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Neotectonics of the southeast Marmara region, NW Anatolia, Turkey

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Abstract

The North Anatolian Fault Zone (NAFZ) bifurcates into three branches in the Marmara Region, which is a transition zone between the strike–slip tectonics manifested by the NAFZ and the N–S directed extensional regime of western Anatolia. The southern Marmara region is characterized by the middle and the southern branches while the northern branch controls the north Marmara region. The south Marmara region is characterized by approximately E–W trending rhomb-like horst and graben complexes bounded by strike slip-faults with normal component, striking mainly in E–W direction. This study documents the geometry and the structural characteristics of the NAFZ in the southeast Marmara region and discusses the commencement age of the strike–slip tectonics using deformation patterns of Neogene units and information available in the literature.

Keywords: Marmara sea; Neotectonics; North Anatolian fault zone; Extensional regime

1. Introduction

Turkey has suffered two severe earthquakes that occurred along two segments of the North Anatolian Fault Zone (NAFZ) on 17 August 1999 (Mw 7.4) and 12 November 1999 (Mw 7.1). More than 20,000 people were killed and over 100,000 people were injured and/or lost their homes and property. The extent of the damage was mainly due to the dense population of the region. A very severe (Mw > 7) earthquake is expected in the Marmara sea region within the next 30 years, which endangers the city of Istanbul, where over 10 million people live.

The NAFZ is a dextral intra-continental transform fault zone extending from the Karlıova triple junction, where it meets the sinistral east Anatolian transform, to the Saros Gulf in western Turkey (Fig. 1). West of the Saros Gulf the NAFZ becomes extension dominated and along the north Aegean trough it extends further west to mainland Greece (Dewey and Şengör 1979; Lybéris, 1984; Barka, 1992; Yaltirak, 2000; Görür et al., 1997; Tüysüz et al., 1998; Okay et al., 1999, 2000; Anastasia and Louvari, 2001).

The current tectonics of northwestern Turkey are controlled mainly by the interaction of (1) an extensional tectonic regime which causes N–S extension of western Anatolia and the Aegean Sea area and (2) the strike–slip tectonics exerted by the NAFZ. The former is effective in a broad zone from Bulgaria in the north to the Hellenic trench in the south (McKenzie, 1972). The mode and commencement ages of the extensional and the strike–slip tectonic regimes are important elements in understanding the development ages and mechanisms of the basins in the Marmara sea region. According to Seyitoğlu and Scott (1991) the extensional regime in west Anatolia started in the early Miocene and has been continued. In contrast, according to Koçyiğit et al. (1999) and Bozkurt (2000, 2001, 2002) the extensional regime in western Anatolia is episodic and has been active since the early Miocene but was interrupted by a period of compression that took place in the Early Pliocene. Yılmaz et al. (2000) propose that the N–S trending grabens are older than the E–W trending grabens and that the N–S basins were formed under an E–W extensional regime beginning during the early Miocene, whereas the present day E–W trending grabens developed during Late Miocene by another extensional regime in NE–SW direction. There is general agreement that the commencement age of the NAFZ is post-middle Pliocene (Koçyiğit, 1991; Şaroğlu, 1988; Barka and Kadinsky-Cade, 1988; Bozkurt, 2000, 2001; Ünay et al., 2001). Therefore these two tectonic regimes are mutually independent.

Morphologically the NAFZ forms a relatively deep and narrow fault zone extending from Karlıova in the east to

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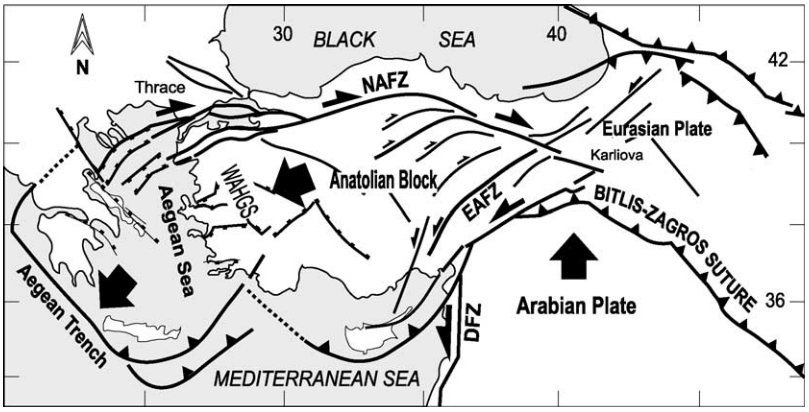

Fig. 1. Tectonic outline of Turkey and eastern Mediterranean area. DFZ: Dead sea Fault Zone, EAFZ: East Anatolian Fault Zone, NAFZ: North Anatolian Fault Zone (Modified from Dewey and Şengör, 1979, Şengör and Yılmaz, 1981).

the Marmara sea in the west (Fig. 1). To the west of Dokurcun (Fig. 2) the NAFZ splits into two branches. In the Marmara sea region, it is further divided into sub-branches forming a zone of distributed deformation more than 120 km wide (Şengör et al., 1985; Barka and Kadinsky-Cade, 1988; Koçyiğit, 1988). These branches are denoted from north to south as the northern branch, middle branch and southern branch (Fig. 2). The branching of the NAFZ is thought to result from the domination of the extensional regime gradually, from east to west, over the strike–slip regime (Şengör et al., 1985).

