

Geophysical Studies in the Marmara Sea; Their Contribution to the Regional Geology

Marmara Denizi Jeofizik Çalışmaları; Bölge Jeolojisine Katkıları

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Abstract

Marmara Sea region is a relatively small inland marine realm of active plate tectonics and crustal movements. In recent years, exploration of the oceans using geophysical methods has had a profound effect on the way we view the structure of the Earth and its behaviour through geological time. Under the light of new geophysical data, various studies have been devoted to the Marmara Sea. The most important studies known by the author will be cited, their relevant results to the regional geology (structural models and palaeogeographic evolution of the Marmara Sea) will be given.

Keywords: Marmara Sea, geology, geophysics, active faulting, tectonic models

Introduction

The Marmara Sea is a 278-km long and 75-km wide intracontinental sea on the waterway between the Mediterranean and the Black Sea. The total coastline length is about 1025 km including 23 islands. Asian coasts (663 km) are 2.5 times longer than the European coasts (264 km). It has a surface area of approximately 11,350 km² and a volume of 3,380 km³.

Beyond the important bays (İzmit, Gemlik, Bandırma and Erdek) placed at both sides of two big peninsulas (Armutlu and Kapıdağ), this inland sea is characterized by deep troughs (1150-1280m) to the north and broad (~32 km) shelf to the south. The northern shelf is narrow (2-13 km) and there is literally no shelf area in front of the Ganos Mountain, where very

steep slopes at the shoreline continue down to deep trough. Continental slope along the northern margin of the Marmara Sea is very steep. The wide southern shelf, on the other hand, is locally interrupted by large and small islands.

These shelves are separated by an E-W deep trough which is segmented by the splays of the North Anatolian fault (NAF) (Ketin, 1948) into three rhomboidal or wedge-shaped transtensional basins. The seafloor morphology of the Marmara Sea was not so evident until the depth measurements using high resolution multibeam acoustic methods. Andrusov was the first researcher who gave the first bathymetric information for the Marmara Sea together with some detailed oceanographic data in 1890. Following studies, based on the classical and single channel acoustical methods, show three central basins lying at depths between 1152 and 1276 m (Ardeh and Kurter, 1970, 1973). The total shelf area occupies 57% of the hypsographic curve. In recent years, new and modern bathymetric data has a profound effect on the way we view the seafloor morphology.

The Marmara Sea is connected to the low salinity Black Sea and the fully marine Mediterranean via two narrow, long and elongated straits. The width of the Strait of İstanbul ranges between 0.7 and 3.5 km with an average of 1.6 km. Its average depth is 36 m with a maximum of 110 m. It has a sill depth of -35 m. At the southern end of the Strait of İstanbul 7-km-long Golden Horn estuary, as named in antiquity because of its shape, is located. The width of the Strait of Çanakkale, on the other hand, ranges between 1.2 and 7 km with an average of 4.0 km. The narrowest part of the Strait of Çanakkale is about 25 km east of its junction with the Aegean Sea. Its average depth is 55 m, with a maximum of 105 m. Whereas the Strait of Çanakkale is connected to the Tekirdağ depression, westernmost of the deep basins aligned in the Marmara Sea, by a gradually widening junction region, it is terminated at the Aegean Sea by an abrupt opening, where a sill is placed between 60 and 65 m contour lines (Alpar et al., 1998). This indicates that the connection between the Marmara Sea and the Aegean Sea would be interrupted if the sea level were dropped about 65 m. It is known that the palaeoshorelines during the Würm glaciation were located at about (115-120), (90-100) and 150 m in the Aegean, Marmara and Black Seas, respectively (Aksu and Piper, 1983; van Andel and Lianos, 1984; Smith et al., 1995; Ryan, 1997). The sills in the Turkish straits are well above than the fossil shores of the neighbouring seas. Therefore, late Quaternary sea level changes have been in effect on the depositional, stratigraphic and palaeogeographic features of the Marmara Sea.

Bottom sediments

Various morphological characteristics along the coastlines of the Marmara Sea display tectonic, depositional, wave and fluvial influences. Low land coast type is mainly dominant around southern (Kocasu and Gönençay) deltas while high land coast type is associated with the hard rock formations around peninsulas (Ardel and Kurter, 1957).

