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An active, deep marine strike-slip basin along the North Anatolian fault in Turkey

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Abstract. The Tekirdağ depression within the Marmara Sea in the Mediterranean region is an active, rhomb-shaped strike-slip basin along the North Anatolian fault with a basin floor at a water depth of -1150 m. New multichannel seismic reflection data and on-land geological studies indicate that the basin is forming along a releasing bend of the strike-slip fault and is filled with syntransform sediments of Pliocene-Quaternary age. The basin is bounded on one side by the North Anatolian fault and on the other side by a subparallel normal fault, which forms the steep submarine slope. In cross section the basin is strongly asymmetric with the thickness of the syntransform strata increasing from a few tens of meters on the submarine slope to over 2.5 km adjacent to the North Anatolian fault. Seismic sections also show that the slope-forming normal fault connects at depth to the North Anatolian fault, implying that the basin is completely detached from its substratum. The whole structure can be envisaged as a huge, rather flat, negative flower structure. The releasing bend of the North Anatolian fault, responsible for the formation of the basin, is flanked by a constraining bend. Along the constraining bend, the syntransform strata are being underthrust, implying a recent change in the direction of the regional displacement vector. This thrusting is responsible for the uplift of the submarine slope to a height of 924 m, possibly by a mechanism of elastic rebound. Regional geology suggests that most of the syntransform strata are lacustrine with only the topmost few hundred meters consisting of deep marine clays. The anomalous present depth of the Tekirdağ depression is due to reduced Quaternary sedimentation coupled with high rates of displacement along the North Anatolian fault, which amounts to 20 mm/yr in the Marmara Sea region.

1. Introduction

This paper describes an active strike-slip basin in the Marmara Sea in the eastern Mediterranean region (Figure 1), and it proposes a model for its origin and development. New multichannel seismic reflection profiles and structural data obtained from the immediate onshore during September 1997 form the basis of the descriptions and the model. Previously published seismic studies from the Marmara Sea include only single-channel reflection profiles [*Wong et al.*, 1995; *Ergün and Özel*, 1995]. The basin studied in the Marmara Sea, called the Tekirdağ basin, has a number of features, which makes its detailed study particularly worthwhile. It started to form in the Pliocene, and because of its relatively young age, the sediments in the basin are largely undeformed, and the relation between faulting and sedimentation is not obscured by later deformational events. This is important as many strike-slip basins show alternating periods of sedimentation and deformation, which often introduces an element of ambiguity to the tectonic setting of these basins [e.g., *Biddle and Christie-Blick*, 1985; *Ingersoll and Busby*, 1995]. For example, origins at both restraining [*Crowell*, 1982] and releasing bends [*May et al.*, 1993] have been suggested for the well-studied Ridge basin in southern California. The regional stratigraphy and structure around the Tekirdağ basin are relatively simple and well known, so that there is little ambiguity in differentiating between pretransform and syntransform sequences and structures. Furthermore, unlike most active continental strike-slip basins, which are terrigeneous, the Tekirdağ basin lies at a water depth of -1150 m and constitutes one of the deepest marine strike-slip basins on the continents.

The North Anatolian fault, with a total length of 1500 km, is one of the world's important active strike-slip faults [*Şengör*, 1979; *Woodcock*, 1986; *Barka*, 1992]. It forms part of the complex plate boundary between Eurasian and African plates in the eastern Mediterranean region (Figure 1). The Anatolian microplate escapes westward along the North Anatolian fault from the collision zone between Arabian and Eurasian plates into the north-south extending Aegean region. The North Anatolian fault consists along most of its length essentially of a single fault zone; however, as it nears the Aegean extensional regime in the west, it splits into two branches (Figure 1). The northernmost branch passes through the Marmara Sea and is responsible for the formation of the strike-slip depressions in the northern Marmara Sea. The North Anatolian fault emerges again on land in the southern Thrace and forms a 45-km-long segment, called the Ganos fault, before reentering the Aegean Sea in the Gulf of Saros (Figure 2). Most of the recent westward displacement of the Anatolian Block with respect to Eurasia has been along this northern branch of the North Anatolian fault. The largest twentieth century earthquake in northwest Turkey, with a surface wave magnitude of 7.4, occurred along the Ganos fault on August 9, 1912. It was responsible for the deaths of over 2000 people and the destruction of more than 300 villages and towns [*Ambraseys and Finkel*, 1987]. During

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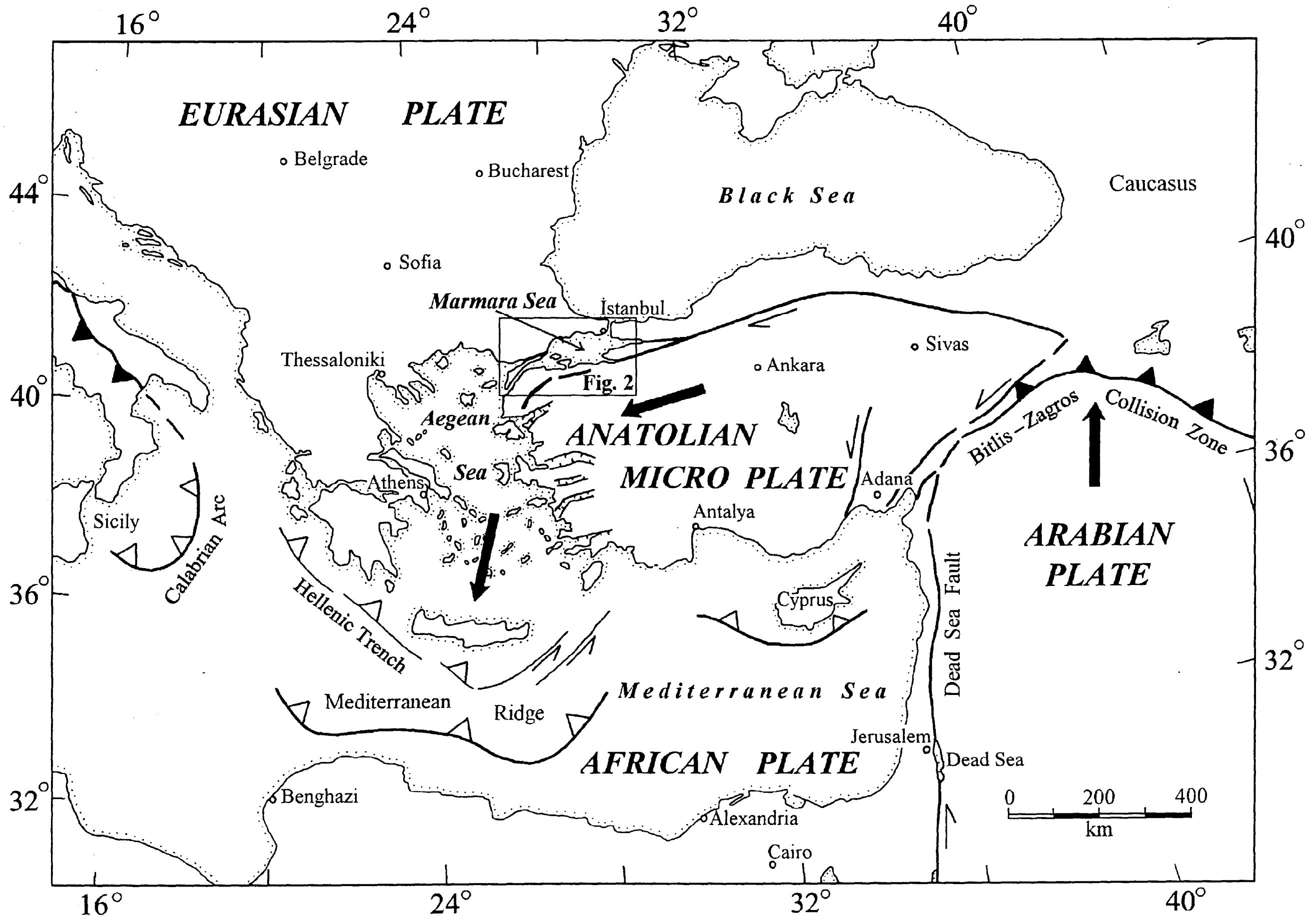


Figure 1. Active tectonic map of the eastern Mediterranean region showing the geological setting of the Marmara Sea. Lines with open triangles show active subduction zones, lines with solid triangles are active thrust faults at continental collision zones, and lines with tick marks are normal faults. The large solid arrows indicate the sense of motion of the lithospheric plates. EAF, East Anatolian fault.

this earthquake the whole fault surface was ruptured with a dextral offset of over 3 m. A recent Global Positioning System (GPS) network around the Marmara Sea with over 45 stations and measurements in 1990, 1992, and 1994 has shown a ~20 mm/yr westward displacement of the Anatolian plate along the northern strand of the North Anatolian fault (Figure 2) [*Straub and Kahle*, 1995].

The northern Marmara Sea is a region of major seismic clustering; in contrast, the on-land segment of the Ganos fault is relatively free of earthquakes [*Üçer et al.*, 1997]. Focal mechanism solutions of major earthquakes in the Marmara region are quite variable, indicating normal, reverse, as well as strike-slip faulting (Figure 2) [*Taymaz et al.*, 1991]. This reflects the complex setting of the Marmara region between the westward escaping Anatolia and the north-south extending Aegea (Figure 1). An important feature of the active deformation in the Marmara region, deduced from earthquake focal mechanism solutions [*McKenzie*, 1972; *Taymaz et al.*, 1991] and GPS measurements [*Straub and Kahle*, 1995; *Oral et al.*, 1995; *Reilinger et al.*, 1997], is that the displacement vectors show an anticlockwise rotation when traced from east to west. In northwestern Turkey the rotation of the displacement vectors is more abrupt and discontinuous than that expected from a smooth rotation around a pole. It starts at ~28°E and increases rapidly westward. The GPS measurements indicate that in the southern Marmara region the displacements with respect to İstanbul are ~20 mm/yr at 28°E, of which 2 mm/yr is the south directed vector component. The south directed vector component increases to 5 mm/yr at 27°E and 7 mm/yr at 26°E (Figure 2) [*Straub and Kahle*, 1997]. This change can also be seen in the curvature of the Ganos fault, of which the trend changes from N68°E in the east to N57°E in the extreme west (Figure 3).

In the Marmara Sea there are three east-west aligned strike-slip depressions (Figure 2). The main subject of this study is the Tekirdağ basin, the westernmost of these depressions with a floor at a depth of -1150 m [*Wong et al.*, 1995]. The Tekirdağ basin is bounded in the west by the Ganos Mountain with a peak of 924 m and in the east by a submarine ridge, which separates the Tekirdağ basin from the Central Marmara basin. The shelf areas of the Marmara Sea form the northern and southern boundaries of the Tekirdağ basin. We first describe the stratigraphy and post-Miocene structures on land

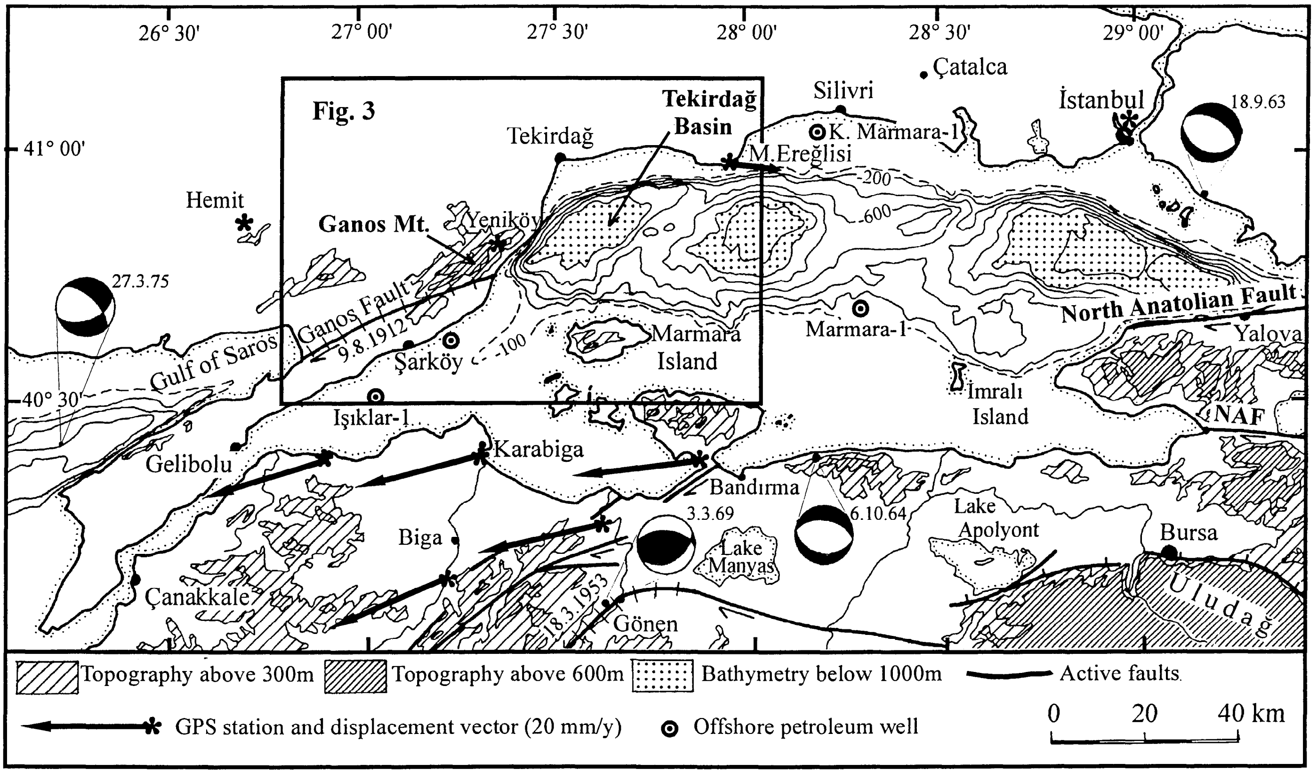


Figure 2. Active tectonic map of the Marmara region. For the location, see Figure 1. The bathymetric contours, drawn at every 200 m, are slightly modified from *Smith et al.* [1995]. The active faults are from *Şaroğlu et al.* [1992], the faults with fine cross-cutting lines indicate the segments which moved in earthquakes during the twentieth century. The fault plane solutions of the major earthquakes ($M > 5$) are from *Taymaz et al.* [1991]. The stars and arrows indicate Global Positioning System (GPS) station localities and displacement vectors, respectively, with respect to a fixed station in İstanbul [*Straub and Kahle*, 1995]. Note the absence of any detectable displacement north of the Ganos fault in Yeniköy and Hemit, indicating that almost all the displacement of the Anatolian microplate is concentrated along this fault and its offshore extensions. NAF represents the southern branch of the North Anatolian fault.

and west of the Tekirdağ basin. In the absence of well data in the Tekirdağ depression, the knowledge of these is essential for the interpretation of the offshore seismic lines.