The Marmara sea is a 280 km long and 80 km wide marine basin located between the Black Sea in the north and the Aegean Sea in the south (Fig. 1). It lies along the NAFZ and has a broad shelf to the south and comprises three deep sub-basins in the north. Structurally the Marmara sea is divided into two parts, the northern and the southern parts (Fig. 3). The northern part is dominated by the northern branch of the NAFZ and comprises mainly three large basins: the Çınarcık basin, the Central basin and the Western basin (Barka, 1997; Le Pichon et al., 2000; Okay et al., 1999, 2000; İmren et al., 2001) each of which is more than 1100 m deep. These basins were thought to have formed due to right stepping of the NAFZ. Barka and Kadinsky-Cade (1988) discussed the segmentation and earthquake activity of the NAFZ in the Marmara sea region and proposed a series of en-echelon pull-apart basins for the Marmara sea to account for the kinematics of the sub-branches of the northern branch of the NAFZ. In contrast, Le Pichon et al. (2001a, b) have argued that the Çınarcık basin is a composite pull-apart basin while the other basins were formed as pull-apart basins prior to 200 ka and have currently lost their pull-apart character. They proposed that from the Çınarcık basin to the western shores of the Marmara sea (up to the Mürefte fault), the NAFZ is characterized by a single continuous fault strand and cuts through the basins along its course (namely the Central and Western basins, see Fig. 3).

In the southern Marmara Sea area, which is dominated by the middle and southern branches of the NAFZ, a number of basin complexes have developed (Fig. 3). In Gemlik Bay the middle branch enters the marine areas and in the bay

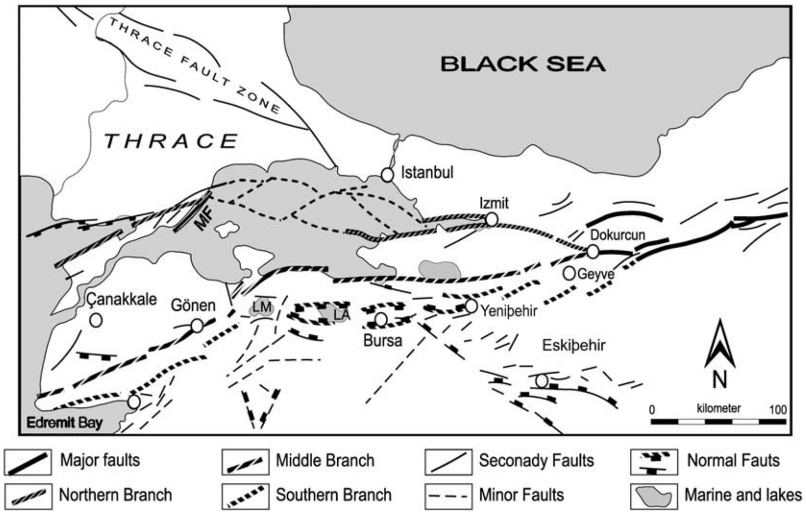

Fig. 2. Major neotectonic structures in the Marmara region (modified from references cited in the text). MF: Mürefte Fault, GB: Geyve Basin, LM: Lake Manyas, LA: Lake Apolyont.

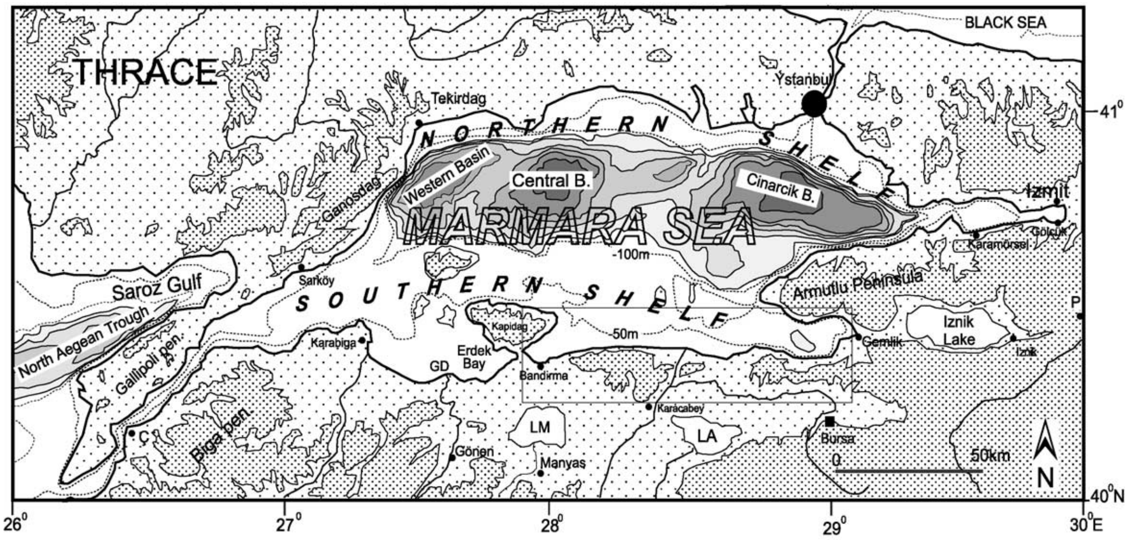

Fig. 3. Bathymetric and topographic map of the sea of Marmara region (modified from Smith et al., 1995). Below sea level, the bathymetric contours with intervals of 200 m are drawn as solid lines; the dashed lines are the 50 and 100 m bathymetric contours. The topography above 200 m is stippled. Ç: Çanakkale, P: Pamukova, LM: Lake Manyas, LA: Lake Apolyont, KD: Kocasu Delta, GD: Gönen Delta.

a number of approximately E–W trending faults with chiefly normal components dominate (Kurtuluş, 1985). According to the bathymetric map, obtained from high-resolution shallow seismic reflection profiling, the bottom of the basin is elongated in a NW–SE direction and the maximum water depth is about 120 m. Kavukcu (1990) recognized a complex pattern of faults in the Bandırma Bay area, where two sets of faults, trending NE–SW and E–W, dominate (Fig. 4). He argued that the basin collapsed inwards and is still active.