Sea-floor of the straits and many near-coastal zones of the Marmara Sea is mostly covered by the coarse-grained sediments. The seaward increase in the fine components along the down canyon-axis of the straits is prominent. Terrigenous constituents of the sediments, largely reflected the influences from the land-based geological sources, most probably delivered by river-runoff and coastal erosion. Finest sediments are found in the deep Marmara basins where the silt/clay ratio is lowest implying low-energy conditions (Bodur, 1991; Ergin and Bodur, 1999).

The sedimentation (^{210}Pb) rate is about 100 cm/ka in the Çınarcık depression (Evans et al., 1989) which is filled with Pliocene-Quaternary sediments over 3 km thick (Okay et al., 2000b). Sedimentation rates are higher especially in the central depression and on the southwest shelf Ergin et al. (1994). The average sedimentation rates, 40 cm/ka for shelf areas, 10 cm/ka for push-ups and 100-200 cm/ka for depression areas (Çağatay et al., 2000) During sea level lowstands, rivers dissected the continental shelf, organic and inorganic materials deposited in the deep basins.

In the İstanbul and Çanakkale straits, where high-energy conditions prevail due to complicated bottom topography and varying hydrodynamic conditions, coarse-grained sediments rich in sand and gravel are widely distributed. These straits cross the shelf and extend to the deep Marmara Basin through canyon-like features. In the canyons along the axial depths, sediments tended to increase in mean grain size in the downcanyon direction. The shelves bounding the outer canyon are marked by the occurrence of large amounts of shell fragments (Ergin et al., 1991a).

Easternmost of the Marmara Sea, the bottom sediments of the 49-km-long İzmit Bay consists of predominantly grained material with various proportion of silt and clay (Yörük, 1988; Eryılmaz, 1990; Eryılmaz et al., 1995). It forms a narrow depression marine realm consisting of three main basins with two straits, 1.8 and 9.8 km width, respectively (Kurtuluş, 1990). The relatively coarse-grained size sediments are abundant along the northern coasts of the İzmit Bay (Algan et al., 1999). Recent sediments at the sea bottom are thicker at the inner parts of the İzmit Bay where the sediment transportation is higher. Deltaic fans

developed in front of the rivers where the currents and waves are weak. Ergin and Yörük (1990) give the deposition rate as 25 cm/ka. Based on the grain size analyses of Doğan and Eryılmaz (1991) at the İzmit Bay, the bottom sediments contain pebbles (0-10%), sand (1-55%), silt (27-70%) and clay (18-61%). The ratio of the biological substances, mainly shell, vary between zero and 58.8%.

Southern Marmara shelves receive significant amount of detrital input from the southerly major rivers. The bottom of the southern Marmara shelves are presently covered by both modern and relict sediments and the varying intensities in the neotectonic uplift mechanisms are responsible for the occurrences of relict sediments at varying depths (Bodur and Ergin, 1994; Ergin et al., 1997).

The carbonate and organic carbon analyses have been attractive in order to investigate the source of the sediment inputs and the dominating marine conditions of the Marmara Sea. They suggest fresh-brackish-lacustrine to marine transitions in oxidising conditions. Total carbonate content in the surficial sediments varies between 10-30% for the southern Marmara shelf (Ergin et al., 1996) and 9-15% for the Golden Horn (Ergin and Yörük, 1990). Due to higher biological activities (especially benthic organism), this ratio is higher (2-45%) at the central and western basins of the İzmit Bay (Ergin et al., 1991b). Highly carbonated areas generally correspond to the areas with calcareous-biogenic fractions, usually sand and gravel.

Organic carbon content of the surface sediments in the Marmara Sea varies between 0.1-2.5%, high values being located along the coast, decreasing away from shore (Bodur, 1991; Ergin et al., 1993; Çağatay et al., 1996). This implies that the organic-carbon is mainly of terrestrial origin and the Marmara Sea show a transitional character between the organic-rich Black Sea and the relatively organic-poor Mediterranean.

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Geophysical Studies

The Marmara Sea region has a complex basement consisting of various paleotectonic units (English, 1904; Ketin, 1983; Erguvanlı, 1957; Saltık, 1974; Brinkman, 1976, Sümengen et al., 1987; Şentürk et al., 1987; Siyako, et al., 1989; Sakınç et al., 1995; Yaltırak, 1996b; Barka, 1997). For example, in the Biga Peninsula, NE-SW trending tectonic zones of pre-Tertiary age forms the basement units, while the Upper Cretaceous-Paleocene ophiolitic melange is the oldest unit in the Gelibolu Peninsula (Okay et al., 1990). Careful onland and marine geophysical studies

including gravity, magnetics, shallow and deep seismic reflection, microseismic data, etc. are have paramount importance to solve these crucial complex tectonic problems.