2. Regional Stratigraphy

The on-land regional stratigraphy consists essentially of two Tertiary sedimentary sequences. The lower one is a siliciclastic sequence of middle Eocene-upper Oligocene age, exposed on both sides of the Ganos fault (Figure 3). North of Ganos fault, the sequence forms a northwest dipping homoclinal series ranging from distal middle Eocene turbidites in the south, through proximal turbidites, to Oligocene deltaic shales and sandstones in the north [*Kopp et al.*, 1969; *Turgut et al.*, 1991; *Sümengen and Terlemez*, 1993; *Görür and Okay*, 1996]. The total exposed thickness of the middle Eocene-Oligocene sequence is ~4000 m.

To the south of the Ganos fault the Eocene-Oligocene sequence is exposed in the cores of the post-Miocene, fault-bounded anticlines (Figure 3). The lower parts of the Tertiary sequence are olistostromal with clasts of serpentinite, radiolarian chert, Cretaceous, and Paleocene pelagic limestone, greenschist, blueschist, diorite, and middle Eocene reefal limestone in a sandstone-siltstone matrix (Figure 4) [*Kopp et al.*, 1969; *Şentürk and Okay*, 1984; *Okay and Tansel*, 1994]. The clasts range from a few centimeters to 1.5 km in size and were derived from a Cretaceous to early Tertiary oceanic accretionary complex. The 9-km-long anticlinal ridge of serpentinite, blueschist, and the unconformably overlying middle Eocene limestone northwest of the village Kocaali is possibly also a megablock in the Eocene sequence (Figure 4). Northwest of Şarköy, the thick olistostromal section passes up into a sequence of intercalated sandstones and siltstones of Oligocene age.

South of the Ganos fault, the middle Eocene-Oligocene sequence is unconformably overlain by Miocene sandstone, shale, and conglomerate deposited in a fluvatile to lagoonal environment (Figure 3) [*Kopp et al.*, 1969; *Sümengen and Terlemez*, 1993; *Görür et al.*, 1997]. The lower part of the Miocene sequence, called the Gazhanedere Formation, consists of variegated sandstone, mudstone, and conglomerate and has a thickness of 500-700 m. Because of its multicolored sandstones and shales, the Gazhanedere Formation forms an easily recognizable marker horizon in the field. It is overlain by yellow, friable, poorly cemented sandstones of the Kirazlı Formation, with a minimum thickness of 700 m, deposited in a nearshore environment. The Gazhanedere and Kirazlı Formations are dated by

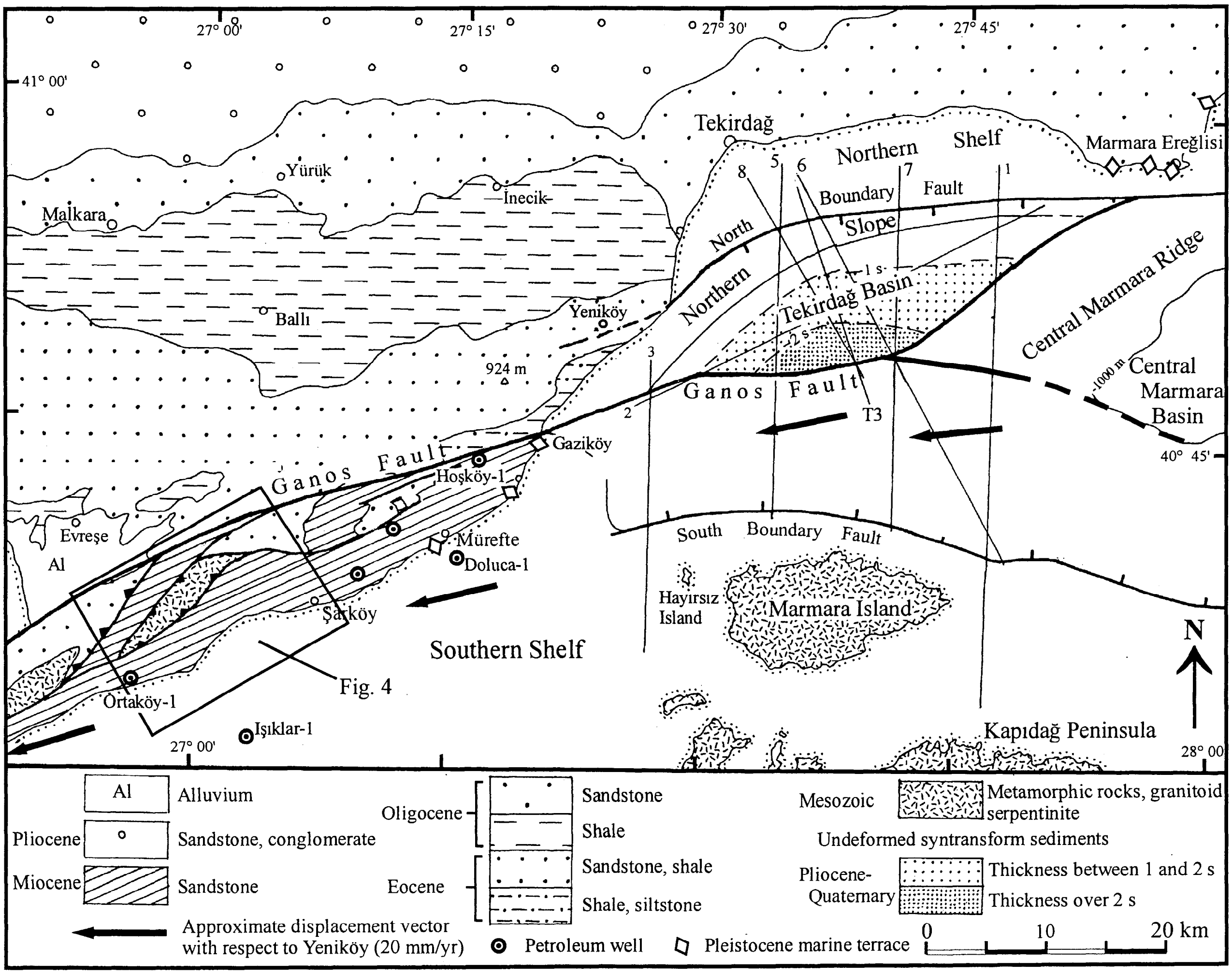


Figure 3. Simplified geological map of the region around the Tekirdağ basin [modified from *Turgut et al.*, 1991]. For the location, see Figure 2. The map also shows the major offshore faults, the thickness (in seconds) of the syntransform sediments in the Tekirdağ basin, as determined in this study, and the location of the multichannel seismic reflection lines obtained on board the Maden Tetkik ve Arama Enstitüsü (MTA) Sismik-1 during September 1997. The solid arrows indicate the general displacement vectors, as extrapolated from the GPS stations 30-50 km farther south (Figure 2).

vertebrate fossils as late early Miocene (Oerlanian equivalent to Burdugalian) and mid-Miocene (Astaracian equivalent to late Burdugalian - Langhian), respectively [*Ünay and de Bruijn*, 1984].

3. Ganos Fault Zone

The main strand of the Ganos fault forms a 45-km-long rectilinear segment between the Marmara and Aegean Seas (Figure 2). The morphotectonic and seismological evidence for dextral motion along the Ganos fault is very strong [*Ambraseys and Finkel*, 1987; *Barka and Kadinsky-Cade*, 1988; *Hancock and Erkal*, 1990]. In the east the Ganos fault forms a prominent topographic feature and is well marked on satellite and air photos (for satellite images of the Ganos fault, see *Allen* [1975], and *Ambraseys and Finkel* [1987]). Westward, the main strand becomes geomorphologically less conspicuous, and in the extreme west the trace of the Ganos fault is lost under the alluvial plain of Evreşe.

The main strand of the Ganos fault defines the northern boundary of a fault zone, ~6 km wide. A geological map and cross section of the Ganos fault zone northwest of Şarköy are shown in Figures 4 and 5, respectively. The fault zone in this region is dominated by transpressive structures, which include thrusts emplacing Eocene-Oligocene sequence over the Miocene beds, and an overturned syncline in the Miocene sandstones. Northwest of the village Kocaali, pre-Miocene rocks are thrust bilaterally over the Miocene beds, forming a positive flower structure (Figures 4 and 5). The dip of the thrust planes observed at a few localities ranges from 40° to 75°. When traced eastward, the transpressive faults bounding the flower structure change their trend gradually and become subparallel with the main strand (Figures 3 and 4). Along with the change in the trend of these faults, the dip direction

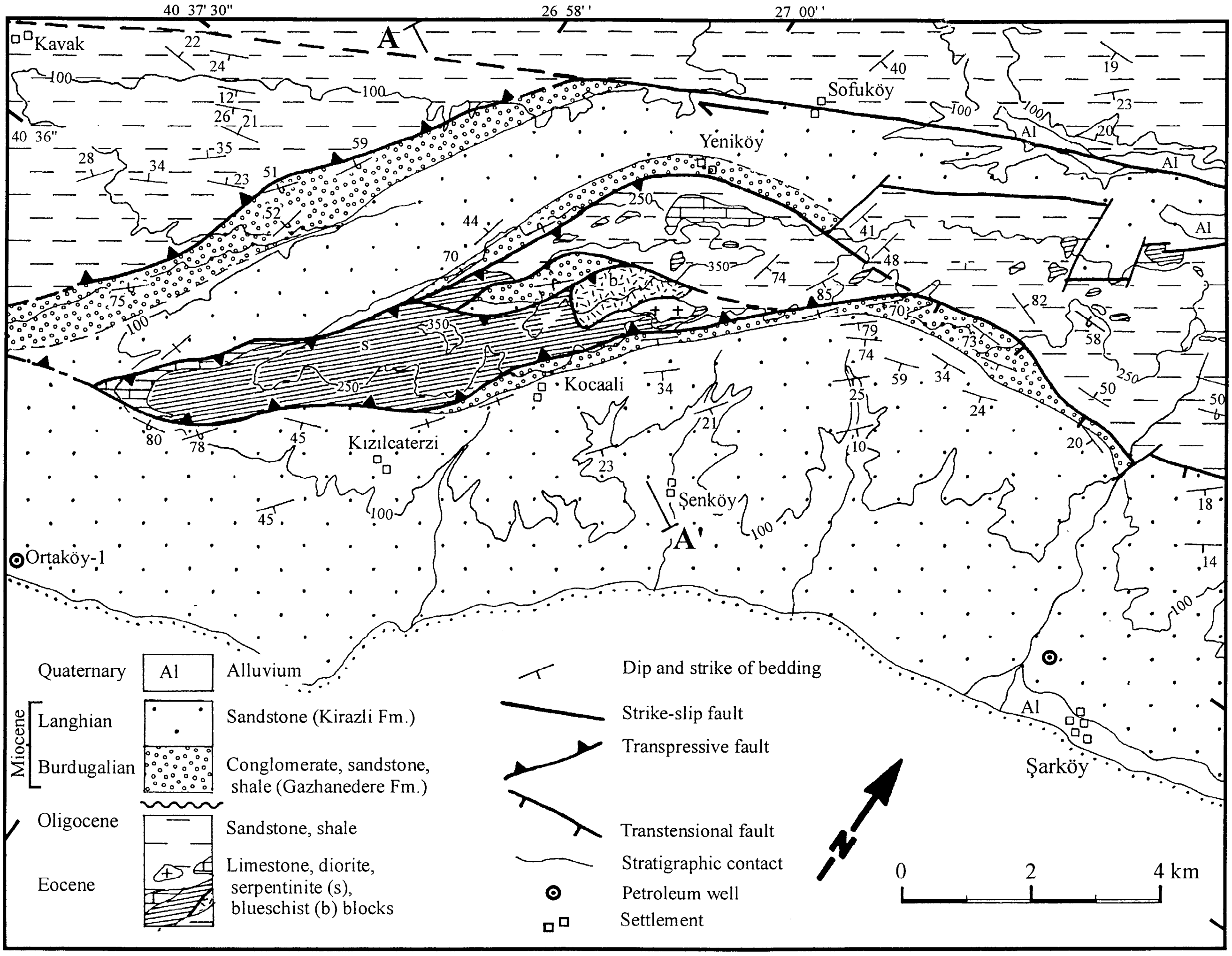


Figure 4. Geological map of the Ganos fault zone north of Şarköy. For the location, see Figure 3.