Current studies in the Marmara Sea region are concentrated mainly on the Northern branch of the NAFZ (e.g. Barka and Reilinger, 1997; Reilinger et al., 2000; Parson et al. 2000; Le Pichon et al., 2001a, b; Taymaz et al., 2001; Wright et al., 2001; Özalaybey et al., 2001; İmren et al., 2001) due to its possible seismic risk for the city of Istanbul.

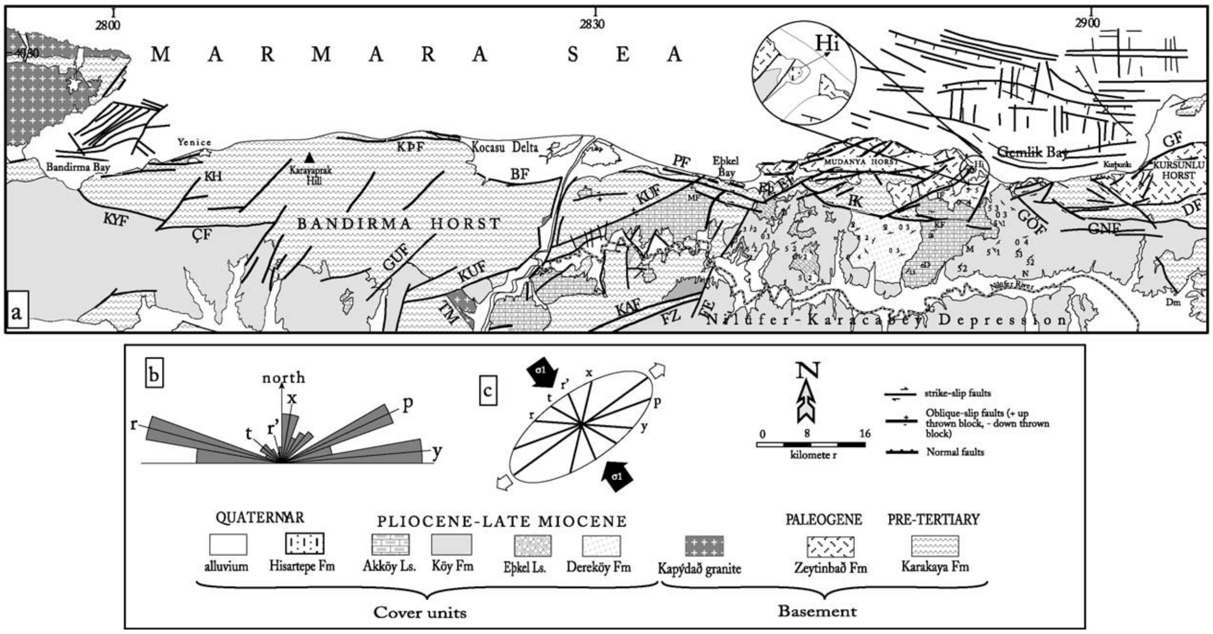

Fig. 4. (a) Simplified geological map of southeast Marmara region. The off-shore faults were compiled from KurtuluŞ (1985 and 1993). Y: Yörükali, Dm: DemirtaŞ, EŞ: EŞkel, Hi: Hisartepe, Ni: Nilüfer, KH: Karayaprak Hill, BF: Bayramdere fault, ÇF:Çakıl fault, DF: Dürdane fault, EF: EŞkel fault, GF: Gençali fault, GÖF: Göynüklü fault, GNF: Gündoğdu fault, GÜF: Güngörmez fault, IF: Işıklı fault, KAF: Karakoca fault, KF: Kaymakoba fault, KUF: Kulakpınar fault, KYF: Kayacık fault, MF: Mesudiye fault, PF: Papazharmanı fault, TM: TamŞalık fault, ZF: Zirafya fault. (b) Length weighted rose diagram prepared from fault traces and corresponding Reidel shears (adopted from Bartlett et al., 1981, Biddle and Christie-Blick, 1985). r: primary synthetic shear, r′: primary antithetic shear, p: secondary synthetic shear, t: extension fracture, x: secondary antithetic shear, y: principal displacement zone or master fault strand. Note the compatibility of the frequencies of the fault traces in the rose diagram with the Reidel shears.

In contrast, the number of studies in the southern part of the Marmara Sea and the middle and the Southern branches is limited. The nature and geometries of the faults in the marine areas have been partially interpreted using various numerical imaging techniques and marine geophysical measurements. However, there are few observations on land. Therefore this study documents the geological and stratigraphical features of the southeastern Marmara region on the basis of field observations to interpret the structural patterns and morphotectonics of the region.

