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Neotectonics of the SW Marmara region, NW Anatolia, Turkey

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Abstract – This study reports on the geometric and structural characteristics of the North Anatolian Fault Zone in the southwest Marmara region. The geometric and kinematic features of the faults in the region are described, based on field observations. In addition, the Neogene and Quaternary basin fill which occupies large areas in the region has been determined, and the tectonic regimes controlling these basins are explained. The neotectonic regime is also explained considering different deformation phases affecting the region. The N–S extension and E–W strike-slip have affected the region possibly since the latest Pliocene–Quaternary. Field observations show that these extensional tectonics around the south Marmara region are related to right strike-slip on the E–W North Anatolian fault zone and the N–S Aegean extensional system. The faults in this zone trend approximately E–W in the eastern part of the region and NE–SW towards the west of the region, indicating that they accommodate rotation in addition to differential movement between adjacent blocks.

Keywords: Strike-slip faults, transtension, kinematics, Marmara region, active faults, Turkey.

1. Introduction

The active deformation in the eastern Mediterranean region, particularly in Anatolia, has occurred as a result of the continental collision between the Afro-Arabian and Eurasian plates since Late Miocene times, following the closure of the last oceanic basin, the southern part of Neotethys. The northward convergence of Arabia produces thickening crust in eastern Turkey and compressional deformation along the Bitlis-Zagros fold and thrust belt. This northward Arabian movement induces the westward extrusion of the Anatolian block bounded by the right-lateral North Anatolian Fault Zone and the left-lateral East Anatolian Fault Zone. These are the intracontinental transform faults along which the Anatolian block or 'wedge' moves westward relative to the Eurasian plate in the north and to the Arabian plate in the southeast. The active, right-lateral North Anatolian Fault Zone system is the largest strike-slip system in Anatolia. This fault zone extends from the Karlıova Triple Junction, where it meets the sinistral East Anatolian Transform, to the Saros Gulf in western Turkey (Fig. 1). Towards the west of the Marmara region, the North Anatolian Fault Zone becomes extension-dominated and continues further west to mainland Greece along the North Aegean trough (Dewey & Şengör, 1979; Lybéris, 1984; Barka, 1992; Görür *et al*. 1997; Okay *et al*. 2000; Anastasia & Louvari, 2001; Armijo *et al*. 2002; Elmas & Gürer, 2004). In addition, towards the west of the Marmara region, fault segments become shorter, discontinuous and often stepped. This created many basins such as the İznik, Bursa, Karacabey, Manyas and Marmara Sea basins (Barka & Kadinsky-Cade, 1988).

Marmara Sea is the largest of these basins, and 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. 2). The Marmara Sea region is one of the most seismically active regions in Turkey. In this region where the structures are very complex, there is an interaction between the extensional and the strike-slip shear structures. The northern part is dominated by the northern branch of the North Anatolian Fault Zone and comprises mainly three asymmetric basins, each of which is more than 1000 m deep (Barka, 1997; Le Pichon, Taymaz & Şengör, 2000; Okay *et al*. 2000; İmren *et al*. 2001). In the southern Marmara Sea, where the central and the southern branches of the fault zone dominate, a number of basin complexes developed (Fig. 2). In Gemlik Gulf, the central branch of the North Anatolian Fault Zone enters the marine areas. A number of approximately E–W-trending faults with significant normal components dominate in this region (Kurtuluş, 1985). Recent GPS measurement results show that southwestward motion is the dominant mode of block kinematics in the Biga Peninsula (Barka & Reilinger, 1997; Straub & Kahle, 1997; Reilinger & McClusky, 2001). This region is characterized by active normal and oblique slip, and locally high rates of moderate magnitude earthquakes, and shows evidence of spatial and temporal partitioning of deformation and displacement during transtension (Armijo *et al*. 2002). The southwest Marmara region is considered to be an ideal area for the study of active transtensional deformation in western Anatolia since active faults are present and mapped in considerable detail.

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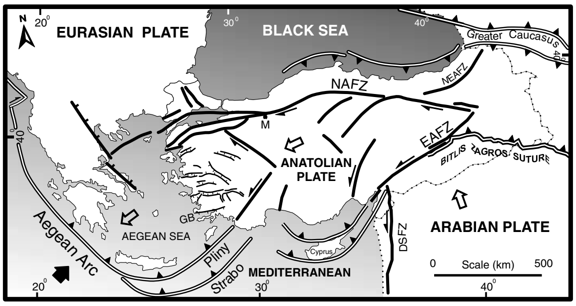

Figure 1. Tectonic outline of Turkey and eastern Mediterranean area. DSFZ – Dead Sea Fault Zone, EAFZ – East Anatolian Fault Zone, NAFZ – North Anatolian Fault Zone, NEAFZ – North East Anatolian Fault Zone, M – Mudurnu, GB – Gökova Bay.

The Marmara region also forms a transition zone between an area of pure strike-slip deformation, where the Anatolian plate is displaced westward in the north, and the western Anatolian extensional province with diffuse N–S extension (Şengör, Görür & Şaroğlu, 1985). The southern region of the Marmara Sea has complex geometry and abundant Neogene to Quaternary basins, which include (1) NE–SW-trending Early–Middle Miocene aged basins, (2) E–W-trending Late Miocene–Pliocene aged basins, and (3) Quaternary aged basins. The last two basin sets are parallel with the graben complexes of the west Anatolia extensional province.

There have been numerous studies related to the tectonics of the Marmara region for the last decade, because it lies within one of the most seismically and tectonically active parts of northwest Anatolia. However, several major questions still are not clearly explained in the literature and require detailed field study. (1) Which tectonic regime formed the Neogene basins in the region? (2) What are the geometric and kinematic features of the faults, causing the transtensional extensional system in the region? (3) Why is it that the North Anatolian Fault Zone, which trends E–W in north Anatolia, has an NE–SW trend to the south?

There are different views on the first subject. Yılmaz & Karacık (2001), Gürer *et al*. (2003) and Elmas (2003) reported that most of these basins were related to the Aegean extensional regime. On the other hand, Yaltırak (2002) proposed that these basins opened as a result of dextral strike-slip along the North Anatolian Fault System. However, the last two questions were not clearly defined and discussed in the literature, and our observations attempt to answer them. We also a present new dataset from the southwestern Marmara region by mapping and evaluating most of the important faults in the southwest Marmara region, many of which had previously been unmapped.

2. Geological characteristics

The study area comprises a heterogeneous suite of Mesozoic to Recent igneous, metamorphic and sedimentary rocks. Two main rock groups are distinguished in the area: pre-Neogene aged basement and the Neogene–Quaternary aged cover (Fig. 3). A detailed description of the basement units is outside the scope of this paper. The main emphasis is given to the Neogene–Quaternary aged cover units because of their relationships with the current structural grain of the region.