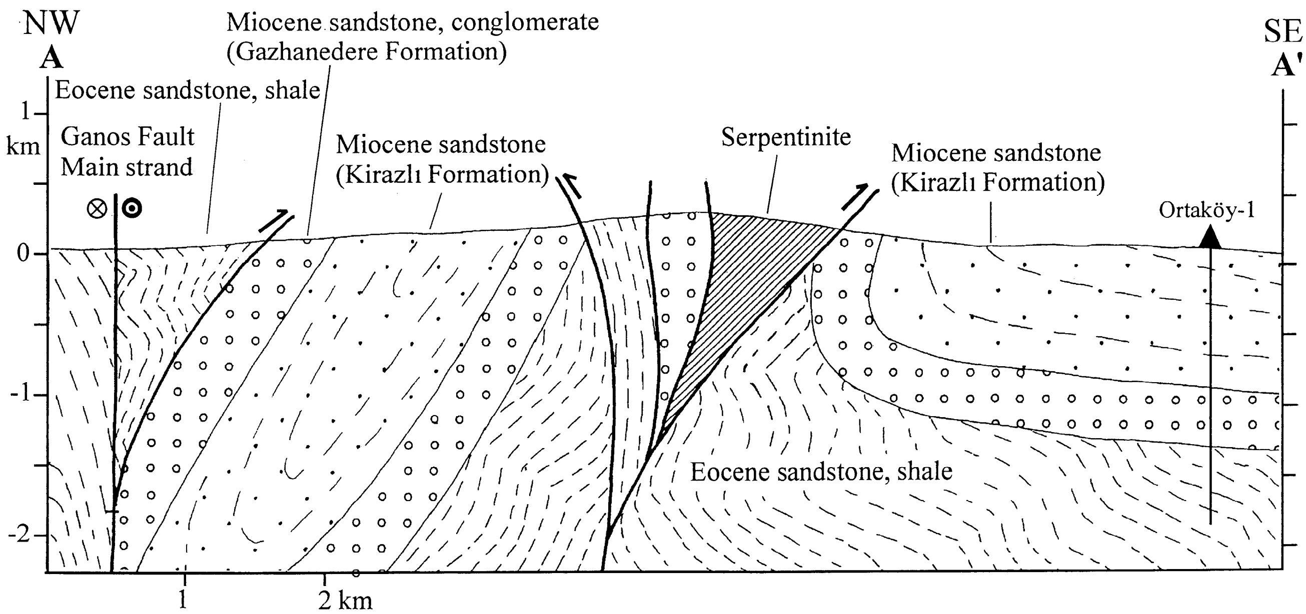


Figure 5. Geological cross section of the Ganos fault zone north of Şarköy. The section is controlled by the Ortaköy-1 well (Figure 3) as well as surface geology. For the location of the cross section, see Figure 4.

of the fault plane also changes, and the faults become transtensional. Such changes in the dip direction along the strike of the fault plane are typical features of the strike-slip faults [e.g., *Sylvester*, 1988].

In contrast to these relatively well-exposed and possibly now inactive transpressional and transtensional faults, the main strand of the Ganos fault follows the river valleys and is often covered by scree deposits, and the fault plane could not be observed in the field. However, the linear trace of the main strand suggests a vertical fault plane and hence largely strike-slip motion. This is corroborated by the results of recent trenches excavated across the main strand of the Ganos fault south of Evreşe. The trenches revealed a vertical fault plane, which according to ^{14}C dating, recorded up to six major earthquakes in the past 4000 years [*Rockwell et al.*, 1997].

The transpressive structures west of Şarköy occur in an area where the main strand of the Ganos fault becomes difficult to define geomorphologically and geologically. Therefore it is highly unlikely that these transpressive structures, along which there has been a major amount of displacement, have formed as secondary structures of the main Ganos fault. One alternative mechanism suggested for their origin is a southward bending of the western segment of the Ganos fault due to north-south extension in the Aegean region. On the basis of GPS velocities, *Reilinger et al.* [1997] describe the motion of the Anatolian microplate as a motion of a single coherent plate around a pole located near the Sinai peninsula. The exception to this coherent plate motion occurs in the western margin of Anatolia, where the Anatolian microplate is deforming internally by north-south extension. Such an extension will result in the southward bending of the western segment Ganos fault, which would become increasingly transpressional and would have been finally abandoned when the current western segment of the Ganos fault was formed (Figure 6c) [cf. *Şengör et al.*, 1985].

4. Age and Offset of the Ganos Fault

Miocene sediments along the Ganos fault do not exhibit features such as fault breccias, disturbed bedding, landslides, liquifaction, etc., which would be indicative of deposition near a major fault. Furthermore, there is no noticeable change in the facies and thickness of the Miocene strata toward the Ganos fault. For example, in the Hoşköy-1 well, drilled 800 m south of the Ganos fault (Figure 3), 568 m of Miocene sediments were encountered, which were similar in facies to those along the coastal strip [*Yaltırak*, 1996]. Thus the Miocene strata must have originally extended to the north of the Ganos fault, but they were removed later by uplift and erosion (Figure 6a). This indicates that the Ganos fault was initiated after the mid-Miocene, which is in agreement with the conclusions of more regional studies inferring a latest Miocene - Pliocene age for the North Anatolian fault [*Şengör*, 1979; *Barka*, 1992].

As described above, the middle Eocene clastic rocks south of the Ganos fault are olistostromal. Numerous olistoliths of serpentinite and middle Eocene reefal limestone occur close to the Ganos fault (Figure 4). In contrast, the age equivalent strata north of the Ganos fault are conspicuously devoid of olistostromes. On the basis of outcrops of olistostromes, a minimum total offset of 40 km can be estimated along the Ganos fault since the latest Miocene. This is compatible with the recent estimates of total offset along the North Anatolian fault, which range between 25 and 85 km [e.g., *Şengör*, 1979; *Barka*, 1992].

5. Sediments and Structures in the Western Marmara Sea

The western Marmara Sea has a narrow northern shelf area, a steep slope, and a flat basin floor, which in the south gradually rises to a wider and better developed southern shelf (Figure 3). Several seismic reflection lines were run across the western Marmara Sea during the Marmara leg of the Maden Tetkik ve Arama Enstitüsü (MTA) Sismik-1 in September 1997 (Figure 3). Continuous positioning of the vessel was maintained by a Differential Geographical Positioning System (DGPS) with a reference station erected near Tekirdağ. The system has an accuracy of better than 5 m.

The data were collected by using an air gun source array of 1380 cubic inches and a 96-channel streamer. The receiver group interval was 12.5 m, and offsets were 50 or 150 m. The recording length, sampling, and shooting intervals were 8 s, 2 ms, and 50 m, respectively. These data collection parameters provided 12-fold reflection seismic data, necessary penetration to reach the subbottom of the Tekirdağ basin, vertical resolution to distinguish the stratigraphy, and horizontal resolution to trace the faults.

Data processing was done at the Data Processing Laboratory of the Department of Geophysics at the İstanbul Technical University (İTÜ). A conventional seismic data processing stream was applied to the data to obtain the interpreted sections displayed in this article. The processing stream was as follows: data reformatting, in-line field geometry definition, trace editing, spherical divergence correction, frequency filtering, sorting, velocity analysis, dynamic correction, muting, predictive deconvolution, stacking, frequency filtering, time domain migration, frequency filtering, and finally automatic gain correction. The structural and stratigraphic information from the seismic sections were transferred to 1:100, 000 scale maps, which formed the basis of our interpretations.

5.1. Shelf

The northern shelf of the Marmara Sea forms a gently southward dipping platform (average dip of 0.4° or 7 m/km), 6 km wide and with a prominent shelf break at a depth of ~100 m. It narrows westward and pinches out completely between the Tekirdağ depression and the Ganos Mountain (Figure 2). Because of the strong multiple reflections, seismic sections are not informative on the nature of the shelf sediments. The Kuzey Marmara-1 well, drilled southwest of Silivri, has encountered less than 20 m of Quaternary marine strata overlying 1100 m of Oligocene-Eocene sandstones and conglomerates [*Ergün and Özel*, 1995]. A similar stratigraphy is expected on the shelf south of Tekirdağ.

5.2. Slope

The northern margin of the Marmara Sea has a very steep slope formed by a major southward dipping fault plane, named the North Boundary fault by *Wong et al.* [1995] and *Ergün and Özel* [1995] (Figure 7). The width of the slope decreases eastward with a concomitant increase in the slope angle from 11° to 23° (Figure 8). Although most of the sequence in the slope is masked by multiple reflections, some of the seismic lines (8 and T3) show undulating subhorizontal reflectors overlain by a thin veneer of sediment less than 100 m thick (Figure 7). The subhorizontal reflectors, which are highly discordant with the attitude of the slope, represent the Eocene-Oligocene sedimentary strata exposed in the immediate onshore, and encountered in the offshore wells (Figure 3).

5.3. Tekirdağ Basin

The Tekirdağ depression is shaped like a rhomb, with a side length of ~15 km and a surface area of ~220 km^2 (Figures 3 and 8). The slope to basin transition occurs at a depth of -1100 m in the west but gradually shallows to -700 m in the east. Most of the floor of the depression lies at a depth of -1150 m and is remarkably flat and structureless (Figures 7 and 9). The Tekirdağ depression is underlain by gently south dipping (average strike and dip: 103/14 SSW) and southward thickening strata with an average velocity of ~2000 m/s. Apart from a few south dipping normal faults with minor offsets (<100 m), the basinal strata are undisturbed. On the seismic lines that trend N-S or NW-SE the basinal strata show a prominent increase in thickness toward a major fault, which abruptly truncates these strata (Figures 7 and 9). This fault, when traced westward in the seismic lines, is seen to join the Ganos fault on land and will be designated by the same name. On the seismic line 2,