2. Geology

Lithostratigraphical units exposed in the region range from Paleozoic to Recent. Mainly two different rock groups are distinguished in the area; (1) pre-Neogene basement and (2) the Neogene cover (Figs. 4 and 5). A very detailed description of basement units is outside the scope of this paper. They will be described briefly and the main emphasis will be given to Neogene cover units because of their relationships with the current structural grain of the region.

The major faults divide the region into east–west elongated horst–graben complexes. Among these the Bandırma Horst, the Mudanya Horst and the Kurşunlu Horst are the most prominent morphological features of the region (Fig. 4).

2.1. The basement units

The southern Marmara region has a complex geology with a wide variety of Paleozoic-Paleogene metamorphic, magmatic and sedimentary rocks. In basement rocks that include the Kapıdağ and Armutlu Peninsula, four distinct basement associations can be defined. The first rock succession is a metamorphic association known as the Karakaya Formation (Bingöl et al., 1973). The Karakaya Formation comprises various types of volcano-sedimentary

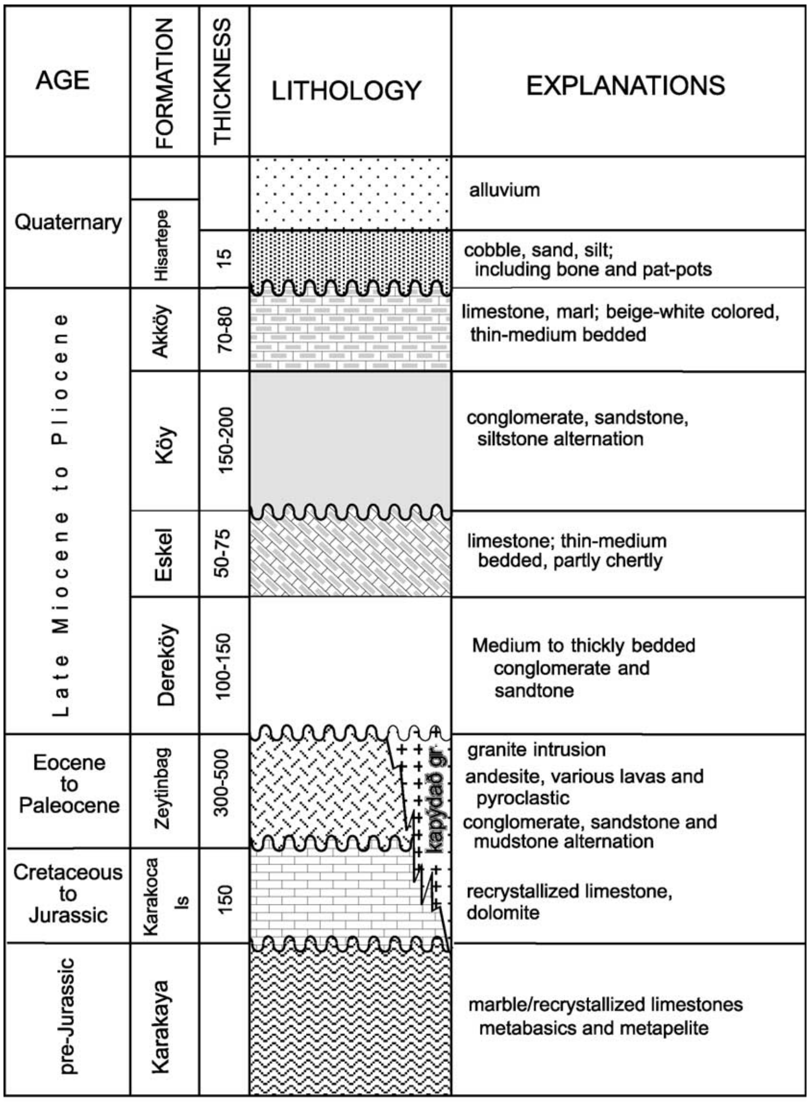

Fig. 5. Stratigraphic column for the southeast Marmara region.

units and tectonic blocks and has undergone very low-grade regional metamorphism during the latest Triassic times (Akyürek and Soysal, 1983; Koçyiğit, 1987; Koçyiğit et al., 1990; Genç and Yılmaz, 1996; Okay et al., 2000. Jurassic–Lower Cretaceous Karakoca limestone rests unconformably on the Karakaya formation. In the eastern part of the Mudanya horst, a granitic pluton was emplaced into the metamorphic rocks of the Karakaya formation during the Latest Cretaceous–Paleocene. The overlying Zeytinbağ formation is composed of a thick (>300 m) volcano-sedimentary succession (Fig. 5). This sequence was deposited in a shallow marine environment during the Eocene. Locally, small stocks of the Kapıdağ Granite were emplaced into the metamorphic rocks in the Bandırma Horst during Oligocene times (Aksoy, 1995).

2.2. The cover units

Neogene and younger terrestrial sedimentary rocks rest unconformably on this complex basement. The Neogene cover rocks can be divided simply into two units defined on the basis of their lithological, sedimentological and stratigraphic characteristics as (a) the lower unit and (b) the upper unit (Fig. 5). These units will be described in the next section.