Since the Marmara Sea is a region where the lateral movement of the NAF and graben systems in the western Anatolia meet, the gravity and magnetic methods may give important clues. For example, gravity anomalies correspond to uplifting blocks or basins, while magnetic anomalies represent the ofiolitic rocks of the Intra-Pontid suture zone.

Gravity

In recent years, gravity surveys at sea has had a profound effect on the way we view the crustal structure (Ekingen, 1978; Oral, 1987; Adatepe, 1988; Özel and Uluğ, 1991; Özel 1992; Ergün and Özel, 1995; Ergün et al., 1995; Şimşek, 1997; Adatepe et al., 1999). Klingele and Medici (1997) determined the depth of the crust-mantle boundary. The depth to the Moho discontinuity is 27 km at the northern margin of the Marmara Sea region and decreases towards northwest. Their model have a stronger NW-SE gradient and significantly different from the model proposed by Hurtig et al. (1991). The residual field does not show any correlation between the anomalies and known seismo-tectonic features. In spite of this contradiction, gravity modelling studies indicate that the Marmara Sea basin has been designated as a deformation area where horizontal and vertical movement systems have come across and mixed. For example, the EW trending graben structure model (4-5 km deep as deduced from gravity data) between Gemlik and Bandırma bays (Demirel, 1999) is believed to be the case of the middle strand of the NAF on the westward extension of the Gemlik Bay (Alpar and Çizmeçi, 1999).

Magnetics

Similar to the gravity studies, magnetic exploration at sea is so important in determining the distribution of the main magnetic bodies below vast water masses. The main magnetic anomalies in the Marmara Sea region lie E-W direction. From second derivative aeromagnetic map some possible tensional and fault zones in the Marmara Sea have been proposed by Kavlakoglu and Özakçay (1973). The depth of the main magnetic bodies which were shifted by the segments of the northern strand of NAF was given as 3-3.5 km (Kale, 1985; Ergün, 1990). In his modelling studies covering southeastern Marmara Sea, Güvenç (1994) proposed a route for the middle branch of the NAF, passing under the İmralı Island.

Using paleomagnetic data from the Senozoik volcanics of Thrace and the Gelibolu Peninsula, Tapırdamaz and Yaltrak (1997) proposed a model explaining the pattern of paleomagnetic block rotations and tectonic evolution from late Oligocene to Plio-Quaternary. It explains that there was a clockwise rotation of Plio-Quaternary age to the north of the Ganos Fault, while it is counterclockwise in its southern part.

Seismic disturbance

The highly industrialised Marmara region is under high earthquake risk. The velocity field deduced from the GPS observations reveals that the Anatolian region is moving as an approximately coherent plate and is rotating anti-clockwise about a pole located near the Gulf of Suez. The Anatolian plate is uncoupled from Eurasia by the NAF that is characterized by right-lateral a strike-slip at a rate of 23 ± 1 mm/yr (Stein et al., 1996; Straub, 1996; Straub and Kahle, 1994, 1995, 1996, 1997; Straub et al., 1995, 1997; Nalbant et al., 1998). These geodynamic processes produce frequent earthquakes. Most deformation occurs along the northern strand of the NAF zone that runs from Mudurnu valley (Ambraseys and Zatopec, 1969) to the Gulf of Saros where it joins the North Aegean Trough.

Available epicenter maps indicate that the Marmara region along the northern strand of the NAF have continuous seismic activity (Omoto and Çoloğlu, 1968; Ambraseys, 1970; Crampin and Üçer, 1975; Toksöz et al., 1979; Soysal et al., 1981; Üçer et al., 1985; Crampin and Evans, 1986; Ambraseys and Finkel, 1987, 1991, 1995; Kalafat, 1989; Öztin and Bayülke, 1990; Ikeda et al., 1991; Yüksel, 1995; Rockwell et al., 1997). Fault plane solutions of micro-earthquakes reveals that strike-slip, pure normal of oblique faulting earthquakes have occurred in the region (Eyidoğan et al., 1998; Taymaz et al., 1991; Kalafat, 1995, Gürbüz, 2000).

The fact that the slip rate is higher along the northern strand of the NAF than its middle strand suggests that there is higher earthquake risk along the northern strand (Barka and Kuşçu, 1996). Using P-wave travel time data, Gürbüz et al. (1991) have studied crust structure and variation of the Moho depth in the Marmara Region. From azimuthal anomalies computed from the particle motion diagrams, the Moho discontinuity in the region gets deeper from north to south and its deepest parts are in the southwest and southeast edges (Özer et al., 1996).