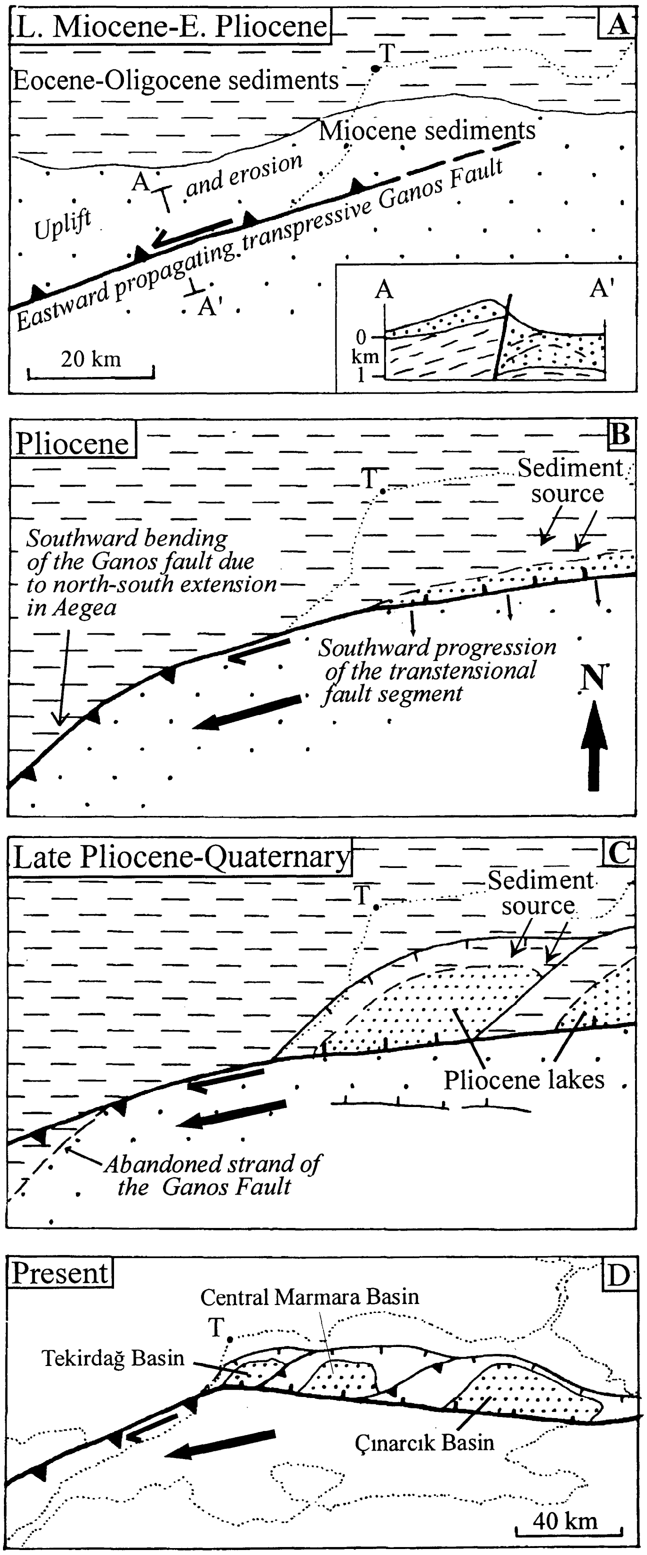


Figure 6. Speculative paleogeographic maps and one cross section illustrating the evolution of the Ganos fault, Tekirdağ basin, and the Marmara Sea in the late Neogene and Quaternary. The location of the present coastline north of the Ganos fault is dotted for reference in each map. T designates the present location of Tekirdağ (see Figure 2). (a) In the latest Miocene-early Pliocene the Ganos fault is initiated in the west and propagates eastward in Miocene sandstones. The eastward progression of the Ganos fault is suggested by the earlier initiation of north-south extension in Aegea (early Miocene) as compared to the westward escape of the Anatolian microplate (late Miocene) [e.g., *Seyitoğlu et al.*, 1992]. The location of the Ganos fault was partly controlled by an underlying pre-Oligocene suture, which probably imposed a transpression along the Ganos fault. As a result of transpression, the Miocene sediments north of the Ganos fault were uplifted and eroded, while those to the south were folded. (b) In the Pliocene a narrow and elongate terrigenous basin is initiated north of the eastern extensional segment of the Ganos fault. The transtensional segment of the Ganos fault migrates southward creating a subsiding basin in the north. (c) In the late Pliocene-Quaternary the basin north of the transtensional segment of the Ganos fault is differentiated into three en echelon basins separated by transpressive faults. These basins form Pliocene lakes fed from sediments coming from the northeast. The Pliocene lakes are flooded by the waters of the Aegean Sea during the Pleistocene. (d) In the Present the Marmara depressions are forming along a very large releasing bend of the North Anatolian fault. Major crustal extension coupled with the lack of sediment supply from the north has resulted in water depths of over -1100 m in the basins.

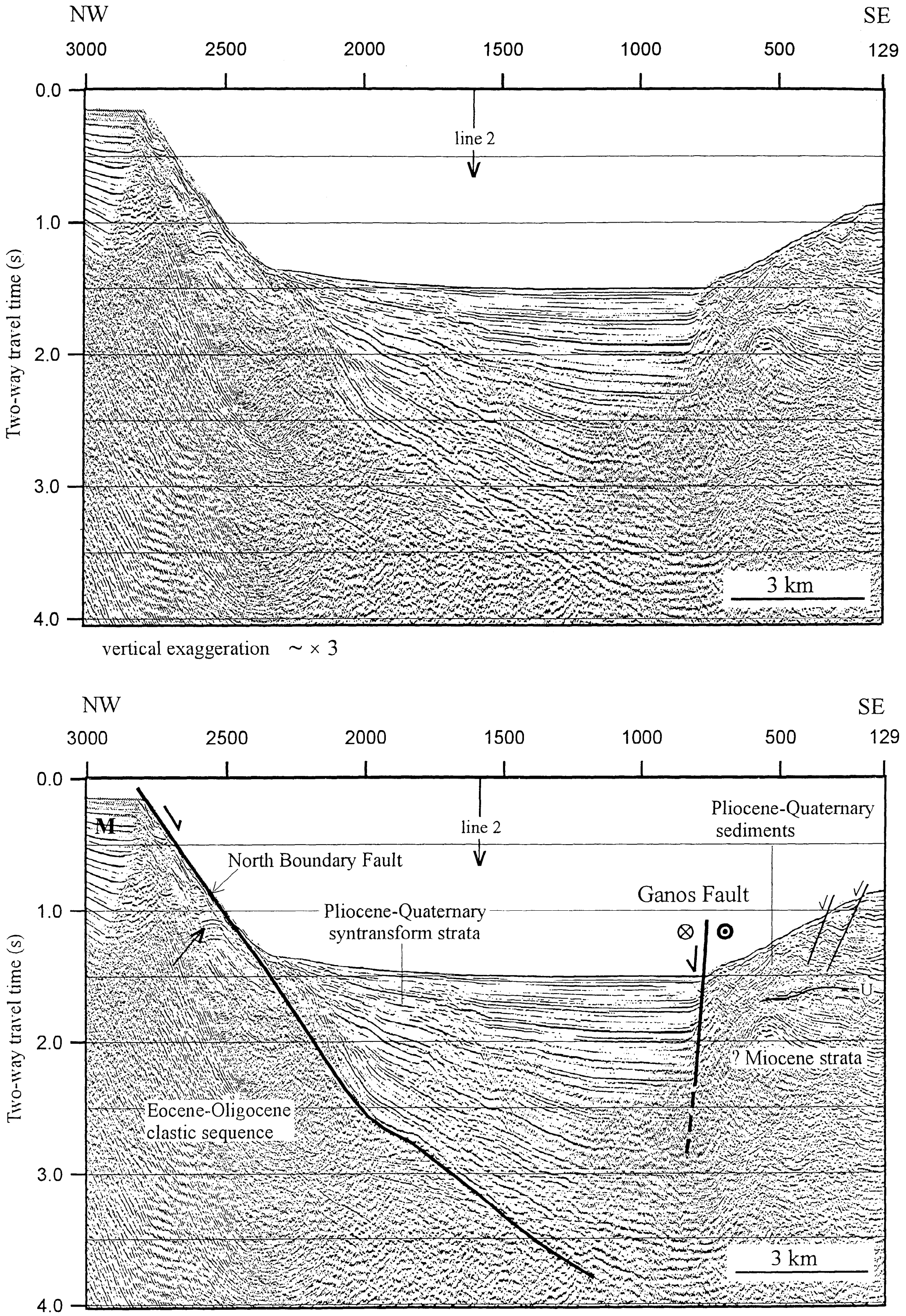


Figure 7. Uninterpreted and interpreted time-migrated seismic reflection section of line T3. The arrow in the northwest below the submarine slope points to the subhorizontal reflections from the Eocene-Oligocene sequence. The digits are the common depth point (CDP) numbers. Multiple reflections are indicated by M, and a possible unconformity is indicated by U. The vertical exaggeration shown is an average and approximate value for the syntransform sediments. See Figure 8 for the profile location.

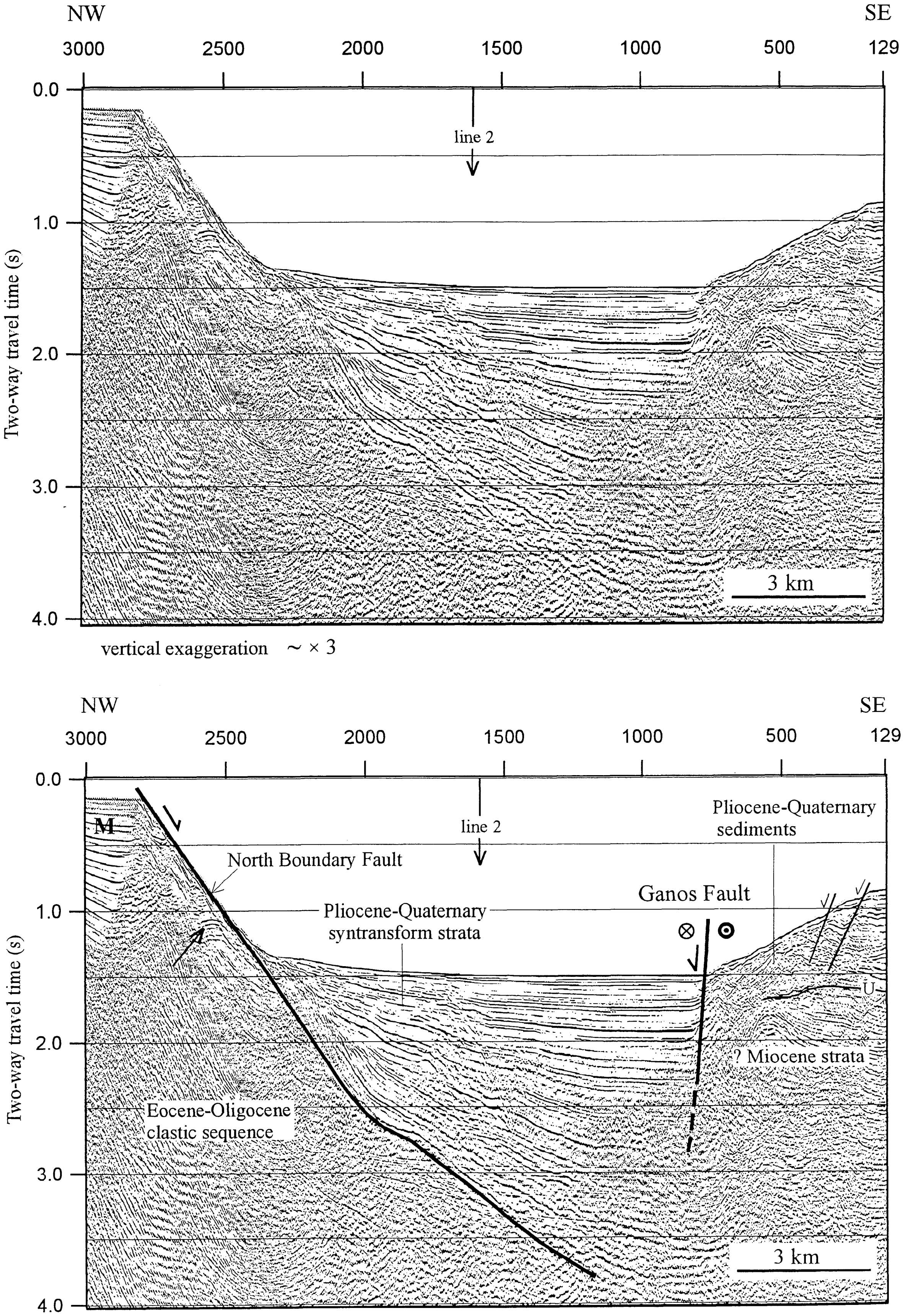


Figure 7. (continued)

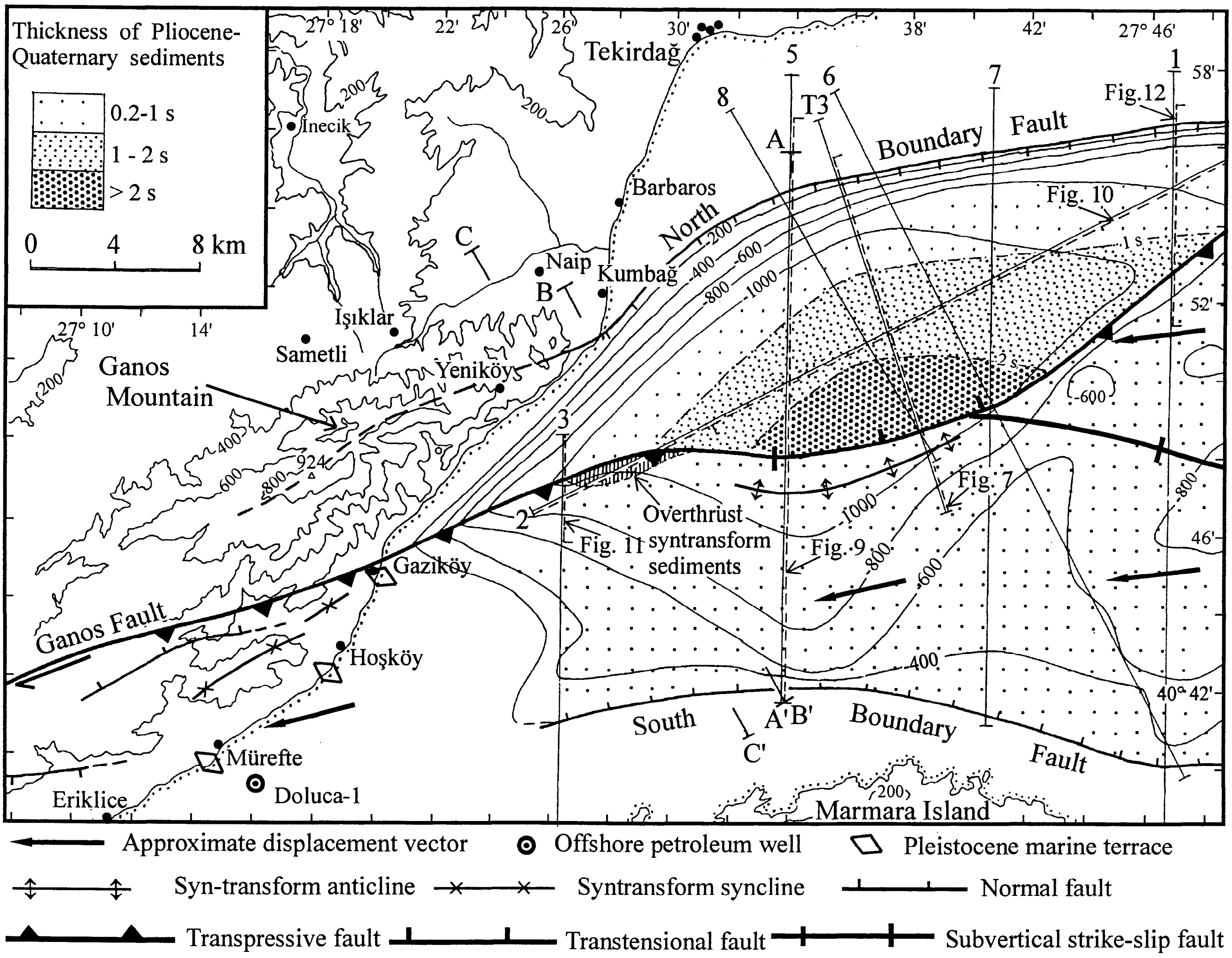


Figure 8. Bathymetric and topographic map of the Tekirdağ basin and surrounding area. The segments of the seismic sections shown in Figures 7, 9, 10, 11, and 12 are shown by dashed lines. The solid arrows represent average displacement vectors, as estimated from GPS displacement vectors 30-50 km farther south (Figure 2). Also shown are the isopachs in seconds two-way travel time of the Pliocene-Quaternary sediments.

which trends NE-SW and cuts the other lines, the reflections show a distinct SW dip, and many of the reflections downlap on the basement (Figure 10). Because of the strong downlap of the basinal strata, the total stratigraphic thickness in the Tekirdağ basin is greater than that which would have been encountered in any single well, a feature also observed in other strike-slip basins [*Crowell*, 1982]. The southwestward progradation of the basinal strata, as observed in the seismic line 2 (Figure 10), indicates that the sediments were fed into the basin from the northeast. Seismic line 2 also shows that the basin center has migrated southwest through time. For example, during the deposition of the strata "a" in Figure 10, the basin center must have been located 7 km farther northeast than the present one.