2.a. The basement units

The southwestern Marmara region has a complex geology with a wide variety of Mesozoic–Palaeogene aged units. The basement, which forms the surrounding mountain ranges and underlies the southwest Marmara Basins, comprises a series of rock units. These mountain ranges comprise four distinct structural and lithological sub-units, including the Karakaya complex, Meosozoic aged carbonates, Palaeogene aged granitoids, and Eocene volcaniclastics.

The oldest rock succession is a metamorphic association known as the Karakaya complex. Bingöl, Akyürek & Korkmazer (1973) defined the Karakaya complex from the Biga Peninsula as a heterogeneous, slightly metamorphosed Triassic aged unit of feldspathic sandstone, quartzite, conglomerate, siltstone, basalt, mudstone and radiolarian chert. The Karakaya complex forms one of the most prominent morphostructural features in northwest Anatolia. This E–W-trending massif was episodically uplifted during the Cenozoic extension, as indicated by several regional planation surfaces. Jurassic–Lower Cretaceous aged limestones rest unconformably on the Karakaya Formation (Fig. 4). A thick Mesozoic aged shelf carbonate sequence is exposed in the mountains that surround the west of Gönen. The overlying Zeytinbağ formation is composed of a thick (> 300 m) volcaniclastic succession. This sequence was deposited in a shallow marine environment during Eocene times. The granitic plutonic associations are composed mainly of granodiorite and diorite.

2.b. The cover units

Analysis of the exposed geology allows the definition of three stratigraphic units: lower, middle and upper, separated from each other by unconformities. The lower unit (Lower–Middle Miocene) is exposed along western part of the southwest Marmara region. It consists of fluvial, deltaic and open lacustrine sedimentary deposits and volcanic rocks. The middle unit includes alluvial to lacustrine facies while the upper unit consists of fluvial–alluvial deposits.

The lower unit is 500–750 m thick and rests unconformably on the basement rocks. It comprises a volcano-sedimentary assemblage of Early–Middle Miocene age. Sediments of the lower unit were deposited in individual NE-trending basins (Yılmaz & Karacık, 2001). Sediments of the lower unit are

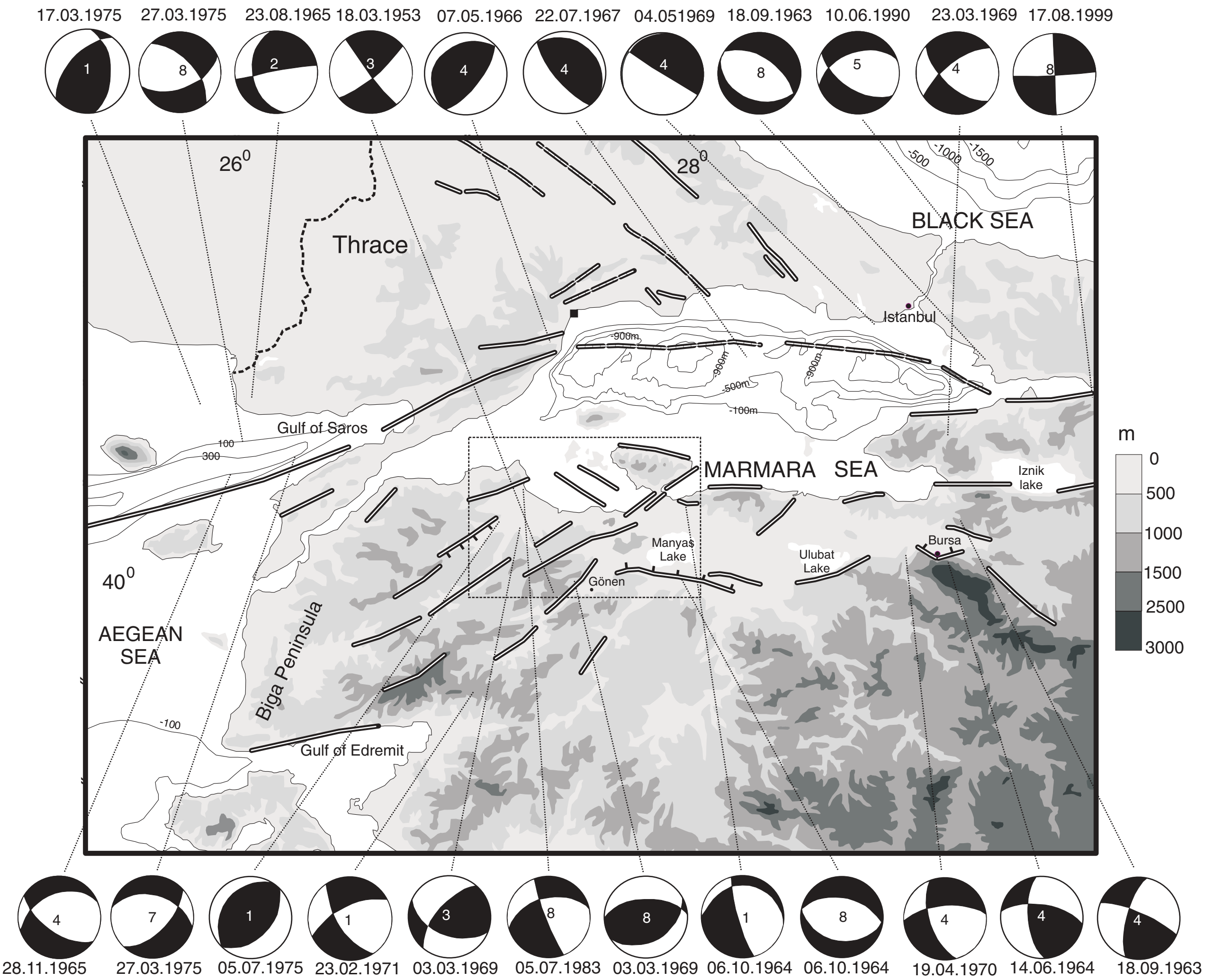

Figure 2. Bathymetric and topographic map of the Marmara Sea region. Below sea level, the bathymetric contours with intervals of 200 m are drawn in the Marmara Sea. The region marked with rectangle shows the location of Figure 3. Fault plane solutions are from (1) Ü. Kıyak, unpub. Ph.D. thesis, İ. Ü. İstanbul, 1986; (2) Canıtez & Toksöz, 1971; (3) McKenzie, 1972; (4) Kalafat, 1998; (5) Kalafat, 1988; (6) Jackson & McKenzie, 1984; (7) McKenzie, 1978; (8) Taymaz, 2001.

restricted to several limited sub-basins, which were active throughout the Miocene, and which began to widen at the end of Early Miocene times. At the bottom of the lower unit are dark sandstone, purple mudstone and beige-white-yellow, finely laminated shales. Volcanic rocks, spatially and temporally associated with the sedimentary rocks of the lower unit, consist predominantly of andesite, latite, dacite lavas and their pyroclastic equivalents. The Early–Middle Miocene volcano-sedimentary association is overlain unconformably by the middle unit and in some places rests directly on the metamorphic rocks. At several localities (near Çobanhamidiye; Fig. 3) the lower unit is intensely folded and the folds trend generally E–W. The folds are commonly open and symmetrical, locally tight and overturned. The lower unit is widespread in northwest Anatolia. Towards the south of the study area, the Lower–Middle Miocene successions were deformed under a compressional regime before Late Miocene times (Yılmaz & Karacık, 2001).