Many tsunamis were described in the Marmara Sea and the surrounding area from antiquity (AD 553) to the present times (Soysal, 1985; Altınok and Ersoy, 1998). Most of them are earthquake generated as the one

produced by Kocaeli 1999 Earthquake, which occurred along the northern strand of the NAF zone with a magnitude of $M_w=7.4$. It was followed by the Düzce Earthquake ($M_w=7.1$) on November 12th, 1999. The surface ruptures of these two catastrophic earthquakes are characterised by an EW trending zone of right-stepping fault strands, which express a component of extension at the western end of the northern strand of the NAF system (Armijo et al., 1999). Even the focal mechanism solution is of pure strike-slip (Barka, 1999), the Kocaeli 1999 earthquake generated tsunami with an average runup of 2.5 m (Altınok et al., 1999). Depending on the tsunami wave periods and arrival times to the coasts, the tsunami source is situated along the central basin of the İzmit Bay closer to the southern coast (Yalçiner et al., 1999) where active strike-slip and normal faults have been observed on seismic data (Alpar, 1999). The normal faults may correspond to the local vertical displacements where the segments step over and cause tsunami.

Applied Seismic

Marathon, an oil exploration company, shot first important deep seismic sections in the Marmara Sea in 1974. The straits, all bays and deep basins have been explored by seismic reflection method (Özhan et al., 1985; Kurtuluş, 1985; Uluğ et al., 1987; Kavukçu, 1987, 1990; Alpar, 1988; Alavi et al., 1989; Smith et al., 1995; Özturan, 1995; Çetin et al., 1998; Yalıtırak et al., 1998a,b; Alpar and Güneysu, 1999; Alpar and Çizmeçi, 1999; Okay et al., 2000a; Alpar and Yalıtırak, 2000a,b). These works have reported many active and non-active faults, flower structures within the sedimentary infill, etc.. The faults terminating against overlying layers indicate reduced or terminated activities in certain areas. In these areas, the motion is taken up on neighbouring faults.

The İzmit Bay, which was first considered as a part of the major graben system in the Marmara Sea Sieberg (1932), is one of the best explored places by many institutions. This active graben system is dynamically interacted with the NAF zone at least for the last 35-80 kyr (Koral and Eryılmaz, 1995). Some researchers defined these grabens as lying at overlapping sections of the faults which display an en-echelon pattern (Koral and Öncel, 1995; Şenöz, 1998). The Tyrhenian marine units (Erinç, 1956; Sakiñç and Bargu, 1989) of the graben in the İzmit Bay, were developed by the influence of the meso-scaled strike slip and other type faults (Şengör et al., 1982).

From multi-channel seismic reflection profiling survey, the Gemlik Bay is also interpreted as pull-apart structure (Kurtuluş, 1985; Özhan, 1986; Barka and Kuşçu, 1996). The chaotic (upper Pliocene ?) acoustic

basement was overlain by the deposits of calmer depositional environment (upper Pleistocene ?). Normal faults are dominant in the gently folded upper Pliocene deposits.

From single and multi-channel seismic reflection data, Smith et al. (1995) observed a clustering of the maximum water depths of delta tops at about -100 m below the present sea level. They inferred that relative sea-level rise in the southern shelf area has been about 90 m since the last lowstand.

Subsequent new single-channel seismic reflection studies of DEU, once again brought out pull-apart origin of the Marmara basins (Wong et al., 1995; Ergün and Özel, 1995; Ergün et al, 1995). They are rhomb-shaped depressions bounded on their sides by two subparallel, overlapping strike-slip faults, and at their ends by perpendicular or diagonal dip-slip faults.

From MTA's multi-channel seismic reflection profiling surveys, the deep depressions aligned in the Marmara Sea was explored. The westernmost depression is 50-km long and 20-km wide Çınarcık basin. It has been known as a pull-apart basin (Barka and Kadinsky-Cade, 1988; Wong et al., 1995). However, using MTA's data, Okay et al. (2000b) claimed that it was a wedge-shaped deep marine depression bounded by two diverging fault splays. The southern edge of the deep central depressions was defined by en-echelon faults between the İmralı and Marmara islands (Kuşçu et al., 1999). Finally, the strike-slip character of the dextral Ganos fault is clear on seismic data gathered in the Tekirdağ fault bend depression. This basin was filled with 2500 m thick Pliocene-Quaternary syn-transform sediments which show releasing seismic character to the north of the Ganos fault and compressional seismic character to the south of the Ganos fault (Okay et al. 1999; Kurt et al., 2000).