The basinal strata are underlain by a largely unreflective basement, so that the contact between the basinal strata and the basement is well defined (Figures 7, 9, and 10). The basement shallows toward the margins of the depression and comes close to the sea bottom at the basin to slope transition (Figures 7, 9 and 10), which suggests that the basement consists of the Eocene-Oligocene sequence exposed in the immediate on land.

An isopach map of the thickness of basinal strata north of the Ganos fault, expressed in seconds of two-way travel time, is shown in Figure 8. Figure 8 shows that the thickness of the basinal strata shows a gradual increase toward the Ganos fault. The thickest strata of ~2.5 s, corresponding approximately to 2.5 km, occur immediately north of the Ganos fault. The distribution of the basinal strata mimics the present bathymetry of the Tekirdağ depression, showing a decrease in thickness toward its margins (Figure 8). These features, the increase in the thickness of basinal strata toward the Ganos fault and the correlation between the thickness isopachs and the shape of the Tekirdağ depression, indicate that the basinal sediments were deposited in the presently active strike-slip tectonic environment and thus represent syntransform sediments. Considering that the North Anatolian fault was initiated in the southern Thrace after the

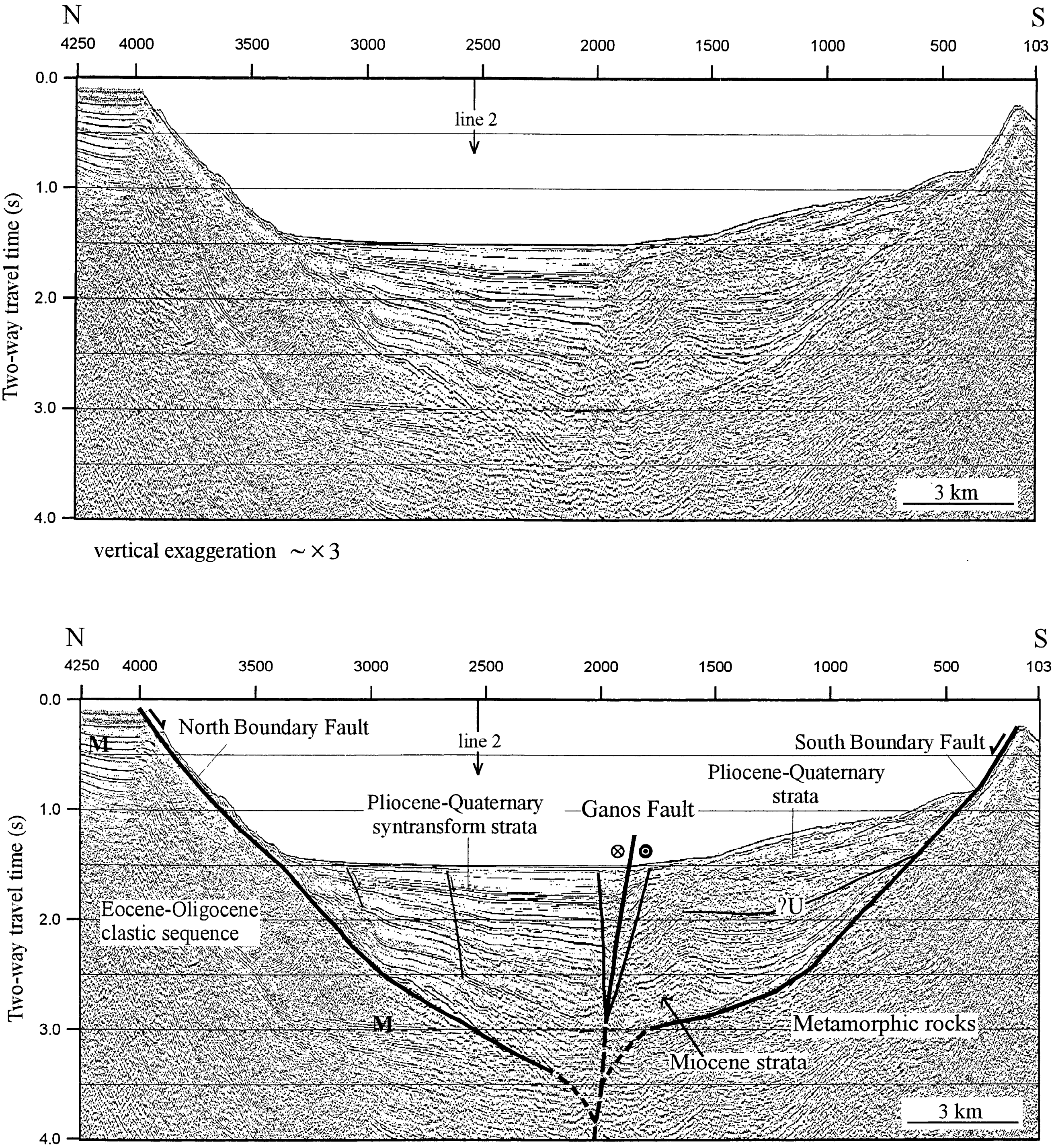


Figure 9. Uninterpreted and interpreted time-migrated seismic reflection section of line 5. The digits on top are the CDP numbers. Multiple reflections are indicated by M, and a possible unconformity is indicated by U. The vertical exaggeration shown is an average and approximate value for the syntransform sediments. See Figure 8 for the profile location.

mid-Miocene and most probably during the Pliocene, the syntransform strata in the Tekirdağ basin must be Pliocene and Quaternary in age.

A sequence of gently folded to subhorizontal sediments occurs immediately south of the Ganos fault zone (Figures 7 and 9). From their reflection characteristics these sediments appear to be different than those to the north of the Ganos fault. North of the Ganos fault, the reflections are continuous, subparallel, and divergent toward the fault, while those to the south are less regular (Figures 7 and 9). The sequence south of the Ganos fault was interpreted as deformed syntransform sediments by *Wong et al.* [1995] and *Ergün and Özel* [1995].

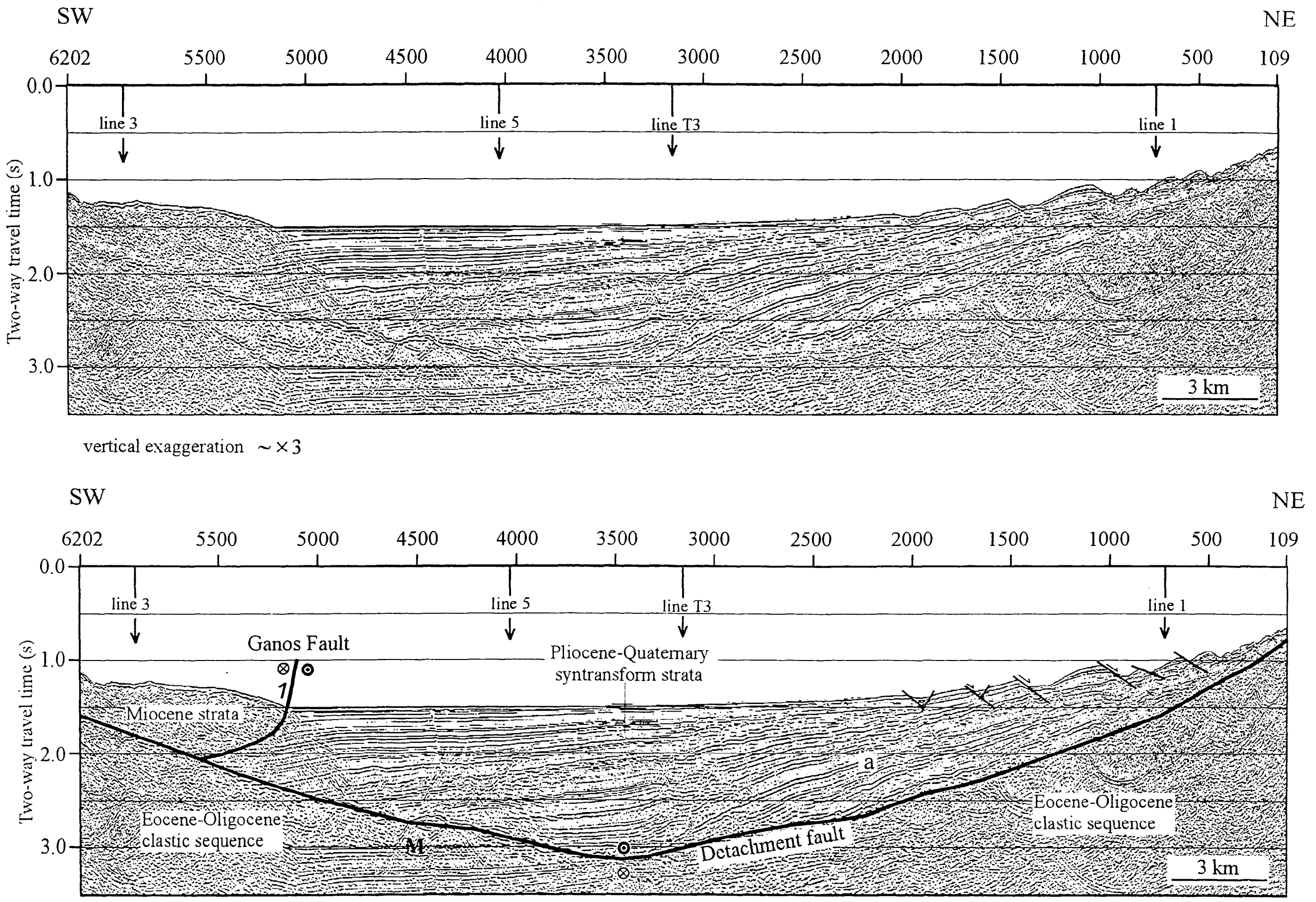


Figure 10. Uninterpreted and interpreted time-migrated seismic reflection section of line 2. Note that during the deposition of strata "a", the basin center must have been located 7 km farther northeast. The digits on top refer to the CDP numbers. Multiple reflections are indicated by M. The vertical exaggeration shown is an average and approximate value for the syntransform sediments. See Figure 8 for the profile location.

However, detailed study of the seismic sections reveals that it consists of two parts, a lower folded part overlain, possibly by an unconformity, by an upper part showing normal faulting (Figures 7 and 9). Neither part shows the close correlation with the bathymetry or with the Ganos fault, as observed in the sequence north of the fault. The main structure in the lower sequence south of the Ganos fault is an anticline with a half wavelength of 1.5 km (Figures 7 and 9) and an axial length of over 11 km (Figure 8). The axis of the anticline trends parallel to the Ganos fault (Figure 8), indicating that it is a syntransform structure. Considering that the Pliocene-Quaternary strata are affected only by normal faulting, the folded sequence to the south of the Ganos fault must be older than the Pliocene. An indication of the nature of the folded sediments south of the Ganos fault comes from the Işıklar-1 and Doluca-1 petroleum wells, drilled on the southern shelf (Figure 3). These wells have encountered no Pliocene or younger rocks but entered directly into the Miocene strata, 265 and 720 m thick, respectively, which were underlain by the Eocene-Oligocene sequence [*Ergün and Özel*, 1995; *Yazman*, 1997]. Broad folds with axis parallel to the trend of the Ganos fault have been mapped in the Miocene sediments on land (Figure 8). Hence the well data, as well as the land geology (Figure 3), suggest that the lower sequence south of the Ganos fault consists of the Gazhanedere and Kirazlı Formations of Miocene age. The upper sequence, which is generally less than 0.6 s thick, is probably Pliocene-Quaternary in age. The Miocene to Quaternary sequence south of the Ganos fault thins southward toward the southern slope of the Marmara Sea and is sharply underlain by a nonreflective unit, the Triassic metamorphic rocks exposed on the Marmara and Hayırsız islands (Figure 3) [*Okay et al.*, 1996].