The middle unit generally displays a fining-upward sequence at the southern margin of the Marmara Sea. It consists of a *c.* 300 m thickness of red continental clastic rocks (mostly derived from underlying basement rocks of the complex), deposited in an alluvial fan-floodplain to lacustrine environment by debris flow and braided river systems. Two major facies assemblages are recognized in the middle unit: the conglomerate assemblage is made up of red and brown conglomerate, and the other is mainly composed of sandstone–mudstone. The gravel deposits are made up of relatively well-sorted and rounded metamorphic and volcanic clasts. Mean grain sizes vary from pebble to gravel. The clasts are subangular to rounded. The conglomerates are generally well bedded in tabular to broadly lenticular sheets. At the base of the basin fill is a pebble conglomerate unit with subrounded to subangular clasts, derived from underlying volcanic rocks, belonging to the lower unit. The clast size decreases rapidly; the pebble conglomerate passes

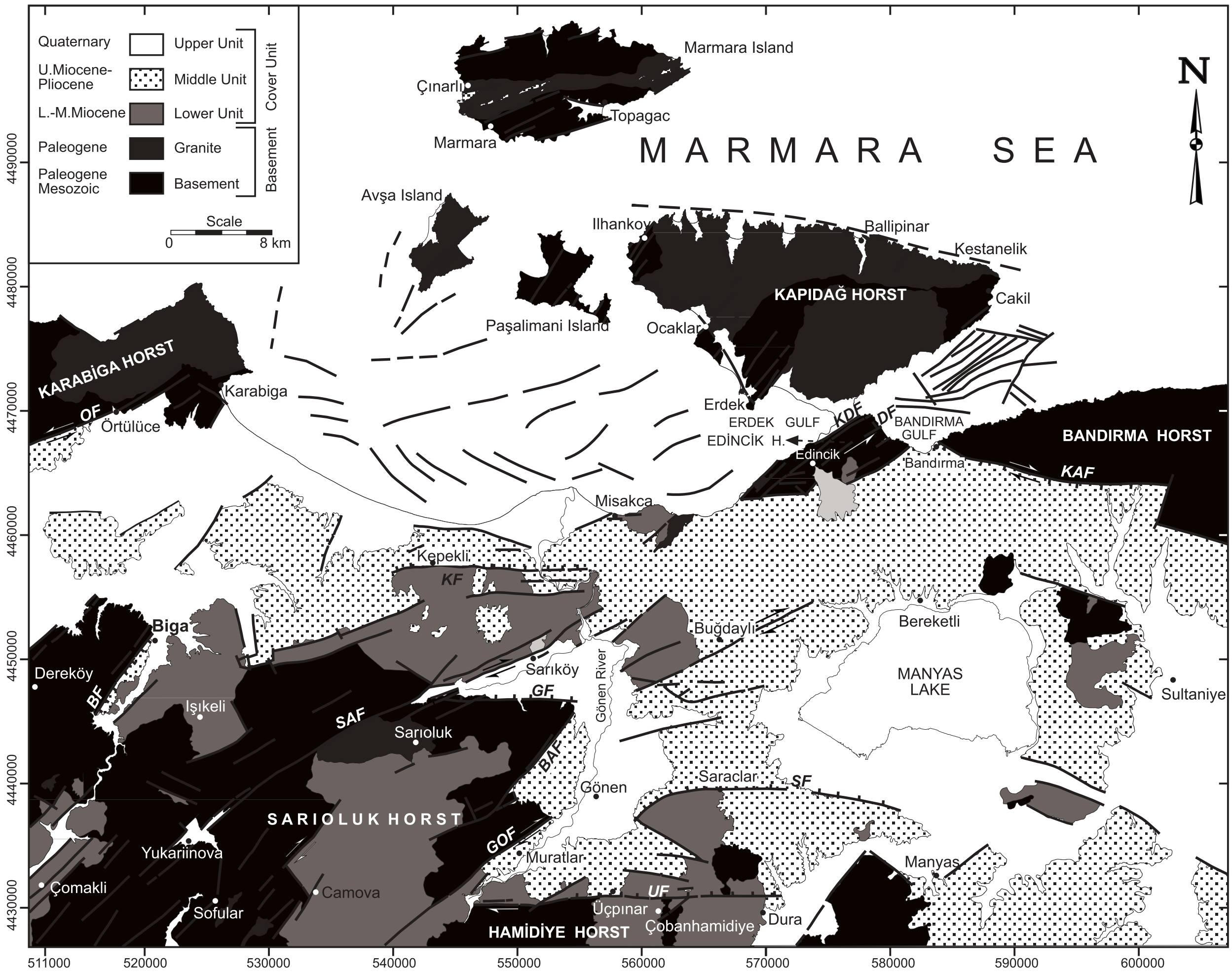

Figure 3. Simplified geological map of southwest Marmara region. The offshore faults were compiled from Siyako, Tanış & Şaroğlu, (2000) and Kavukçu (1990). BF – Biga Fault, BAF – Babayaka Fault, DF – Dostel Fault, GF – Gündoğan Fault, GOF – Gönen Fault, KDF – Kapıdağ Fault, KF – Kepekli Fault, KAF – Kayacık Fault, OF – Örtülüce Fault, SAF – Sarıköy Fault, SF – Saraçlar Fault, UF – Üçpınar Fault. Map grid using Transverse Mercator (Gauss-Kruger) Projection.

laterally into a well-bedded conglomerate–sandstone alternation. At the top of the sequence, these are replaced by red mudstone, siltstone and marl. A few limestone lenses also occur at the top of the succession. The Upper Miocene and younger units are commonly unfolded. However, they may be folded near faults as a result of displacements along the faults. No direct fault control over this terrestrial sedimentation was reported, because neither characteristic fault-related facies (thick talus scree breccias, conglomerates) nor fault traces were recorded in the area. Many faults cut the Neogene basin fill. Based on its stratigraphic position and unconformable relationships with the underlying units, a Late Miocene–Pliocene age was assigned to the upper unit by Sickenberg *et al*. (1975). Moreover, freshwater pulmonata gastropod shells are widespread.