Due to limited the sill depths of the Strait of Çanakkale and the Miocene basement at the Aegean exit (Alpar and Doğan, 1999) and regional uplifting (Yaltırak et al., 2000), the fluctuations in sea level during Quaternary are small-amplitude. From single-channel air gun and deep-tow boomer profiles, Aksu et al. (1999) showed that these fluctuations together with moderate subsidence along the southern shelf of the Marmara Sea created several stacked deltaic successions. In the Western Marmara Sea, they explored a series of sand-prone deposits under the uppermost transparent mud drape (Holocene). The authors suggest that glacial meltwater stored in the Black Sea lake developed into a vigorous southward flow toward the Aegean Sea (~9.5 kyr BP) and these sandy bedforms were created from this unidirectional flow until ~7 kyr BP.

Detailed shallow seismic data along the Strait of Çanakkale demonstrates that the valley floor on the Miocene basement is developed by fluvial erosion (Alpar et al., 1996). The sedimentary sequence disconformable on the Miocene basement overlap the old valley floor. Demirbağ et al., (1998) proposed that the northeastern part of the Strait of Çanakkale and its Marmara Sea exit gained its final form by faulting, i.e. this part of the strait was evolved into its final form as a graben.

Recently, following the Kocaeli 1999 earthquake, high resolution geophysical data, including multibeam swath, shallow and deep seismic reflection, were collected in the Marmara Sea by different institutions such as MTA (R/V Sismik-1), Turkish Navy (TCG Çubuklu), Dokuz Eylül University (R/V Koca Piri Reis) and İstanbul University (R/V Arar). Most of their results have been revealed or published. For example, from seismic data gathered by R/V Arar, an active fault, between the Tuzla Peninsula and the Balıkcı island was discovered (Alpar, 1999). This fault is closest to the southern coasts of the İstanbul city and has a strike slip character. Some possible interactions of the faults in the eastern Marmara basin and in the Gemlik Bay were suggested (Yaltrak et al., 2000; Alpar and Yaltrak, 2000a,b).

Meanwhile, some new or modified tectonic models were also introduced (Armijo et al., 1999; Le Pichon et al., 1999, 2000; Okay et al., 2000a,b; Parke, 2000). Some important studies on the neotectonic settings of the Marmara Sea will be given below with respect to chronology.

Neotectonic setting of the Marmara Sea region

Neotectonics of the Marmara region has been a subject of considerable debate for a long time. Calvert and Neumayr (1880) were the first innovators who made their geographic expedition mainly on terraces. Sieberg (1932) considered the deep Marmara Trough as a part of the major graben system including İzmit Bay and Gulf of Saros.

Pınar (1943) proposed a fault by extending the Ganos-Eksamil Fault (Gutzwiller, 1923) towards the troughs placed in the Marmara Sea and into the Gulf of Saros (Figure 1a). However, her theory was not accepted by Pfannensteil (1944), who proposed as Sieberg (1932) affirmed in the past (Figure 1b).

The Strandja and İstanbul zones are to the north and the Sakarya zone to the south (Okay, 1989; Okay et al., 1990). These zones were juxtaposed as a result of the closure of the intervening Neotethyan ocean (the Intra-Pontide Ocean) during the early Eocene to Oligocene. The Rhodop-Pontid Block was collided with the Sakarya Zone in Oligocene (Şengör,