The lower units consist of medium to thickly-bedded clastic rocks at the bottom and cherty limestones on top. The clastic rocks consist of 100–150 m thick pebble conglomerates and sandstone of the Dereköy formation. The clasts were derived from underlying schist, marble, limestone and volcanics. The clastic rocks are medium to thickly-bedded, poorly sorted and sub-rounded to sub-angular. Paleocurrent directions obtained from clast imbrications indicate mostly northwest to southeast directed flow. Poor sorting and lack of internal structure of the matrix-supported conglomerates suggest deposition from sediment gravity processes such as debris flows.

The clastic rocks grade Laterally and vertically into a white marly-cherty-limestone succession known as the Eşkel limestone. These rocks are interpreted as low energy lacustrine deposits. Sickenberg et al. (1975) collected *Anchitherium*, *Percrocuta* and *Schizochoerus* fossils from the lower clastics around Kemalpaşa and assigned a Late Miocene age. Around Yörükali village (Fig. 2(a)) they also recognized *Amebelodon* sp. ('fricki'-Typ) and inferred a Middle–Late Miocene age. Based on this information, the age of the lower unit is Late Miocene.

In the vicinity of Eşkel the lower unit is intensely folded and the folds trend generally NE–SW. The folds are asymmetrical and locally overturned, indicating a NW tectonic transport direction.

The upper unit rests unconformably on the lower unit. At the base it consists of fluvial, red to pink, pebble-cobble conglomerates of the Köy formation. This clastic unit is poorly sorted and sub-rounded to sub-angular and derived from erosion of underlying magmatic and metamorphic rocks. The paleocurrent direction, as measured from clast imbrication, is due south to southwest. The coarse clastics grade laterally and vertically into fine-grained sandstones and siltstones. Some of these strata may be of meandering river, fan-delta origin (Şahbaz et al., 1988) indicating tectonic activity. The top of the sequence consist of white marl and limestone known as the Akköy formation. The sequence indicates a rapid transition from a high-energy fluvial depositional environment to a low-energy lacustrine environment. Based on its super position and its unconformable relationships with the underlying units a Late Miocene–Pliocene age was assigned to the upper unit by the Sickenberg et al. (1975). In the Armutlu Peninsula, the same carbonate rocks contain vertebrate fossils dated as middle Early Pliocene (Akartuna, 1968).

2.3. Quaternary units

The Quaternary units consist of marine deposits at the bottom and fluvial deposits at the top. The marine lithologies are exposed in Hisartepe and Sivritepe hills to in the west of Mudanya (Fig. 2). They consist of unconsolidated gravel, sand and silt. The gravel is composed of diverse-sized, poorly sorted and sub-rounded to sub-angular rock fragments within a sandy-clay framework. This unit contains marine fossils, such as *Murex*, *Pecten*, *Ostrea*, *Mytilus*, Chlamys, bone clasts and pots. The thickness of the unit is about 20 m.

It is known that sea level in the Marmara sea fluctuated twice during the Quaternary. Sea level rose in the Late Pleistocene (Tyrrhenian) and later during the Flandrian (Holocene). Yılmaz and Oktay (1996) and Sakınç and Yaltırak (1997) suggest that the second sea level rise in Flandrian time was a global event and related to eustatic sea level rise. Barka et al. (1998) and Emre et al. (1998) suggested that the Manyas and Ulubat Lakes, Gönen and Kocasu deltas (Fig. 3) formed under the influence of a rise in sea level during the Holocene. In the Hisartepe hill, marine fauna containing Murex, Pecten, Ostrea, Mytilus, Chlamys and vertebrate fragments and pots were identified during our field studies. Therefore, we suggest that the Hisartepe formation (Fig. 4) was deposited during the Flandrian sea level rise.

3. Structural geology

The Marmara sea region is characterized by a broad zone of distributed deformation (ap. 120 km width in N–S direction) controlled by the NAFZ (e.g. Barka and Kadinsky-Cade, 1988; Suzanne et al., 1990; Okay et al., 1999, 2000; Le Pichon et al., 2001a, b; İmren et al., 2001). The active structures and morphological features in the region trend approximately E–W. The coastline between

Bandırma and Gemlik (Fig. 4) is straight and in some places it is characterized by steep coastal slopes.

As stated previously, in addition to the northern branch of the NAFZ in the northern Marmara Sea basin, there are two sub-branches in the southern Marmara region, the middle and the Southern branches. The middle branch passes through the Geyve basin towards Gemlik Bay (Fig. 2). Between Mudanya and Bandırma (Fig. 4), the fault zone trends approximately E–W. To the west of Bandırma, it bends counter-clockwise and follows an approximately WSW–ENE trend. Further to the southwest it bifurcates into a number of splays in the Biga Peninsula and it enters the Aegean Sea (Fig. 2). The southern branch passes through the Bursa and Manyas-Karacabey basins, and to the west, traverses the Biga Peninsula sub-parallel to the middle branch and enters the Aegean Sea in Edremit Bay.

The area between the Middle and the Southern branches is characterized by three E–W oriented horst-like blocks forming rhomb-like structural highs along which the basement rocks are exposed.

The Bandırma horst is located in the western part of the study area. It is the largest horst in the region and trends approximately E–W. Along this horst basement metamorphics are exposed and it is bordered by a series of steep, en echelon oblique-slip faults. The majority of the faults displayed are typical dextral strike–slip faults with a minor normal component (Fig. 4). The fault planes are steeper than 60° and the slickenlines plunge $<40°$. Karayaprak hill is the highest peak of the Bandirma Horst and rises steeply to over 780 m elevation.