The upper unit is represented by the infill of the recent southwest Marmara basin. The present basin-floor sediments are related to ongoing active processes controlled by the basin-bounding faults. Fan deposits form along different directions at the basin margin. Active tectonism during the formation of the upper unit had a major control on sedimentation. In the southwest Marmara region, there are two major types of Quaternary depositional systems: one in a marginal depositional setting and the other in an axial depositional setting. The marginal depositional setting is characterized by fault terraces, alluvial fans and aprons. Each of these are well developed and recently active. The main drainage system in and around the northern Biga Peninsula is dominated by the Gönen River, which has a fault-valley character for most of its course (Fig. 3). The axial depositional system of the region is characterized by an alluvial plain, swamp and active plain settings. Most parts of the alluvial plain are cultivated and covered by dense vegetation.

Different sized alluvial fans are observed in the study area. The most typical fan is in the west of Biga. The sediments represent coarse debris-flows deposited in proximal areas of alluvial fans. This suggests that the dominant sediment source area in the west was from the Biga block. These coarse clastics are bounded by the NE–SW-trending Biga Fault. The spatial arrangement

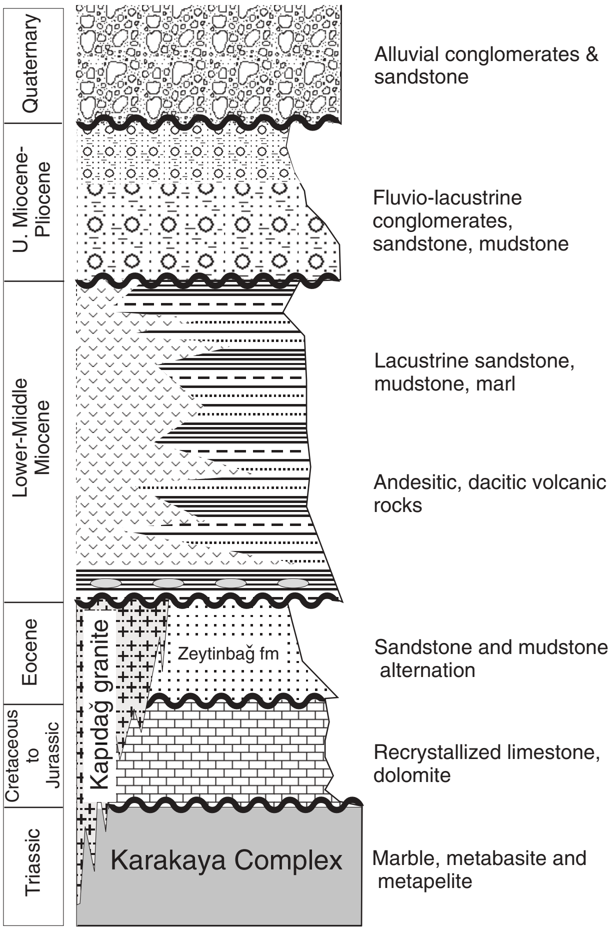

Figure 4. Stratigraphic column for the southwest Marmara region.

of debris-flow deposits dominating in proximal areas and sheet floods dominating the distal areas are also considered to be characteristic of alluvial fans.

3. Structural geology

In the Biga Peninsula, transtensional crustal deformation seems to be distributed over a large area and is dominated by E–W-striking normal faults and NE-striking right-lateral oblique-slip faults. Both inferred Plio-Quaternary stress regimes produced right-lateral shear along the North Anatolian Fault Zone and thus contributed to the extrusion of Anatolia. Tectonic controls on the development of the landscape and drainage system are evident. The most prominent morphological entities are the Kapıdağ, Karabiga, Sarıoluk, Hamidiye and Bandirma horsts.

Faults and folds are common in the region. Faults are by far the most dominant structure. The folds are recognized mostly in the lower unit, which was folded around approximately E–W-trending axes. The folds are commonly open and symmetrical, locally tight and overturned. The folding occurred before Late Miocene times. Clear evidence for an approximately N–S-trending compressional phase of deformation affecting the lower unit is seen near Çobanhamidiye village.

The study area is affected by a dense fault network. Most of the faults with striations show pure slip to low-angle oblique slip. There is very limited evidence for pure strike-slip displacement. We recognize two first-order faults. One suite of faults trends approximately E–W, parallel to the Marmara margin faults. E–W high angle fault systems are generally N-dipping. The geometry and kinematic indicators of these faults imply that their movements were mainly normal or oblique and that they are related to the Plio-Quaternary extensional tectonics. The second group of faults trends NE–SW. They can be observed at every scale from metric to kilometric in the study area. These two sets of structures appear to be the dominant control on the region in the Plio-Quaternary. The two fault families were probably coeval. The numerous NE–SW oblique-slip and E–W normal faults correlate with the fault-scarps that dominate the modern-day topography (Figs 3, 5).

The kinematics of a fault population are defined using the striations measured on the fault planes at several sites. The slip data were measured both along major and minor fault planes. Measurements were made on outcrops of fault scarps ranging from a few centimetres to several metres in size, often related to much larger fault scarps that were inaccessible. The fault scarps measured are usually characterized by smooth, polished surfaces with well-preserved slickensides and fibres. Slickenfibres are relatively common in Neogene volcanics; where possible, they were used to determine sense of motion. Our detailed mapping of these faults revealed geomorphic features, including steep linear range fronts, faceted scarps, offset streams, and scarps that cut young alluvium, all of which indicate Quaternary slip.

In the east of study area, E–W-trending rhomb-like blocks are dominant between the central and the southern branches. In the west, NE–SW-oriented rhomb-like structural highs are observed. From west to east, six major horsts including Karabiga, Kapıdağ, Edincik, Bandırma, Sarioluk and Hamidiye horsts are differentiated (Fig. 3).