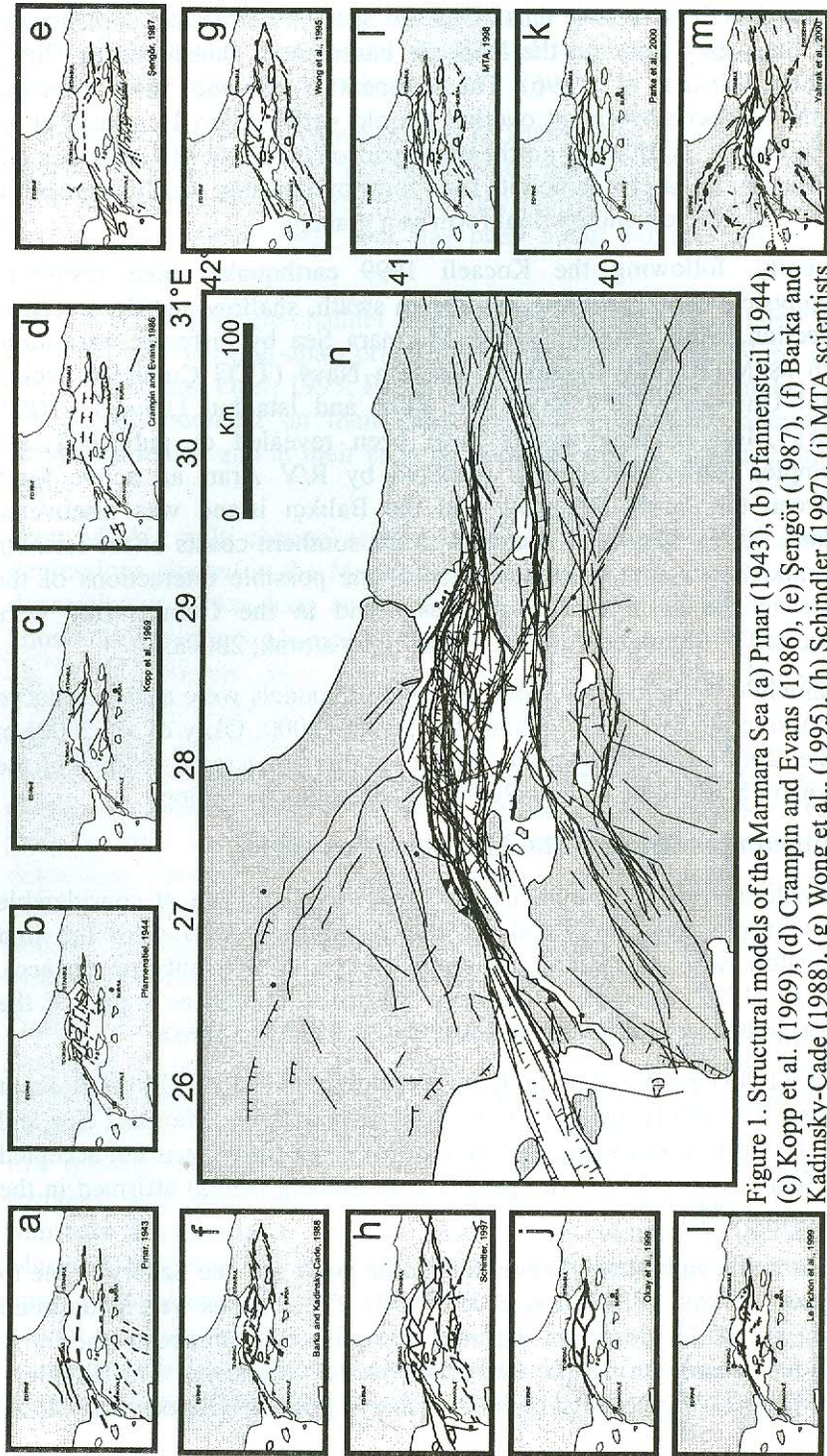


Figure 1. Structural models of the Marmara Sea (a) Pinar (1943), (b) Pffannensteil (1944), (c) Kopp et al. (1969), (d) Crampin and Evans (1986), (e) Şengör (1987), (f) Barka and Kadinsky-Cade (1988), (g) Wong et al., (1995), (h) Schindler (1997), (i) MTA scientists (1998), (j) Okay et al. (1999), (k) Parke et al. (1999), (l) Le Pichon et al. (1999), (m) Yaltrak et al., (2000) and (n) all of the models superimposed on one chart.

1995). The resultant suture is now largely replaced by the NAF zone which is well-known right lateral strike-slip transform fault of the world (Şengör and Yılmaz, 1981; Perinçek, 1991; Barka, 1992, 1996; Okay and Tansel, 1992; Okay and Görür, 1995).

Kopp et al. (1969) separated the northern and middle strands of the NAF (Figure 1c). Later, Crampin and Evans (1986) proposed that there was an E-W trending graben structure in the Marmara Sea (Figure 1d).

The NAF shows interesting morphological and structural characteristics around Gaziköy and Mürefte area. The lower-middle parts of the sequence are represented by transgressive deposits, whereas the upper parts are regressive deposits (Gaziköy Formation), which was overlain unconformably by a Holocene succession. The NAF has strike-slip and vertical components. The vertical slip rate of the southern block from late Pleistocene to present is 0.5 mm per year (Bargu, 1990). Early Miocene was a non-depositional period in Thrace and the Gelibolu Peninsula (Keskin, 1974).