The Mudanya Horst is located in the central part of the study area. It has an average elevation of 500 m. It is 8 km long and 4 km wide in E–W and N–S directions, respectively. It is bounded by the Işıklı fault in the east, Zeytinbağ fault in the north, Eşkel fault in the west and Kaymakoba fault in the south (Fig. 4).

The Kurşunlu Horst is located in the eastern part of the study area and trends approximately E–W. The horst is bounded by the Gençali Fault in the north, Göynüklü Fault zone in the west and Gölcükbaşı Fault in the south (Fig. 4).

The rose diagrams prepared from overall faults exposed in the study area display Riedel pattern for simple shear (Fig. 4(b), Biddle and Christie-Blick, 1985; Dresen, 1992). The y-shears are almost parallel to the general trend of the NAFZ while r-shears make an approximately 15° angle and p-shears a 20° angle (in the opposite direction) with the y-shears. Extensional fractures (t) and r′-shears are not well developed, while x-shears (Bartlett et al., 1981) are well developed. Based on this information, it can be concluded that the faults in the south Marmara region developed within a dextral simple shear zone apparently manifested by the branches of the NAFZ.

4. Discussion

4.1. Tectono-stratigraphical development of the southeast margin of the Marmara Sea region

In this study, partially metamorphosed basement units are exposed only in the structural highs. The Neogene sedimentary rocks are exposed both in the depressions and on the flanks of the structural highs. These units are composed of clastic rocks and limestones of Late Miocene–Pliocene age. They are interpreted to have been deposited in fluvio-lacustrine environments and are widespread in the southern Marmara region. The main structural elements (i.e. strands of the NAFZ) that shape the active tectonic scheme of the region neither delimited the spatial distribution and boundaries of sedimentary units in the study area nor controlled their deposition. Besides, the age of these units is older than the development age of the NAFZ, which is thought to be Late Pliocene to Pleistocene. Others also suggest that the initiation age of the NAFZ in Marmara and the northern Aegean is Pliocene or Late Pliocene (Emre et al., 1998; Okay et al., 1999, 2000; Ünay et al., 2001). These units are widespread in Southeast Marmara and not restricted to the east–west horst–grabens of the Bandırma-Mudanya-Gemlik region. They are partly preserved on top of the horsts along the middle branch, suggesting that they developed before the development of the NAFZ. Furthermore, continental basins similar in terms of lithology, stratigraphy and depositional features developed, which cover very large areas in the western Anatolia (Fig. 6). Late-Miocene–Pliocene intervals correspond to region-wide denudational phases in western Anatolia (Yılmaz et al., 2000). All of these points indicate that the development of the basins in the study area was not directly related to the development of the NAFZ but rather the basins were formed by the influence of the earlier tectonic regime that

Table 1

Fault	$\sigma1$ (deg)		$\sigma2$ (deg)		$\sigma3$ (deg)		Φ (deg)	# Faults
	Trend	Plunge	Trend	Plunge	Trend	Plunge		
Gençali	097	55	297	34	201	09	0.6	8
Kayacık	316	66	132	23	223	01	0.2	6
Kaymakoba	323	74	158	15	067	04	0.7	8
Kulakpınar	313	63	130	27	221	01	0.3	8
Papazharmanı	128	26	236	32	006	46	0.02	6

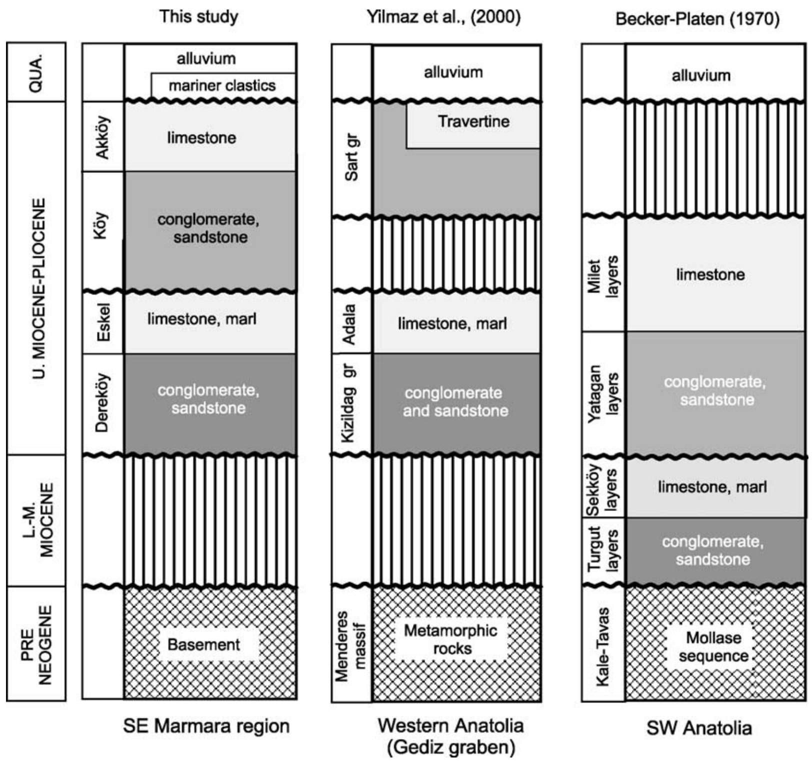

Fig. 6. Chronostratigraphic relationships within the southeast Marmara, mid-west Anatolia (Gediz graben) and Southwest Anatolia.

influenced the whole of western Anatolia, as proposed previously by Yilmaz et al. (2000).