The NE–SW-striking and steeply S-dipping Örtülüce Fault is characterized by a ~20 m thick zone of breccia and cataclasite. The Örtülüce Fault corresponds to the southern boundary of the Karabiga horst and extends more than 15 km between the Marmara Sea and the west of the study area (Fig. 3). The fault planes are steeper than 60° (Fig. 6a). Numerous fault planes are present, mainly within Mesozoic carbonate rocks, located around Örtülüce with well-developed slickensides. Two populations of striae are present on the fault surface. The dominant set plunges shallowly northeast and indicates left-lateral oblique slip. A less common set plunges steeply and indicates pure extension. Fault-related morphology was

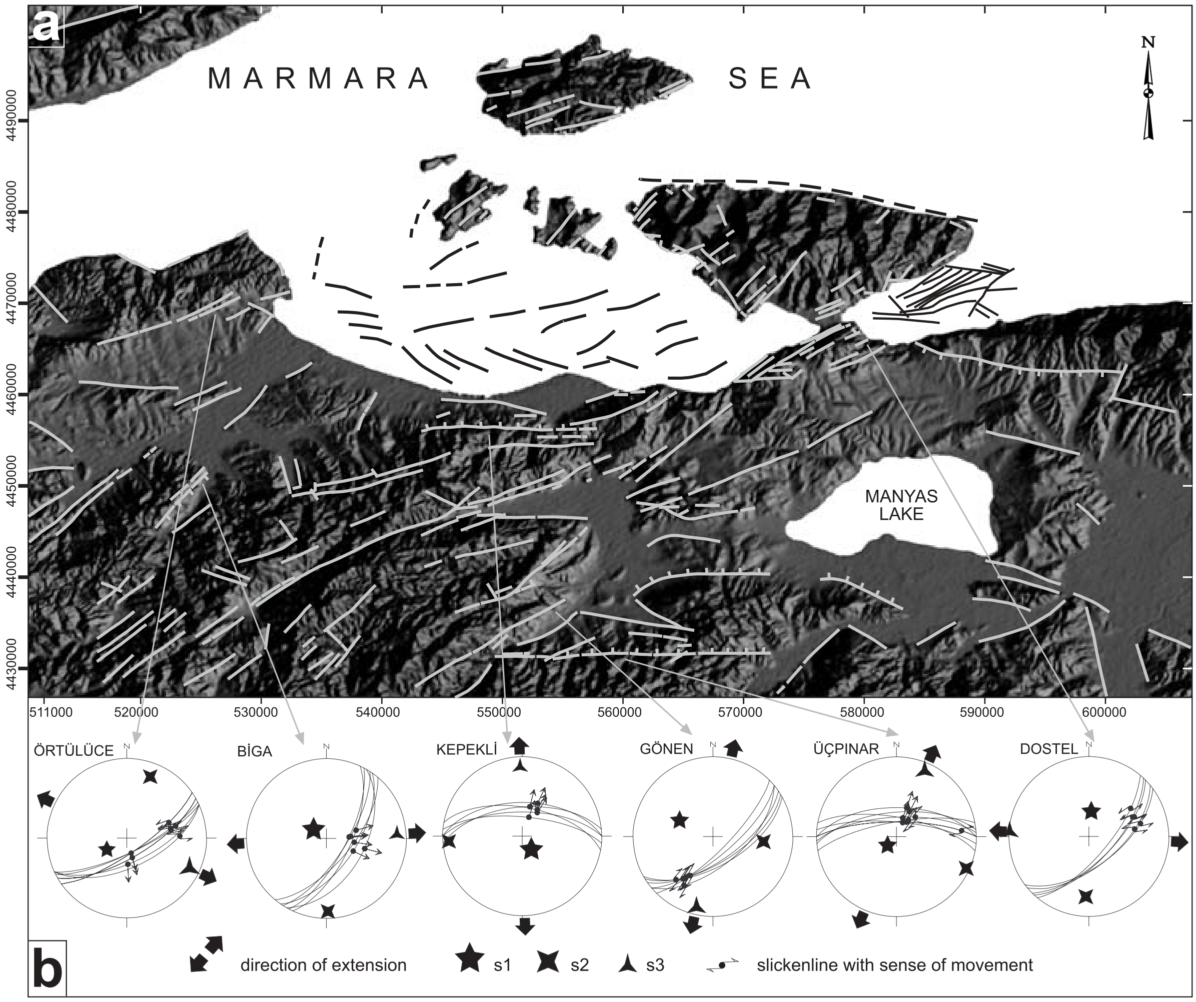

Figure 5. (a) Raised relief image of SW Marmara produced from 3 arc second (∼ 90 m) Shuttle Radar Topographical Mission data obtained from NASA Jet Propulsion Lab. The locations of major faults in the region are indicated. (b) Lower hemisphere, equal area projection of principal stress axes constructed from fault-slip data using Direct Inversion Method (Angelier, 1994). The data used to construct the projection are from Table 2.

largely obliterated by erosion at the western part of Örtülüce Fault.

Another left-lateral oblique slip fault is the Dostel Fault, which extends from the Marmara Sea through Edincik (Fig. 6b). This is also a typically oblique fault zone with left lateral and normal displacements. The fault cuts the basement metamorphic rocks and the Quaternary cover. The fault surface is steeply SE-dipping with an average angle of about 70°. Slickenside striations observed on the fault surfaces show a strong tendency to plunge 40–60° NE.

The most prominent fault among the NE–SW faults is the Sarıköy Fault, which defines the northern boundary of the Gönen basin (Fig. 3). It extends more than 35 km between Sarıköy village and the south of the studied area. These fault scarps strike NE–SW and dip southwards at 50–70° (Fig. 6c). Slickenlines are not exposed. The fault surfaces are often degraded or buried under thick soil.

This fault was clearly an important structure during at least the later stages of development of the Quaternary Gönen basin. In 1953 and 1969 two earthquakes of magnitude 7.2 and 5.7 occurred on the Gönen Fault, which bounds the present southeastern Sarıoluk block. A 50 km long continuous fault segment occurs along the west margin of the Gönen Basin (Herece, 1990). The position of the Gönen Fault is shown by a marked change in topography (Figs 3, 5) with Mesozoic aged limestones in its footwall that were uplifted 800 m above the basin floor. The surface trace of the fault is straight and trends NE–SW (Figs 3, 6d).

Slip vectors are mostly observed on basin-bounding fault planes. In the southern part of the Gönen basin, major faults bound the graben on the west and the south and control graben subsidence. These faults show clear active fault morphology such as scarps and triangular facets (Fig. 5).