The NW-SE compression, due to counter-clockwise rotation of the Thrace and Biga peninsulas during middle-late Miocene, caused the westerly escape of the central block placed between the northern dextral and southern sinistral faults in the Gulf of Saros (Yaltrak et al., 1998b). These compression later (Quaternary) formed the Anafartalar Thrust Fault on the Gelibolu Peninsula (Yaltrak, 1995a).

The Marmara Sea represents the inundated part of the northwestern Anatolian graben system. This system has developed as a result of the interaction between the NAF and the present N-S extensional tectonic regime of the Aegean (Hancock and Barka, 1981).

The presence of three E-W oriented deep marine basins in the Marmara Sea is related to the NAF zone which is a relatively simple, narrow and right-lateral transform across most of the Turkey (Şengör, 1979). The NAF originated during the late middle Miocene with an original concave-to-the-south geometry in the area where the Marmara Sea formed (Figure 1e) (Şengör, 1987). This fault zone became active in the late Miocene to Pliocene. The amount of its displacement (30-80 km) is still open to argument.

A variety of transtensional and transpressional features are observed along the NAF zone. The east-west trending Marmara Trough is segmented into a series of rhomboidal or wedge-shape small sub-basins. These small fault-bounded-pull-apart basins, which separate the narrow northern shelf from the much broader southern shelf, were generated by

movement of the NAF along its northern strand. They have a mostly NE-SW orientation and are separated by structurally controlled saddles rising ~600 m above their surroundings. Continuous N-S extension accentuated the original curvature of the fault and led to the formation of southward-migrating new strands with narrow and NE-SW-oriented graben complexes, pull-apart basins, and intervening push-up structures (Figure 1f) (Barka and Kadinsky-Cade, 1988). In this model, İzmit and Gemlik bays are strike-slip basins which are filled by slightly lithified to loose fluvial-lacustrine and marine sediments of Plio Quaternary age. This geometric fault relationship in this model indicates that the orientation of maximum principal stress axes during the basin evolution is NW-SE. This may explain the rotation of the NAF zone from E-W to NE-SW. Four different right-stepping segments between Düzce and Karamürsel, which were obtained from detailed mapping of the surface rupture of the Kocaeli 1999 earthquake (Armijo, et al., 1999; Barka, 1999), agrees with this model. In addition, the mechanism proposed by Barka and Kadinsky-Cade (1998) also explains the saddles between the sub-basins.

In the model introduced by Wong et al. (1995), there is a northeast-trending dextral strike-slip fault along the Central Marmara Ridge (Figure 1g). The sub-basins are internally cut by numerous steeply dipping faults which have taken up Quaternary strike-slip motion (Ketin, 1969) along the NAF.

Another similar model was given by Schindler (1997) (Figure 1h). Such a morphology is due to the splaying of the NAF west of the longitude 31°E, where a N-S extension occurs (Şengör et al., 1985; Dewey and Şengör, 1979; Görür et al., 1995).

Based on the middle deep seismic reflection data of R/V Seismic-1, MTA researchers (1998) published a tectonic map of the Marmara Sea (Figure 1i). In this model, the deformation caused by the N-S extension across the northern Marmara Sea is taken up by a series of fault splays.

Okay et al., (1999) introduced a new junction model (Figure 1j) in which dextral strike-slip movement along the northern, inner and southern boundary faults in the eastern Marmara Sea led to the opening of the Çınarcık Basin. They drew the North boundary fault (as named by Wong et al., 1995) along the southern boundaries of the Silivri and Tekirdağ shelf areas and connected it to the Ganos fault. The authors later changed their model radically by introducing central Marmara fault which occupies a position between the southern boundary of Tekirdağ basin and the northern boundary of Çınarcık basin (Okay et al., 2000a,b). In their new model, the Çınarcık Basin has formed around an unstable triple

junction of three dextral strike-slip faults. The arms of the triple junction correspond to the İzmit segment of the NAF in the İzmit Bay, the North boundary fault and the Biga fault in the Biga Peninsula. The Inner boundary fault of their old model (1999) was now considered as part of the İzmit fault. One important feature of this model is that the two arms of the triple junction are highly oblique to the regional displacement vector and to the İzmit fault as well. Dextral strike-slip movement along the arms of this triple junction created the wedge-shaped Çınarcık Basin. This model, which implies at least 53 km of offset along the NAF in the eastern Marmara Sea, does not require any regional NS extension. Therefore, the brittle deformation in the continental crust can be modelled by rigid block translation with little internal deformation.