5.4. Offshore Extension of the Ganos Fault

The offshore trace of the Ganos fault was mapped with the aid of the seismic lines and bathymetry (Figures 3 and 8). In the seismic lines the Ganos fault forms a 2- to 3-km-wide zone characterized by disturbed reflections (Figures 7 and 9). The northern boundary of this fault zone is sharp with the syntransform sediments, while the southern boundary is more gradational.

Traced offshore from Gaziköy, the Ganos fault maintains its trend for 11 km and occupies the bottom of a major submarine valley (Figures 8 and 11a). In this segment the Ganos fault is strongly transpressional and is represented by a fault plane, which dips at 25° to SSE. Along this active shallowly dipping fault plane the syntransform strata are being overthrust by a deformed sequence (Figure 11b), which can confidently be correlated with the Miocene rocks in the immediate on land (Figure 8). Toward the west, the syntransform strata pinch out, and the Miocene rocks are overthrusting the Eocene-Oligocene sequence (Figure 11a). The shallowly dipping fault planes observed on the seismic lines 2 and 3 must steepen southward and with depth. Extrapolation from subvertical fault planes of the Ganos fault from farther east indicates that the steep belt occurs ~4 km south of the transpressional segment (Figure 11c).

The transpressional segment of the Ganos fault ends with an abrupt releasing bend at 27°30' E. Along this transtensional segment the Ganos fault plane dips north at ~70°. This central segment must have accommodated the deposition of 2.5-km-thick syntransform sediments. Traced eastward, the Ganos fault bifurcates into northeast and east trending faults (Figure 8). The northeast trending fault forms a transpressive segment along which the Central Marmara ridge is overthrusting the Tekirdağ basin along a plane dipping southeast at ~50° (Figure 12). This fault can be compared to the transverse structures with dominant dip-slip offsets, which are encountered at the terminations of some strike-slip basins [e.g., *Ben-Avraham and Garfunkel*, 1986]. The main transtensional branch of the Ganos fault trends eastward and is probably responsible for the development of the Central Marmara basin (Figure 3). In the region of the Central Marmara ridge the displacement is complexly partitioned between dominant reverse faulting along the transverse fault and strike-slip plus normal faulting along the main branch.

A striking feature of the transpressional segment of the Ganos fault as observed on seismic line 2 is that it soles to the main reflector at the base of the syntransform stata (Figures 10 and 11b). Comparison of the intersection planes of seismic lines 2 and 3 (compare Figures 11a and 11b) indicates clearly that in this region the Ganos fault and the basal reflector are the same structure. Furthermore, in the N-S seismic lines the slope-forming North Boundary fault appears to join the Ganos fault through the basal reflector (Figures 7 and 9). These observations imply that the Tekirdağ basin is detached at a shallow crustal level. The detachment fault has a dip of ~15° to the southeast and a maximum depth of 3 km. A detached basin model also provides an explanation for the southwestward migration of the depocenter as observed in the longitudinal seismic section (Figure 10). In many ways the Tekirdağ basin can be viewed as a huge, flattened, negative flower structure with the North Boundary fault forming the northern limit of this structure (Figure 13).

The downward extension of the South Boundary fault appears to follow the contact between the Miocene strata and the crystalline basement (Figure 9). This may indicate that the interface between the Miocene sediments and the underlying metamorphic rocks is also detached, so that the southern limb of the megaflower structure is represented by the South Boundary fault (Figure 13). The observation that the anticline south of the Ganos fault has nucleated at the interface between the Miocene sequence and the crystalline basement (Figure 9) also suggests a detachment along this major contact. In a transverse section the western Marmara megaflower structure has a length of ~24 km, and it probably roots at the contact between the Eocene-Oligocene sequence in the north and the metamorphic rocks in the south. The syntransform strata and the poorly lithified Miocene rocks form an easily deformable float over the more competent Eocene-Oligocene sequence and the metamorphic rocks (Figure 13).

6. Origin and Development of the Tekirdağ Basin

The straight coastline between Gaziköy and Kumbağ is characterized by a very steep cliff (Figures 8 and 14) and by an absence of a shelf. On the basis of these morphological features, as well as the sharp topographic-bathymetric contrast between the Tekirdağ depression (-1150 m) and Ganos Mountain (924 m), all previous workers considered that the Ganos fault makes a sharp northward restraining bend as it enters the Marmara Sea at Gaziköy [*Şengör*, 1979; *Şengör et al.*, 1985; *Barka and Kadinsky-Cade*, 1988; *Wong et al.*, 1995; *Ergün and Özel*, 1995; *Barka*, 1997]. Thus, in all previous maps, a major transpressive fault was shown trending parallel and very close to the shoreline between Gaziköy and Kumbağ. *Şengör* [1979] and *Şengör et al.* [1985] suggested, in the absence of seismic data, that the Tekirdağ depression was a compressional basin formed in front of this transpressive fault flanking the southeastern face of the Ganos Mountain. However, the thickness distribution of the syntransform sediments and the geometry of the basin indicate that the Tekirdağ depression is not a foreland basin. *Barka and Kadinsky-Cade* [1988] regarded the Tekirdağ basin as a pull-apart basin formed between overlapping northeast trending segments of the North Anatolian fault. This view was adopted with some modifications by *Wong et al.* [1995] and *Ergün and Özel* [1995]. These studies again postulate a major restraining bend of the North Anatolian fault as it enters the Marmara Sea at Gaziköy, a fault segment for whose origin there is no independent evidence except the Ganos uplift. In the pull-apart model of Barka and Kadinsky-Cade, Wong et al., and Ergün and Özel, the major strike-slip movement occurs along the northeast trending faults with the east-west trending faults having a role of subsidiary normal faults bounding the basin. In such a case the center of the pull-apart basin, and hence the area of major sediment accumulation, should be centrally located between the overlapping northeast trending faults. Furthermore, the thickness distribution of the syntransform sediments should be roughly symmetrical with respect to the NE-trending faults [e.g., *Sylvester*, 1988]. Both of these predictions of the pull-apart model for the origin of the Tekirdağ basin are not borne out by the thickness distribution of the syntransform sediments in the Tekirdağ basin (Figure 8), which is strongly asymmetrical and shows the greatest thickness adjacent to the east-west trending fault. The distribution of the syntransform sediments in the Tekirdağ basin, as well as the observation that the Ganos fault does not bend at Gaziköy but continues along strike for 11 km (Figure 8), do not allow a pull-apart origin for the Tekirdağ basin.

We suggest that the Tekirdağ basin forms at a releasing bend of the Ganos fault. The evidence for this is that the

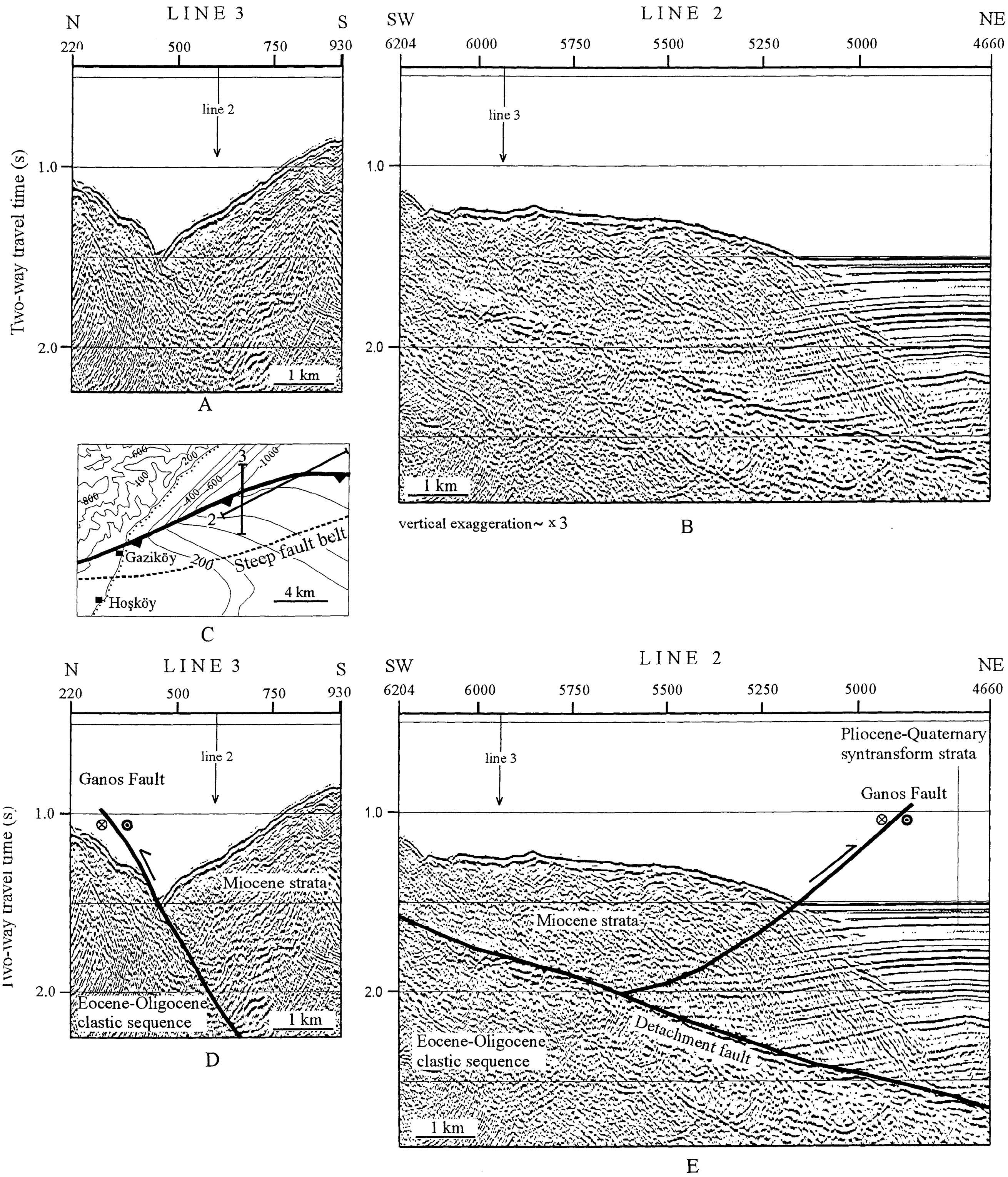
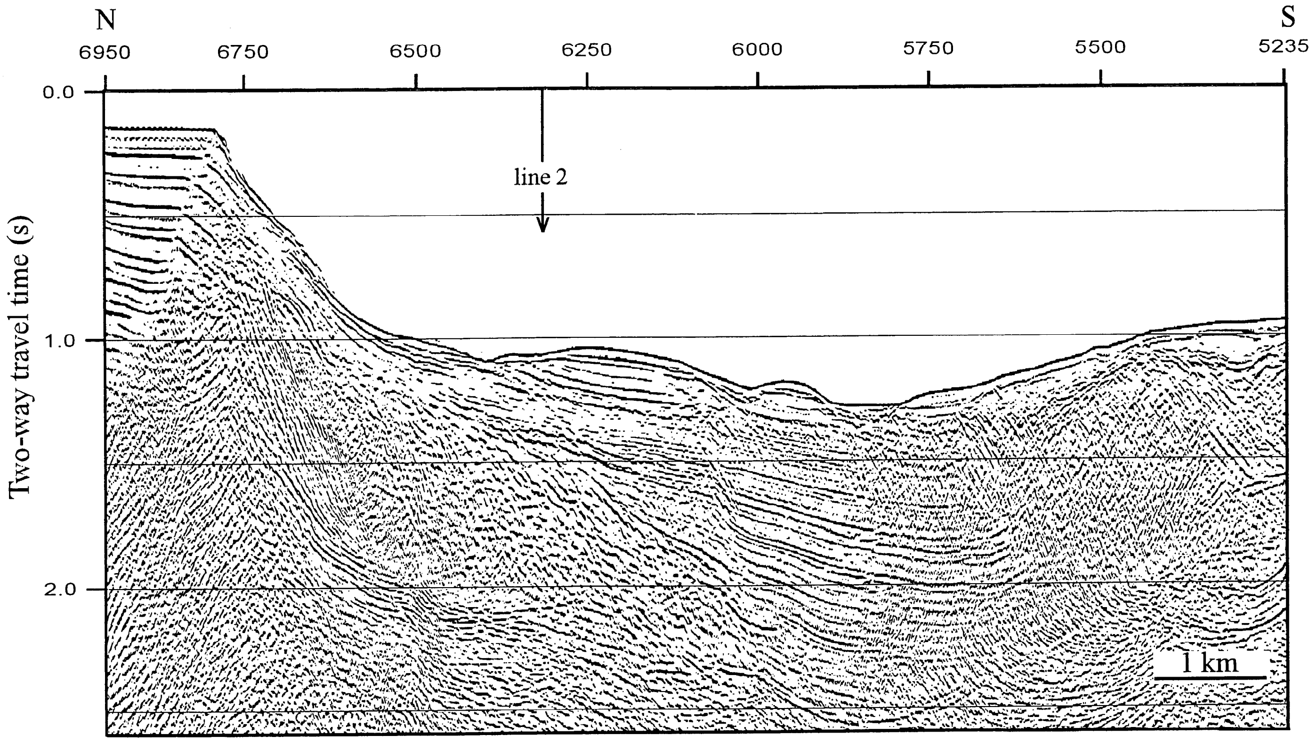


Figure 11. Uninterpreted time-migrated seismic reflection sections of critical segments of (a) line 3 and (b) line 2 showing the Ganos fault. (c) The location of the seismic sections, see Figure 8 for a larger framework. (d, e) Interpreted time-migrated seismic reflection sections for the critical segments in Figures 11a and 11b. Note that the Ganos fault in line 3 corresponds to part of the basal detachment in line 2. The dipping reflectors, which overlap the reflections from the syntransform strata in Figure 11b, are side echoes from the steep walls of the submarine valley (see Figure 11c). The digits on top are CDP numbers. The vertical exaggerations shown are average and approximate values.