Morphologically the most prominent fault system is the Gönen Fault, which forms the northern boundary of the Gönen basin (Fig. 3). The fault bounds the present valley floor and runs along the base of the topographic escarpment on the northern side of the

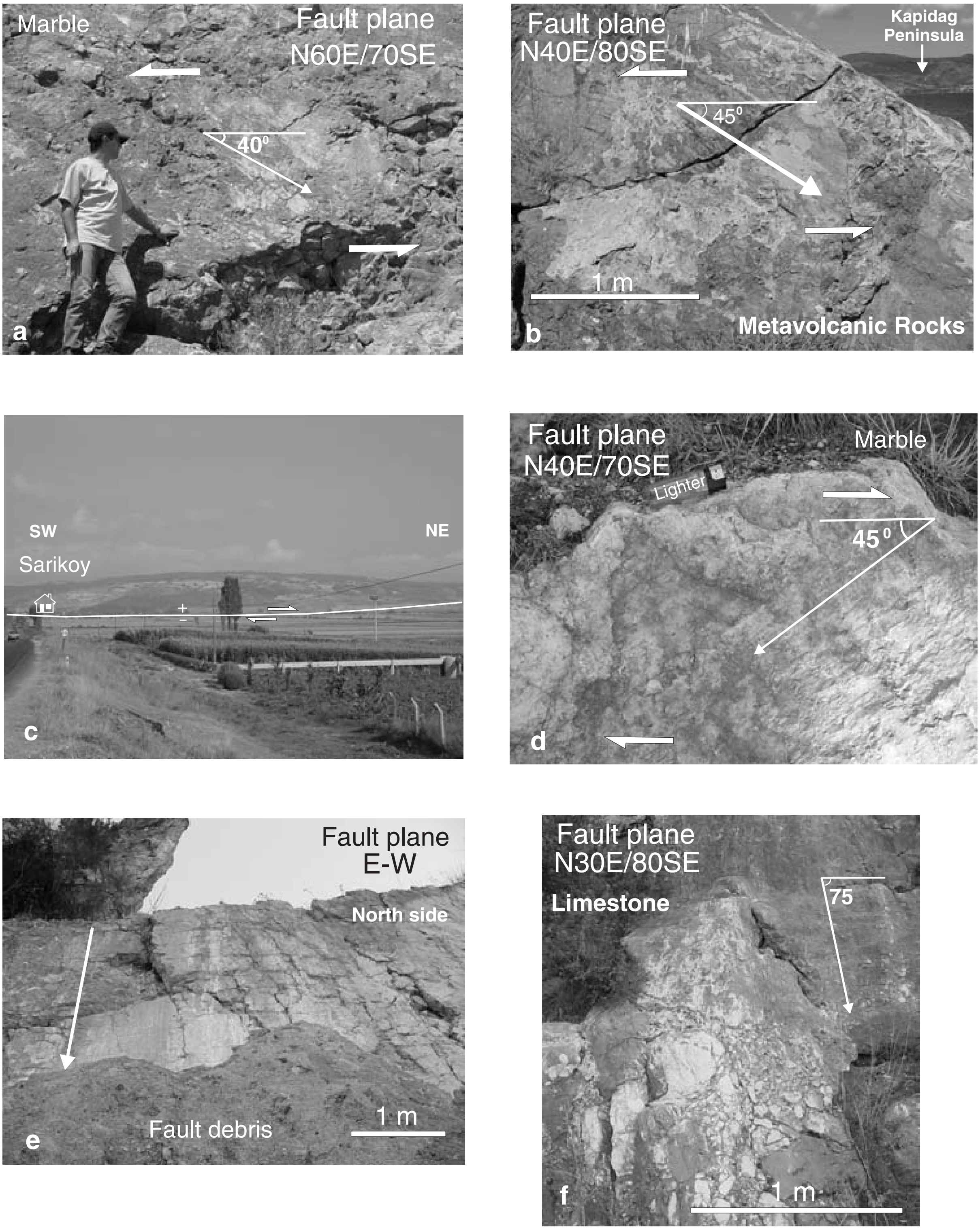

Figure 6. Field photographs of (a) Örtülüce Fault, (b) Dostel Fault, (c) Sariköy Fault, (d) Gönen Fault, (e) Üçpınar Fault, (f) Biga Fault. Arrows indicate direction of movement.

Gönen River Valley. The topography is much steeper along this side of the graben, where the Sarıoluk horst rises steeply over 600 m from the graben floor, which is only a few metres above the sea level. Steeply south-dipping (> 70°) oblique-slip faults display right lateral oblique displacements. A steep, polished and brecciated fault surface is commonly observed along the fault zone.

The Hamidiye block is located in the southern part of the study area and trends E–W (Fig. 3). The E–W-trending Üçpınar fault runs between the Hamidiye uplift in the south and Manyas depression in the north.

To the north of the horst, the Üçpınar fault strikes parallel to the northern front of the Dede Hill and forms a gentle escarpment. These fault scarps strike E–W, dipping northward at 60–80° and display normal-faulting striae on slickensides (Fig. 6e). Numerous hot and cold springs discharge along the fault plane.

Another young and morphologically prominent fault is the Biga Fault, which extends from the Biga through the west of the study area. The fault cuts the basement limestones and the Neogene–Quaternary cover. The fault cuts the southeastern edge of the Biga high and forms abrupt cliffs along the eastern slope of the Biga high. The fault plane steeply dips southeast at an angle of 70–80° towards the axial depression (Fig. 6f). This fault is a normal fault having more than 100 m dip-slip displacement. The fracture zone of the fault mainly consists of fault gouge and breccia. A well-exposed NE–SW fault with striations trending 70–85° contained tool marks suggesting nearly pure extensional motion.

The North Anatolian Fault Zone in the study area is composed of numerous parallel to subparallel fault segments displaying an en échelon fault pattern. The parallel to subparallel arrangement of the different fault segments results in a typical strike-slip fault-controlled step-like morphology indicating the oblique-normal nature of the faults.

In general, N-striking faults in the study area show evidence of sinistral-oblique and dextral-oblique motion, and most E–W-striking faults show evidence of vertical displacements. All fault systems appear to develop coevally because they cut across one another and also across the Neogene rocks, and played major roles in shaping the prominent morphological entities of the region.

Table 1. Major earthquakes in the SW Marmara region

	Date	Place	Depth (km)	Ms	Io
1	04.01.1935	Erdek and Marmara Islands	30	6.4	VIII
2	18.03.1953	Yenice-Gönen	10	7.2	IX
3	06.10.1964	Manyas	24	7	IX
4	03.03.1969	Gönen	4	5.7	VIII
5	05.07.1983	Biga	7	6.1	VIII

1, 2, 4 – Ambraseys, 1988; 3 – Ergin, Güçlü & Uz, 1967;
5 – Bayülke, Inan & Koşan, 1983.
Ms – Surface wave magnitude; Io – Mercalli Intensity.

Table 2. Results of stress tensor determinations with the direct inversion method

Fault	$\sigma 1$ (deg) Trend	Plunge	$\sigma 2$ (deg) Trend	Plunge	$\sigma 3$ (deg) Trend	Plunge	ϕ (deg)	Number of faults
Biga	306	74	179	10	087	13	0.271	6
Dostel	005	62	190	28	099	02	0.665	4
Gönen	296	52	096	37	193	10	0.668	6
Kepekli	146	74	266	09	358	14	0.104	5
Örtülüce	240	67	021	19	116	14	0.552	8
Üçpınar	156	76	277	07	009	12	0.463	7

4. Seismicity of the Marmara region

The North Anatolian Fault Zone is one of the well-known active strike-slip fault zones in the world because of its extraordinary seismic activity and its importance for the tectonic evolution of the Eastern Mediterranean region. The fault zone has mostly a single fault trace character for about 1000 km between Karlıova in the east and Mudurnu town in the west (Ketin, 1969; Dewey & Şengör, 1979; Barka & Kadinsky-Cade, 1988; Koçyigit, 1988; Taymaz, Jackson & McKenzie, 1991; Stein, Barka & Dieterich, 1997). However, to the west of Mudurnu, the fault zone splits into three major strands separated from each other by rhomb-like basins and horst complexes elongated approximately E–W (Dewey & Şengör, 1979).