Using 1500km high resolution seismic reflection data crossing the deepest basins in the Marmara Sea, Parke et al., (2000), indicated that the sediment source varies in each of the basins, complicating the local stratigraphy (Figure 1k).

Supposing that a number of short and discontinuous (en echelon) fault segments separated by three distinct depressions along the Marmara Sea basin cannot produce an earthquake significantly larger than magnitude 7, as occurred in historical records, Le Pichon and his friends proposed one fault model cutting the Marmara Sea as one piece (Figure 1l) and called this large through-going fault as "Marmara fault" (Le Pichon et al. 1999). However, later on, the same authors admit that they were not sure about the existence of the eastward prolongation of Marmara fault across the Çınarcık basin (Le Pichon et al. 2000).

Yaltrak and his friends proposed that the age of the NAF ranged between 3.3 and 3.7 my and introduced the Thrace-Eskişehir fault (TEF) zone which cuts the Marmara Sea in NW-SE direction (Yaltrak et al., 2000; Alpar and Yaltrak, 2000a,b) (Figure 1m). The NAF interacts with right-lateral TEFZ zone (Yaltrak et al., 1998a; Sakinç et al., 1999; Yaltrak et al., 2000). The TEF zone underlies the transtensional tectonic regime and aged as early Miocene-early Pliocene. It considerably lost its activity 3.7 million years ago when the NAF reached to eastern Marmara region. In spite of that, some parts of the TEF, such as the northern margin of the Çınarcık depression and the region between the Gemlik Bay and mid-Marmara basin, lasted their activities, turning their right-lateral character into normal. The displacement came out from the interaction of NAF with TEF in the eastern Marmara is about 62 km during last 3.7 my. In addition, about 8 km shift of TEF was caused by the middle strand of the NAF and opened the Gemlik Bay (Alpar and Yaltrak, 2000a).

As seen, tectonic models for the Marmara Sea have been extensively discussed in the literature. However, if one lay these models on top of each other, it can be seen that the tectonic model of the Marmara Sea is not brought to a conclusion (Figure 1n). However, because no geophysical data generally was used, the explanation of the paleogeographic evolution of the Marmara Sea is not so unclear!

Palaeogeographic evolution of the Marmara Sea region

Following the continental collision and cratonization during the late Oligocene-early Miocene, the Intra-Pontide Ocean closed terminally (Okay and Tansel, 1992; Görür and Okay, 1996). The consequent suture zone formed largely in the area where the Marmara Sea developed. Meanwhile, the Thrace Neogene Basin developed by the activities of the two-strike slip fault system namely, the Thrace-Eskişehir fault (TEF) and Ganos fault zones (Sakıncı, et al., 1999). Paratethys was only effective north of the İstanbul Peninsula during the early-middle Miocene period, meaning that there were no connection between the Black Sea and the Mediterranean Sea along the Turkish Straits System (Sakıncı, et al., 1999). Beyond the NAF, these two marine realms; the saline Mediterranean and the brackish Paratethys/Black Sea (a part of Neogene Paratethys until late Quaternary) are responsible for the geological evolution and palaeogeographic history of the Marmara Sea.

The palaeogeographic history of the Marmara Sea began in the late Serravalian with a brief Mediterranean inundation along the shear zone of the incipient NAF. However, the deep Marmara basins did not start developing as strike-slip transtensional structures until the NAF became fully active. Continuous tilting, block rotation, and subsidence, which were linked to the activity of the NAF, exercised control over all water movement in the basin, together with the changes in global sea level.

Marked differences in faunal assemblages indicate that both sea occupied the Marmara basin alone or together, on occasion. The Paratethyan waters appear to have occupied the basin first in the Pontian, longer than those of Mediterranean. The connection with this brackish-marine realm appears to have continued up to the present, if a short disconnection during the last glacial age is omitted (Görür et al., 1997; Emre et al., 1998).

Seismic stratigraphy has become an extremely important discipline in seismic exploration, particularly in offshore areas. Its success depends upon the integration of seismic wiggles with subsurface information to identify depositional systems, and upon the determination of the influence of stratigraphic controls on these systems (Vail et al., 1977).