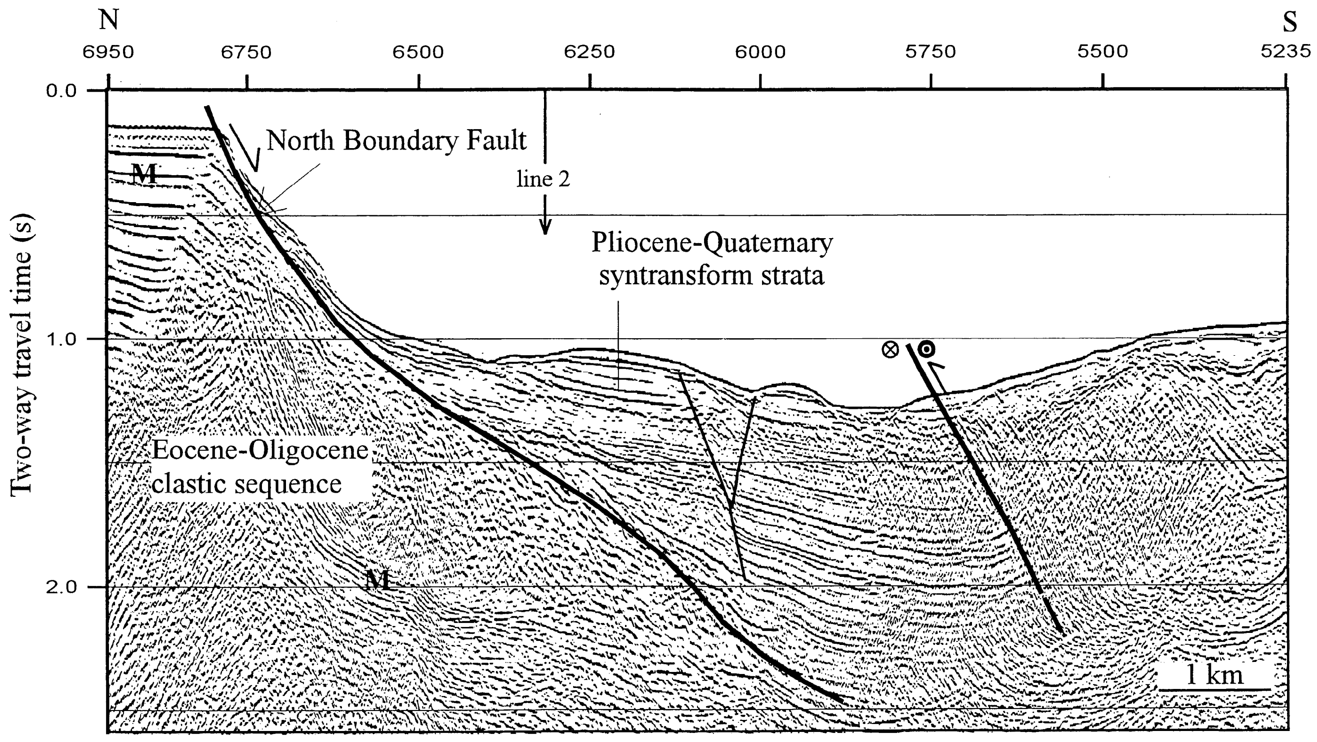


Figure 12. Uninterpreted and interpreted time-migrated seismic reflection sections of line 1. The digits on top are CDP numbers. Multiple reflections are indicated by M. The vertical exaggeration shown is an average and approximate value for the syntransform sediments. See Figure 8 for the profile location.

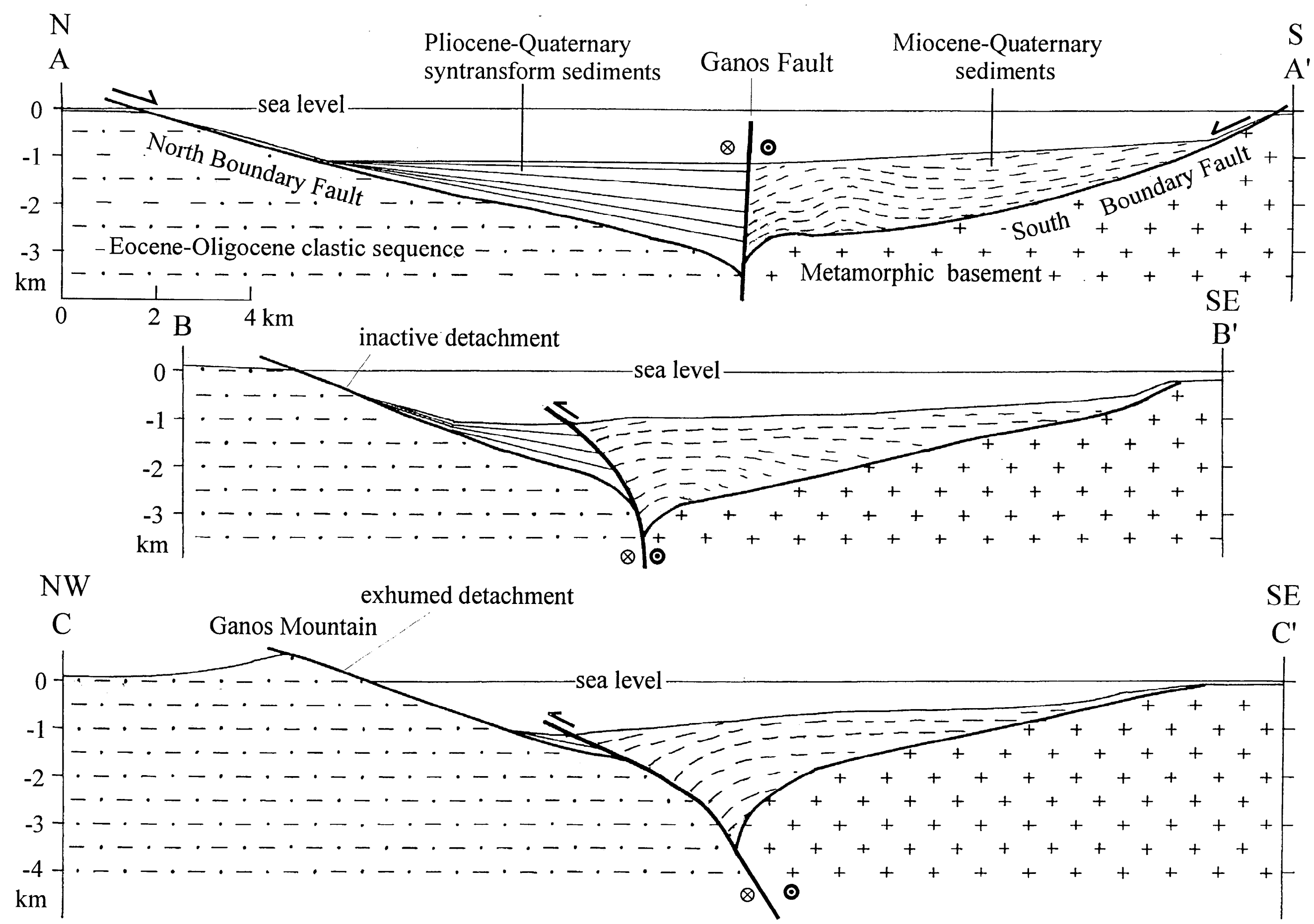


Figure 13. Unexaggerated cross sections across the Tekirdağ basin and the Ganos Mountain. For location of the sections, see Figure 8.

region of the thickest syntransform sediments coincides with the transtensional segment of the Ganos fault (Figure 3). The present GPS displacement vectors also indicate extension along this central segment and compression in the western segment (Figures 3 and 8) [*Straub and Kahle*, 1995].

There is no well data to constrain the facies of the Pliocene-Quaternary syntransform sediments in the Tekirdağ basin. upper Miocene and Pliocene strata are not present along the coast between Şarköy and Tekirdağ. The Marmara-1 well drilled on the southern shelf (Figure 2) has cut through 126 m of Quaternary marine calcareous clay and through 2174 m of fluviatile and lacustrine mudstone, sandstone, and marl of Pliocene age [*Ergün and Özel*, 1995]. The Pliocene rocks in the central Thrace basin and in the Dardanelles region are also made up of fluviatile and lacustrine sandstones with thicknesses of up to 300 m (Figure 3) [*Kopp et al.*, 1969]. Thus the available data indicate that the Marmara Sea region was a land area during the Pliocene. The first direct evidence of late Cenozoic marine environment in the Marmara Sea is the marine terraces, which line its shores with the notable exception of the Ganos Mountain region (Figure 3) [*Sakınç and Yaltırak*, 1997]. Fauna in the terrace deposits are typically Mediterranean, indicating influx from the Aegean Sea, and isotopic analysis of the shells in the marine terraces gives mid- to late Pleistocene ages (260, 000-130, 000 years) [*Paluska et al.*, 1989]. Thus the present Marmara Sea was first formed during the Pleistocene, possibly late Pleistocene following the Tyrrhenian marine transgression. Therefore most of the Pliocene-Quaternary syntransform strata in the Tekirdağ basin must be lacustrine and/or fluavitile, with probably only the topmost few hundred meters being marine. The considerable thickness of syntransform strata in a relatively small area, as observed in the Tekirdağ basin, suggests that the Tekirdağ basin was a lake during the Pliocene (Figure 6c). This lake was separated from the Aegean Sea through the Dardanelles strait, which has a present-day sill depth of 60-70 m. Considering the strong extension in the Tekirdağ depression and its present-day depth (-1150 m), it is interesting to speculate that the surface of the Pliocene lake must have been well below the Pliocene sea level, like the present-day Dead Sea, whose surface lies at -400 m. Flooding of this Pliocene lake by the Mediterranean waters, once the sill at the Dardanelles was breached during the late Pleistocene, must have been sudden and catastrophic, possibly a smaller-scale example of the flooding of the Mediterranean after the Messinian desiccation [e.g., *Hsü et al.*, 1972].

7. Origin of the Ganos Uplift

The northern shelf of the Marmara Sea, which is delimited by the North Boundary fault, narrows westward and pinches out completely south of Kumbağ, where it abuts against the Ganos Mountain (Figure 8). The westward continuation of the North Boundary fault is closely linked with the formation of the Ganos Mountain, an anomalously high uplift (+924 m) bordering the Tekirdağ depression (-1150 m) (Figures 2 and 8). It is striking that the Ganos uplift occurs directly in front of the transpressional segment of the Ganos fault and that it dies out eastward as the transpression gives way to transtension (Figure 8), indicating a genetic link between compression and uplift. It is suggested here that the Ganos uplift is an elastic bulge forming in front of the transpressional segment of the Ganos fault. A further argument for the transpressional origin of the Ganos uplift is based on the source area of the syntransform sediments. It is noteworthy that in the Tekirdağ basin most of the sediments were derived from the northeast rather than from the Ganos Mountain, which at present constitutes by far the strongest erosional region in the whole area. This would have been highly unlikely if the Ganos Mountain had been present during the Pliocene when the syntransform strata were being deposited. On the other hand, a more recent Quaternary uplift of the Ganos Mountain, which is compatible with its transpressional origin, would explain the absence of a westerly sediment source in the Tekirdağ depression. Compared to other described elastic bulges, the Ganos uplift is distinguished by the very short distance between the thrust and the bulge. However, unlike other elastic bulges, which result from the bending of an essentially horizontal plane, the Ganos Mountain is forming from the bending of the slope of the Tekirdağ basin, which is inclined at 17° toward the thrust plane. This explains the relatively short distance between the thrust and the elastic bulge and the comparatively high elevation of the bulge. The elastic bulge model for the Ganos uplift implies that the southern face of the Ganos Mountain represents the exhumed slope of the Tekirdağ basin and hence that of the North Boundary fault (Figure 13). A supportive argument for this model is that the transverse cross sections from the Ganos Mountain give a profile similar to that of the slope of the Tekirdağ depression (Figure 13).