The entire North Anatolian Fault Zone seismic belt has been the focus of a series of large ($M > 6$) earthquakes accompanied by surface ruptures for the last century (Ambraseys, 1970; Jackson & McKenzie, 1984; Barka & Kadinsky-Cade, 1988; Westaway, 2003; Çakır, Barka & Evren, 2003). These ruptures represent a variety of structural styles that change spatially and continuously from reverse oblique-slip and pure strike-slip in the east to normal oblique- and dip-slip in the west direction (Bellier *et al*. 1997). West of Mudurnu, the most active features of fault morphology are observed along the central and the northern segments while the southern segment is less active. In addition, seismic activity is linear along the northern strand of the fault zone, but it is more diffuse on the central and the southern strands (Gürbüz *et al*. 2000).

In the Marmara region, fault plane solutions of some recent earthquakes indicate that the region has been deforming dominantly by strike-slip faulting with normal components in the central and southern strand (Fig. 2). The focal mechanisms are compatible with the geometry of the faults mapped at the surface. Earthquakes affect the upper crust in its first 20 km and are concentrated in the first 0–15 km depth zone. There are only five reverse and four extensional focal solutions known in the literature (Fig. 2) (Kalafat, 1988).

In the southern Marmara region, the seismic activity is controlled mainly by the major structural elements of the region. Major earthquakes recorded in the area are listed in Table 1. The 1953, 1964, 1969 and 1983 events were the most destructive earthquakes that occurred along the central and the southern branches of the North Anatolian Fault Zone (Fig. 2, Table 1). Fault plane solutions of the 1953 and 1969 Yenice earthquakes on the eastern part of the central strand give NE–SW-trending thrust faults with right-lateral component and pure right-lateral strike-slip faults, respectively (Fig. 2; Taymaz, 2001). With the exception of the 1969 event (Fig. 2), the direction of over-all extension in all other events ranges between N–S and NE–SW. This relationship indicates a strong correlation between focal mechanism solutions and stress orientations obtained from fault slip data (Fig. 5b). Variation of compression and extension (P and T) directions between the seismic events (Fig. 2) 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 Gönen Fault (Fig. 2).

The present-day structural framework and morphology of the region is characterized by NE–SW- and E–W-striking en échelon fault systems and approximately NE–SW- and E–W-elongated horst and graben. The Karabiga, Kapıdağ, Edincik, Sarıoluk, Hamidiye and Bandirma blocks and adjacent depressions were formed by a normal component of motion along the strike-slip faults. These horst systems are bordered by the Marmara depression in the north (Fig. 3). 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 & Kadinsky-Cade, 1988; Wong *et al*. 1995; Ergün & Özel, 1995). This study proposes that similar morphotectonic patterns develop along the southern margin of Marmara Sea region. Correlation of the results 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 southern Marmara region. Therefore, it is expected that the westward migration of major earthquakes along the North Anatolian Fault Zone (Ambraseys, 1970) may trigger some of the faults in the Central and the Southern branches, which may lead to a destructive earthquake.

5. Discussion

In western Anatolia, two sets of basins trending E–W and NE–SW are present. E–W-trending basins with their intervening horsts and related normal faults are the most prominent neotectonic features of western Anatolia. Other, less prominent structural elements of western Anatolia include the NE-trending basins and their intervening highs. There are about 20 major basins trending approximately N–S in western Anatolia between the Marmara Sea in the north and the Gulf of Gökova in the south. The graben do not appear to continue east of longitude 29° E (Yılmaz *et al*. 2000). The N–S-trending graben are commonly bounded by oblique slip faults (strike-slip faults with dip-slip components). The localized Lower–Middle Miocene sedimentation and volcanism are the most important features of these basins (Yılmaz *et al*. 2000; Gürer & Yılmaz, 2002; Bozkurt, 2003).

The current tectonics of northwestern Turkey are controlled mainly by the interaction of (1) an extensional tectonic regime that causes N–S extension of the western Anatolia and the Aegean Sea area and (2) the strike-slip tectonics exerted by the North Anatolian Fault Zone. The former is effective in a broad zone from Bulgaria in the north to the Hellenic trench in the south (McKenzie, 1972). The cause and origin of N–S extension in western Turkey is debated. The age of the graben is also controversial and proposals fall into three main categories: (1) the basins started to form during the Early Miocene (Seyitoğlu & Scott, 1991, 1996); (2) the extension started during the Late Miocene (Dewey & Şengör, 1979; Şengör, 1987) and (3) present-day E–W-trending graben are Plio-Quaternary structures (Koçyigit, Yusufoğlu & Bozkurt, 1999; Sarica, 2000; Yılmaz *et al*. 2000; Gürer *et al*. 2001; Gürer & Yılmaz, 2002; Bozkurt, 2000, 2001, 2003; Bozkurt & Sözbilir, 2004).

The age and the cause of right-lateral motion along North Anatolian Fault Zone is also controversial and there are basically three different views. (1) The right-lateral motion commenced by the Middle Miocene and is the result of the westward motion of Anatolia away from the collision zone in the eastern Turkey when Arabian and Eurasian plates collided (McKenzie, 1972; Şengör, 1979). (2) Others claimed that the fault zone did not initiate until latest Miocene or Early Pliocene times (Şaroğlu, 1988; Barka & Kadinsky-Cade, 1988; Barka & Gülen, 1989; Bozkurt & Koçyigit, 1995, 1996; Yaltırak, 1996; Barka *et al*. 2000). (3) There are also claims that the movement along the North Anatolian Fault Zone was initiated in eastern Anatolia during the Late Miocene and propagated westwards reaching the Sea of Marmara region during the Pliocene (Şengör, 1979; Barka, 1992; Suzanne *et al*. 1990; Barka, 1997; Görür *et al*. 1997; Tüysüz, Barka & Yiğitbaş, 1998; Emre *et al*. 1998; Yaltırak, Sakınç & Oktay, 2000; Okay *et al*. 2000; Ünay *et al*. 2001; Gürer *et al*. 2003; Elmas, 2003).