According to Güneysu (1998), the Marmara Basin first developed as a marine basin in the Serravalian. The present shape of the sea was formed by the broadening of the northern and southern shelves (Fig. 3) since then. During that time interval, the southern Marmara region (including the study area) was a relatively high altitude flat-lying plateau which was dissected and faulted in the Late Pliocene, resulting in the current horst–graben morphology in which cover units were preserved in the lowlands and locally in the fault terraces along the horst shoulders. The first completely marine conditions in the Marmara Sea are recorded in the Pleistocene marine terraces north of the Armutlu Peninsula (Erinç, 1955; Sakınç and Bargu, 1989).

4.2. Seismicity of the Marmara region

The North Anatolian Fault Zone is one of the best known strike–slip faults in the world because of its remarkable seismic activity and its importance for the tectonics of the Eastern Mediterranean region (Fig. 7). The fault zone has mostly a single fault trace character for about 900 km between Karlıova in the east and Mudurnu town in the west (Ketin, 1969; Dewey and Şengör, 1979; Barka and Kadinsky-Cade, 1988; Koçyiğit, 1988; Stein et al., 1997). However, to the west of Mudurnu, the NAFZ splits into three major strands separated from each other by rhomb-like basin and horst complexes elongated approximately E–W. (Dewey and Şengör, 1979) Deformation along these branches has produced numerous damaging earthquakes affecting the areas far beyond their vicinities, both in modern and historical times (Ambraseys and Finkel, 1991, 1995). The last two of these destructive earthquakes occurred on 17 August 1999 (Mw = 7.4) and 12 November 1999 (Mw 7.1). These two earthquakes ruptured the two westernmost segments of the Northern branch of the NAFZ to the northeast of Marmara Sea. Unfortunately, a major earthquake (Mw $<$ 7) is expected within the Marmara sea in the next 30 years (with 95% confidence), which endangers several major cities (eg. İstanbul, İzmit, Bursa) that are located along the branches of the NAFZ within the deformation zone. In addition, major industrial areas and commercial areas are concentrated in this region.

GPS measurements (Straub, 1996; Straub and Kahle, 1997), geomorphology, bathymetry, the thickness of sediments in the basins and historical earthquake records (Ambraseys and Finkel, 1991) in the eastern Marmara Sea region show that the slip rate is higher along the Northern branch than the middle and the Southern strands. In addition, seismic activity is very linear along the northern strand of the NAFZ, but it is more diffuse on the middle and the Southern strands (Gürbüz et al., 2000, Sayısalgrafik, 2001). Considering its historical activities (Ambraseys and Finkel, 1995), the Northern strand is the most active and destructive (Barka and Kuşcu, 1996), suggesting a higher earthquake risk than the other two strands for the next 30 years. The southern strand also produced important historical earthquakes such as the large 1737 event (Ambraseys and Finkel, 1995) (Fig. 7(a)). However,

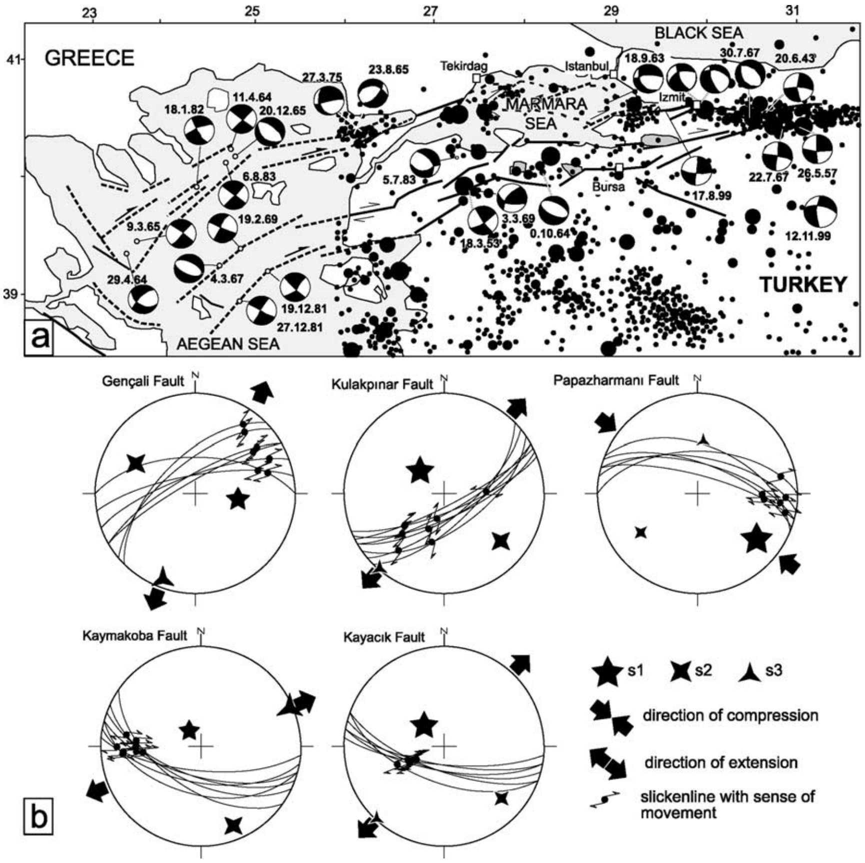

Fig. 7. (a) Fault plane solutions of the significant earthquakes along the strands of the NAFZ in the Marmara Sea and north Aegean region (Barka, 1992). 17 August 1999 Gölcük and 12 November 1999 Düzce earthquakes adapted from KOERI (Kandilli Observatory and Earthquake Research Institute). N: Northern branch of NAFZ, C: Central branch of NAF, S: Southern branch of NAFZ. (b) Lower hemisphere, equal area projection of principal stress axes constructed from fault slip data using Direct Inversion Method (Angelier, 1994). The data used to construct the projection are from Table 1.

the paucity of the southern strand indicates that it may also result in a very high magnitude earthquake in the future.

