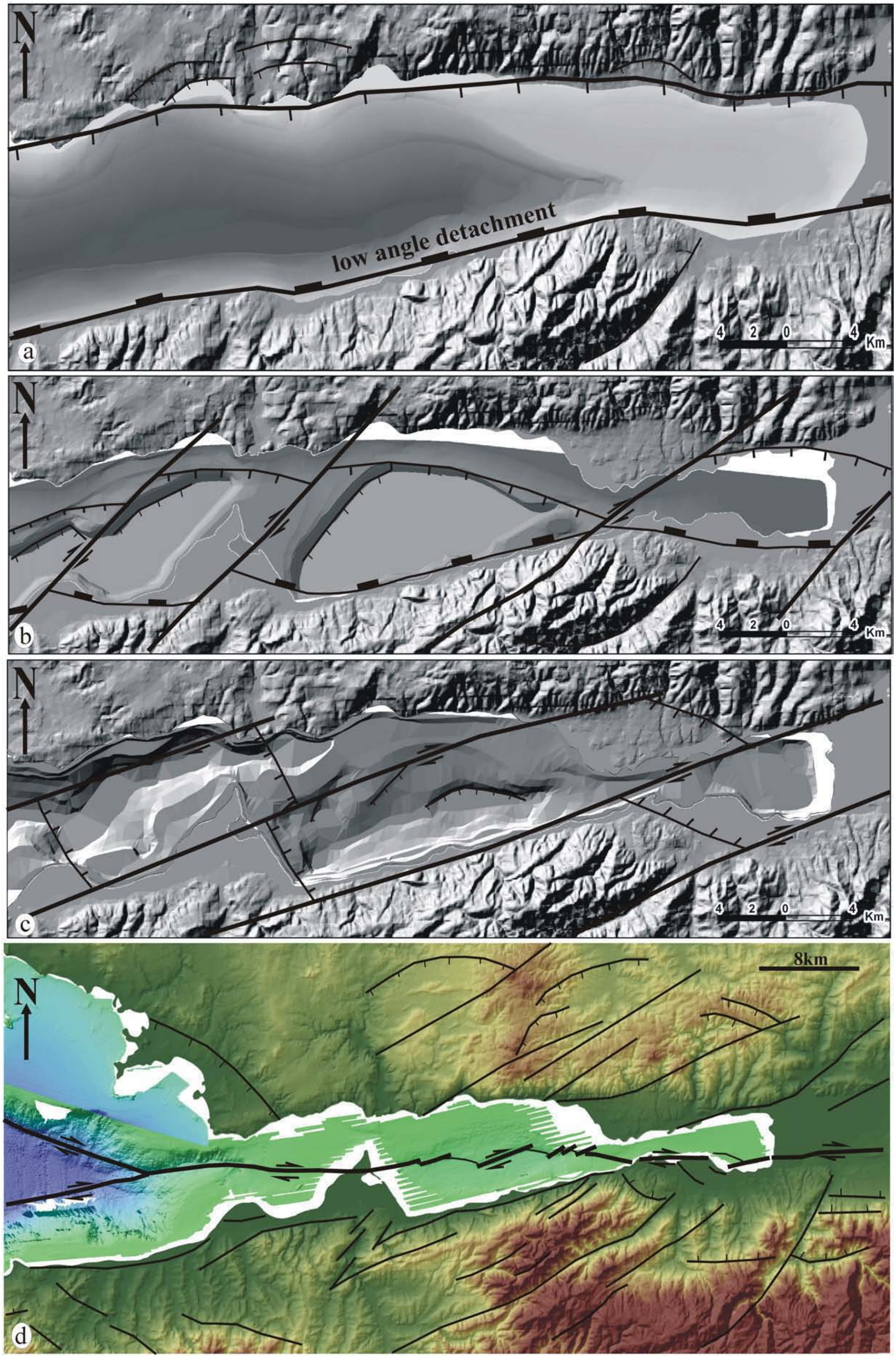


Fig. 14. a–d) Evolutionary stages of the İzmit Gulf (modified after Dolu et al., 2007, Fig. 19).

block-boundary faults has formed the Bosporus channel. Contrary to this view, Yılmaz (2007) suggested an anti-clockwise rotation mechanism. He argues that the morphological pattern and the NW trends of structural lineaments and the morphological entities accord well with the anti-clockwise rotation generated by the dextral shear.

Before the tectonic events, however, during the rather quiet period, when the peneplain was formed, meandering rivers existed in place of the Bosporus as the morphological data indicates. The water-divide extending across the Bosporus between Anadolukavağı and Rumelikavağı (Fig. 7) which separates two river valleys flowing to the Marmara Sea and the Black Sea extended to much larger areas to the north and the south than what they are today (Fig. 7) (Gökaşan et al., 1997). Pamir (1938) was the first scientist who recognized the two separate river valleys and the water-divide in the place of the Bosporus. The present pattern of the Bosporus appears to have inherited this profile (Fig. 7). The rise of the structural block as a horst and the consequent deep carving down along the river valley have left the ancient river valleys as hanging valleys with the low slope angle observable on both sides of the Bosporus (Fig. 4).

3.3. Morphotectonic development of the Izmit Gulf as an analogues model to the Marmara Sea Basin

The detailed, problem-oriented research study around the Izmit Gulf that we undertook in order to clarify the problems on the development of the Marmara Sea Basin, summarized above, produced new morphotectonic data. Together with the data derived from previous works this has collectively led us to propose the following model for the morphotectonic evolution of the Marmara Region. This model agrees well with the models proposed in different scales applying to the different parts of the region by Şengör et al. (2005) and Dolu et al. (2007).

a- E–W trending pure listric normal faults were generated during the initial stage (Fig. 14a). The basin began to open during this stage. The listric normal faults were formed under a N–S extensional regime and affected a much wider region than the present boundary of the structural depressions of the Marmara Sea. These listric faults are clearly observed in the bathymetric and the topographic map by their curvilinear map pattern from the strike-slip faults, which are straight (Figs. 1 and 5). As the extension continued, the depression gradually subsided and localized along the main axis of the basin. This view is supported by the presence of thick sediments, which have been deposited continuously above the upper Miocene–lower Pliocene transitional sequences (Parke et al., 2002; Okay et al., 2000; İmren et al., 2001; Gökaşan et al., 2003; Carton 2003). A considerably wide structural E–W trending depression bounded by the listric normal faults began to form during this initial phase (Fig. 14a). Today the morphological distinctions of the listric normal faults are not as significant as the strike-slip faults.

b- The strike-slip faults began to form during the ensuing phases (Fig. 14b–d). They trend dominantly in the NW and NE directions. Thus, they align obliquely to the main axis of the Marmara Basin. These faults form en-echelon patterns. As a result of this, a number of adjacent pull-apart sub-basins developed (Fig. 14b). The oblique slip faults of the pull-apart basins cut and offset the previously formed listric normal faults.

c- During the progression of the shear regime, the oblique-lying pull-apart sub-basins were flattened by the generation of newly-developed, ENE–WNW trending strike-slip faults (Fig. 14c). They make acute angles with the main axis of the basin (Fig. 14c).

d- In the latest stage, the shear regime was concentrated in a narrow zone and flattened the sub-basins. Extending as one narrow strike-slip fault zone, the NAFZ displays an amostomising pattern (Fig. 14d). This fault zone presently extends along the main E–W axis of the Marmara Sea.

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