Field analysis of the fault kinematics of Neogene deformation conducted in the different zones in the southern Marmara demonstrated changes in the direction of extension over the Neogene. A chronology of four tectonic phases and the associated Neogene basin evolution in northwest Anatolia can be established and summarized as follows:

(1) Early–Middle Miocene extension trended NW–SE, nearly perpendicular to the convergence between the Sakarya and Tauride-Anatolide continents. Over a slightly inclined topography, a lake basin was established during the Early Miocene period and the lower unit was deposited during this phase. This was followed by the development of a set of approximately NE–SW-trending faults formed under an approximately N–S-trending compressional regime, accompanied by intense volcanic activity (Fig. 7a).

(2) During Late Miocene times, the rifted region in northern Anatolia was subjected to regional subsidence and basaltic volcanism. The extension direction changed to N–S, nearly parallel to the orientation of

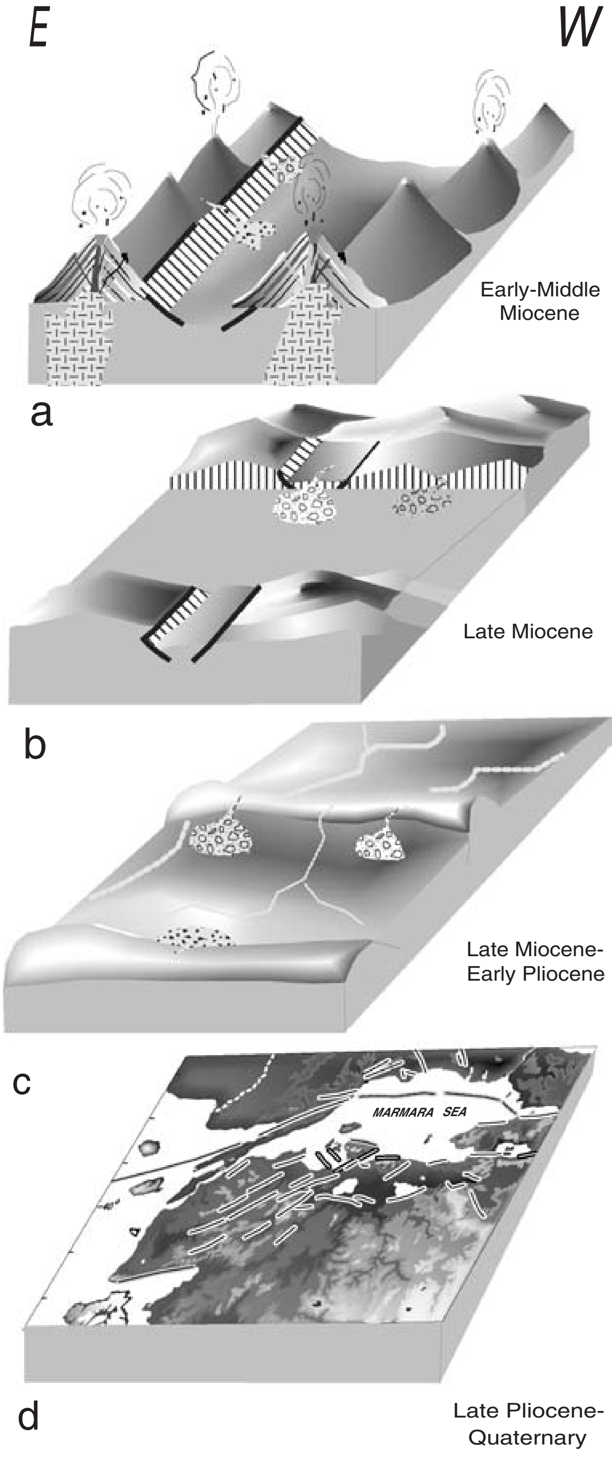

Figure 7. Schematic block diagrams showing the consecutive stages of morpho-tectonic evolution of the study area from Early Miocene to present.

Sakarya–Tauride–Anatolide plate convergence. Since latest Miocene times, a new phase of extension has become dominant with intensive normal faulting and differential subsidence mainly localized along the graben systems around the Thrace and Marmara region (Yılmaz & Karacık, 2001).

The middle unit was widely deposited in the fluvio-lacustrine environments in the southern Marmara region (Fig. 7b). The main structural elements (strands of the North Anatolian Fault Zone) that shape the active tectonic scheme of the region neither delimited the spatial distribution and boundaries of the middle unit in the study area nor controlled their deposition. In addition, the age of these units is older than the development age of the North Anatolian Fault Zone, which is thought to be Late Pliocene to Pleistocene.

(3) The N–S extension appears to be discontinuous. Before the latest phase of the uplift, all developed horst and graben lost their topographic identities as a result of this erosional phase (Fig. 7c).

(4) The region was affected by two different but contemporaneous tectonic regimes during the Late Pliocene–Quaternary: (1) an ongoing N–S extensional regime that prevails over the whole of western Anatolia; (2) the NE–SW strike-slip deformational regime associated with the North Anatolian Fault Zone. The first tectonic regime formed E–W-trending normal faults, whereas the second regime shaped NE–SW-trending faults that are characteristic of the region. Although the North Anatolian Fault Zone has an E–W trend along 1000 km from Karlıova to Manyas, it shows a NE–SW trend in the study area. Our field studies showed that the faults in the North Anatolian Fault Zone follow the NE–SW-trending faults that were formed in the first regime since they lie parallel to the borders of the Lower–Middle Miocene aged basins in many localities (Fig. 7d).

6. Conclusions

In this study we determined the Neogene–Quaternary stress regimes acting in the southwest Marmara region, which is located at the northwestern corner of Anatolia. The following conclusions can be drawn from our investigation of the southwest Marmara region along the central and the southern branch of the North Anatolian Fault Zone.

(1) Our investigation mainly reports the evolution of the southwest Marmara region in the Plio-Quaternary. Normal-slip strike and right-lateral slip movement began in the Late Pliocene–Quaternary. During this period, transtensional basins and the modern morphological and tectonic elements of the region were developed. The present topography of the region was formed mainly as a result of the E–W-trending normal faults and NE–SW-trending oblique faults, which led to the development of the Marmara Sea and the elevation of the horst blocks.

(2) The principal features of active faulting in the region are NE–SW-trending strike-slip faults, both right-lateral and left-lateral, and E–W-trending normal faults, all of which display coeval motion. There is a significant consistency between the results of fault slip data and the earthquake focal mechanism solutions. Based on focal mechanism solutions, faults were interpreted as moving predominantly right-laterally.

(3) The effect of strike-slip activity along the central and the southern branches of the North Anatolian Fault Zone changes from E–W to NE–SW, suggesting that the main faults controlling the lower units were pre-existing faults that were reactivated during this phase. The arcuate traces of the North Anatolian Fault Zone in this region also suggest that they accommodate rotation in addition to differential movement between adjacent blocks.

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