Fault plane solutions of some recent earthquakes indicate that the region has been deforming dominantly by strike–slip faulting with local normal components in the Northern strand (Fig. 7(a)). These normal faults are of two types, (1) due to fault off-set and/or right stepping of the major faults and (2) the contribution of the Aegean extensional regime. Magnetotelluric (MT) profile modeling results (Gürer, 1996) crossing the middle and the Southern strands indicated a very conductive zone at the depth of 26 km to the south of Pamukova (Fig. 2). This conductive zone is not present beneath the stable areas north of the fault zone and is interpreted as a region of partial melting in the crust as a result of adiabatic compression exerted by crustal extension (Gürer, 1996). This feature can therefore be related to the crustal extension caused by the Aegean extensional system.

4.3. Structural features related to the earthquake activity

The southeast Marmara region is a seismically very active zone (Fig. 7(a)). The seismic activity is controlled mainly by the major structural elements of the region. The 1953, 1964, 1969 and 1983 events were the most destructive earthquakes, which occurred along the middle and the Southern branches of the NAFZ (Fig. 7(a)). With the exception of the 1969 event (Fig. 7(a)), the direction of overall extension in all the other events ranges between N–S to NE–SW, which is similar to the field based paleostress patterns (Fig. 7(b)). This relationship indicates a high correlation between focal mechanism solutions and stress orientations obtained from fault-slip data. Variation of compression and extension (P and T) directions between the seismic events (Fig. 7(a)) is thought to be the result of local stress perturbations due to changes in the strikes of the faults. For example, the 1969 event along which compressional deformation dominates (with sub-vertical T axis) occurred along the bend of the Yenice Fault (Fig. 7(a)).

The present day structural framework and morphology of the region is characterized by NW–SE, NE–SW and E–W striking an echelon fault systems and approximately E–W elongated horst and grabens. Our results indicate that all the fault systems are acting in conformity with the current tectonics of the region.

Fault slip data indicates that most of the faults in the southern Marmara region have a prominent dip-slip component with main dextral slip motion (Fig. 4(b)). The Kurşunlu, Mudanya and Bandırma horsts and adjacent grabens formed by a normal component along the dextral faults. These horst systems are bordered by Marmara and Nilüfer-Karacabey depressions in the north and south, respectively (Fig. 4(a)). Previous studies documented that several rhomb-like and triangle blocks had developed along the Northern branch in the northern half of the Marmara sea (Barka and Kadinsky-Cade, 1988; Wong et al., 1995; Ergün and Özel, 1995). Similarly, this study proposes that similar morphotectonic patterns have developed along the southern margin of Marmara Sea region. Correlation of the results of this study with the previous offshore studies suggests that the same tectonic regime and structural characteristics are present both on land and continuing into the marine areas in the south Marmara region. Therefore it is expected that the westward migration of major earthquakes along the NAFZ (Ambraseys, 1970) may trigger some of the faults in the middle and the Southern branches, which may lead to a destructive earthquake along these branches. In addition, our results suggest that detailed field observations are useful for interpreting the offshore measurements as indicated by the similarity between the land and marine structures.

The lower sequence (possibly the Early–Late Miocene Eşkel Limestone) in the North Imralı Basin (west of the Armutlu Peninsula) is folded (locally overturned) and faulted indicating compressional deformation during the Late Miocene. In contrast, the upper sequence (Fig. 5) is almost undeformed, except, where very close to active faults. Such contrasting degrees of deformation and the presence of an angular unconformable relationship between the lower and upper sequence imply a change in the regional tectonic configuration after deposition of the Eşkel limestone and before the deposition of the Köy and Akköy formations, possibly during the Pliocene. Based on the results of this study and the available literature (Emre et al., 1997, 1998; Okay et al., 1999; Ünay et al., 2001), it is concluded that the current tectonic regime in the southeast Marmara region commenced in Pliocene time.

5. Conclusions

In this study the geometry and structural characteristics of the NAFZ in the southeast Marmara region have been documented. Based on this study, the following conclusions are drawn.

The Lower sequence exposed in the region pre-dates the development of the NAFZ and was deposited in a very broad depression which experienced compressional deformation before the deposition of the Upper sequence possibly during the Pliocene.

The horst and graben morphology of the region is due to a combined result of west Anatolian extension and segmentation of the NAFZ in the region.

Morphotectonic characteristics of the region are similar to the northern branch of the NAFZ and to the offshore areas.

There is a very high similarity between the results of fault slip data and the earthquake focal mechanism solutions.

Westward migration of major earthquakes along the NAFZ may trigger some of the faults in the middle and the Southern branches.

Field observations are useful for interpreting the offshore areas.

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