To further constrain the nature of the Ganos uplift, a detailed study of the minor structures was made in the Eocene turbidites along the well-exposed coastal section between Gaziköy and Kumbağ (Figure 14). The middle Eocene turbidites form a homoclinal, moderately north dipping sequence. They are truncated by numerous postdepositional, mesoscopic normal fault planes striking NW and dipping at 60°-80°, generally to the NE with displacements ranging from a few centimeters to one meter (Figure 14). Although the dip of the fault planes is higher than that expected for the normal faults, rare slickensides indicate pure dip slip. The normal faults are scarce in the inland exposures (A. I. Okay, unpublished data, 1997), suggesting that their formation is related to the activity along the Ganos fault. The traces of northwest striking normal faults enclose an angle of ~70° with the trace of the Ganos fault. This angle is considerably more than the expected angle of 45° [e.g., *Sunderson and Marchini*, 1984; *Hancock*, 1985], and it provides independent evidence for transpression along this segment of the Ganos fault. *Hancock and Erkal* [1990] describe mesoscopic and map-scale normal faults with similar orientations in the Miocene sediments between Eriklice and Gaziköy south of the Ganos fault.

Turbidites along the coastal section northeast of Gaziköy are also transected by numerous extensional veins filled with blocky calcite. The veins are very regular in orientation, up to 6 mm thick, and appear to be contemporaneous with normal faulting. They represent extension normal to the fracture plane with no detectable sideways movement. The calcite veins strike northeast subparallel to the trend of the Ganos fault and dip at moderate angles to the SE (Figure 14). Their formation may be ascribed to the longitudinal fracturing of the crust as a result of bending of the lithosphere during the formation of the elastic bulge.

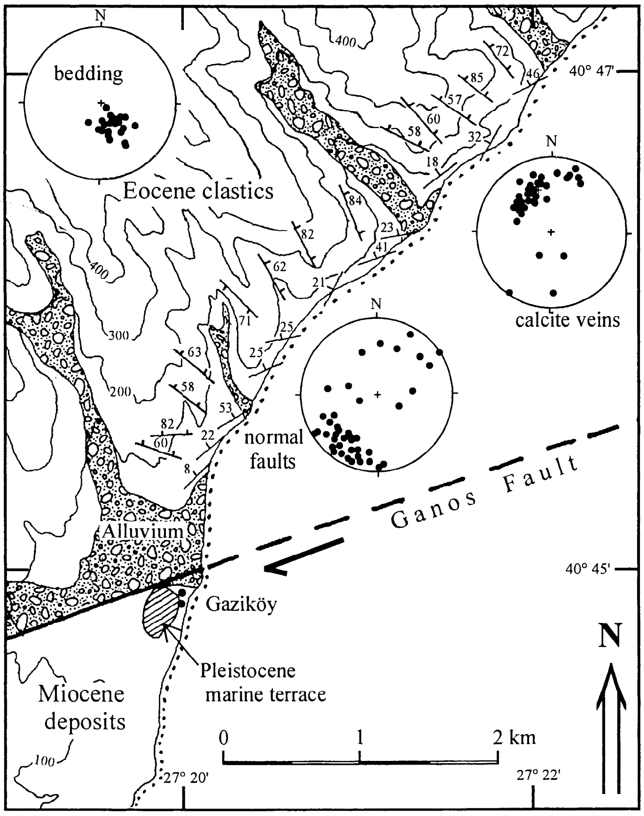


Figure 14. Structural map of the coastal section northeast of Gaziköy, where the Ganos fault enters the Marmara Sea. The stereograms show poles to the bedding, poles to the mesoscopic fault planes, and poles to the extensional calcite veins. Topographic contours are shown at every 100 m. For illustrative purposes, representative mesoscopic faults on the coastal exposures are projected a few hundred meters inland.

8. Conclusions

The Tekirdağ basin is a small, rhomb-shaped strike-slip basin, which is forming at a releasing bend of the North Anatolian fault. The other two basins in the Marmara Sea (Figure 2) probably had a genesis similar to that of the

Tekirdağ basin, and they all have formed along a major releasing bend of the North Anatolian fault (Figure 6d). The Tekirdağ basin is bounded on one side by the North Anatolian fault and on the other side by a subparallel major normal fault. At depth the normal fault joins the North Anatolian fault along a major subhorizontal detachment fault, indicating that the whole basin is detached. The structure of the Tekirdağ basin resembles a very large, broad negative flower structure. The Tekirdağ basin has an infill of up to 2.5-km-thick, undeformed syntransform sediments, which are distributed very asymmetrically. The maximum sedimentary thickness occurs next to the North Anatolian fault, and the thickness decreases rapidly toward the limiting normal fault (Figures 7 and 9). The thickness distribution of the syntransform sediments indicates extension at right angles to the North Anatolian fault (Figure 8). Such asymmetric strike-slip basins with inferred extension perpendicular to the strike-slip fault have been described among others from the Dead Sea and San Andreas faults, and they imply simultaneous strike-slip motion and transform normal extension [*Aydın et al.*, 1990; *Ben-Avraham and Zoback*, 1992]. This is contrary to the classical strike-slip basin model in which extension occurs in a direction parallel to the regional strike of the strike-slip fault. This apparent anomaly is explained by a model of a weak strike-slip fault in a strong crust; in which case, divergent plate motion results in a nearly fault normal extension [*Ben-Avraham and Zoback*, 1992].

Regional paleogeography indicates that most of the Pliocene-Quaternary sedimentary infill of the Tekirdağ basin is terrigeneous and most probably lacustrine. The Tekirdağ basin was flooded by the sea probably during the late Pleistocene. At present, no large rivers drain into the Marmara Sea from the north. The sediments, which are brought by rivers draining from the south, are trapped in the southern shelf by back-tilted blocks bounded by north dipping normal faults [*Smith et al.*, 1995]. Therefore the Tekirdağ basin has been starved of sediment since at least the late Pleistocene. Continuing extension coupled with sediment starvation resulted in a depth of -1150 m for the Tekirdağ basin. In the stratigraphic record this will be reflected by a sudden change in facies from lacustrine sediments to deep sea silts and clays, which are currently being deposited in the Tekirdağ depression [*Ergin et al.*, 1991].

Although the Tekirdağ basin is only of Pliocene age, the western margin of the basin is already being compressed with the syntransform strata being overthrust by the Miocene rocks. This suggests a clockwise rotation of the displacement vector during the Quaternary, which is also inferred from strike-slip associated structures on land. The clockwise rotation also explains the contradiction that although at present the whole of the Ganos fault appears to be transpressional [*Straub and Kahle*, 1995], transtensional faults subparallel to the main branch of the Ganos fault occur northeast of Şarköy (Figure 8) [*Hancock and Erkal*, 1990]. The major upright anticline in the Miocene sediments south of the offshore Ganos fault, which is overlain by younger Pliocene-Quaternary strata showing normal faulting (Figure 7), suggests a transpressional tectonic environment for the early period of strike-slip faulting in southern Thrace (Figure 6a). Folds with similar geometry and trends have been mapped in the Miocene sediments on land (Figure 8). *Tüysüz et al.* [1998] also inferred a similar transpressional tectonic environment from the Neogene stratigraphy of the Gelibolu peninsula. The active thrusting of Miocene strata over the older Eocene-Oligocene sequence implies an earlier period of uplift and erosion north of the Ganos fault, which most probably occurred during this early period of transpressive strike-slip faulting (Figure 6a). The Ganos fault in southern Thrace follows an early Tertiary suture, as marked by outcrops of blueschist, serpentinite, and pelagic limestone north of Şarköy (Figure 4) [*Şengör and Yılmaz*, 1981; *Görür and Okay*, 1996]. The main complexity in the evolution of the Ganos fault probably arises in the obliquity of the paleotectonic faults defining this suture to the neotectonic displacement vectors.

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References

Allen, C.R., Geological criteria for evaluating seismicity, *Geol. Soc. Am. Bull.*, *86*, 1041-1057, 1975.

Ambraseys, N.N., and C.F. Finkel, The Saros-Marmara earthquake of 9 August 1912, *Earthquake Eng. Struct. Dyn.*, *15*, 189-211, 1987.

Aydın, A., R.A. Schultz, and D. Campagna, Fault-normal dilation in pull-apart basins: Implications for the relationship between strike-slip faults and volcanic activity, *Ann. Tecton.*, *4*, 45-52, 1990.

Barka, A.A., The North Anatolian Fault Zone, *Ann. Tecton.*, *6*, 164-195, 1992.

Barka, A.A., Neotectonics of the Marmara region, in *Active Tectonics of Northwest Anatolia: The Marmara Poly-project*, edited by C. Schindler and M. Pfister, pp. 55-87, Hochschulverlag AG an der ETH, Zürich, 1997.

Barka, A.A., and K. Kadinsky-Cade, Strike-slip fault geometry in Turkey and its influence on earthquake activity, *Tectonics*, *7*, 663-684, 1988.

Ben-Avraham, Z., and Z. Garfunkel, Character of transverse faults in the Elat pull-apart basin, *Tectonics*, *5*, 1161-1169, 1986.

Ben-Avraham, Z., and M.D. Zoback, Transform-normal extension and asymmetric basins: An alternative to pull-apart models, *Geology*, *20*, 423-426, 1992.

Biddle, K.T., and N. Christie-Blick, Strike-slip deformation, basin formation, and sedimentation, *Spec. Publ. Soc. Econ. Paleontol. Mineral.*, *37*, 386 pp., 1985.

Crowell, J.C., The tectonics of the Ridge basin, southern California, in *Geological History of Ridge Basin, Southern California*, edited by J.C. Crowell and M.H. Link, pp. 25-41, Soc. of Econ. Paleontol. and Mineral., Pacific Sect., 1982.

Ergin, M., M.N. Bodur, and V. Ediger, Distribution of surficial shelf sediments in the northeastern and southwestern parts of the Sea of Marmara: Strait and canyon regimes of the Dardanelles and Bosporus, *Mar. Geol.*, *96*, 313-340, 1991.

Ergün, M., and E. Özel, Structural relationships between the Sea of Marmara basin and the North Anatolian Fault Zone, *Terra Nova*, *7*, 278-288, 1995.

Görür, N., and A.I. Okay, Fore-arc origin of the Thrace basin, northwest Turkey, *Geol. Rundsch.*, *85*, 662-668, 1996.

Görür, N., M.N. Çağatay, M. Sakınç, M. Sümengen, K. Şentürk, C. Yaltırak, and A. Tchapalyga, Origin of the Sea of Marmara as deduced from Neogene to Quaternary paleogeographic evolution of its frame, *Int. Geol. Rev.*, *39*, 342-352, 1997.

Hancock, P.L., Brittle microtectonics: Principles and practice, *J. Struct. Geol.*, *7*, 437-457, 1985.

Hancock, P.L., and T. Erkal, Enigmatic normal faults within the European sector of the North Anatolian transform fault zone, *Ann. Tecton.*, *4*, 171-181, 1990.

Hsü, J.J., W.B.F. Ryan, and M.B. Cita, Late Miocene desiccation of the Mediterranean, *Nature*, *242*, 240-244, 1972.

Ingersoll, R.V., and C.J. Busby, Tectonics of sedimentary basins, in *Tectonics of Sedimentary Basins*, edited by C.J. Busby and R.V. Ingersoll, pp. 1-51, Blackwell Sci., Cambridge, Mass., 1995.

Kopp, K.O., N. Pavoni, and C. Schindler, Geologie Thrakiens IV: Das Ergene Becken, *Beih. Geol. Jahrb.*, *76*, 136 pp., 1969.

May, S.R., K.D. Ehman, G.G. Gray, and J.C. Crowell, A new angle on the tectonic evolution of the Ridge basin, a "strike-slip" basin in southern California, *Geol. Soc. Am. Bull.*, *105*, 1357-1372, 1993.

McKenzie, D., Active tectonics of the Mediterranean region, *Geophys. J. R. Astron. Soc.*, *30*, 109-185, 1972.

Okay, A. I., and İ. Tansel, New data on the upper age of the Intra-Pontide Ocean from north of Şarköy (Thrace), *Bull. Miner. Res. Explor. Inst. Turk.*, *114*, 23-26, 1994.

Okay, A.I., M. Satır, H. Maluski, M. Siyako, P. Monie, R. Metzger, and S. Akyüz, Paleo- and Neo-Tethyan events in northwest Turkey: Geological and geochronological constraints, in *Tectonic Evolution of Asia*, edited by A. Yin and M. Harrison, pp. 420-441, Cambridge Univ. Press, New York, 1996.

Oral, M.B., R.E. Reilinger, M.N. Toksöz, R.W. King, A.A. Barka, I. Kınık, and O. Lenk, Global Positioning System offers evidence of plate motions in Eastern Mediterranean, *Eos Trans. AGU*, *76*(2), 9-11, 1995.

Paluska, A., T. Poetsch, and S. Bargu, Tectonics, paleoseismic activity and recent deformation mechanism in the Sapanca-Abant region (NW Turkey, North Anatolian Fault Zone), in *Proceedings of the Turkish-German Earthquake Research Project*, edited by J. Zschau and O. Ergünay, pp. 18-32, Earthquake Research Institute, Ankara, Turkey, 1989.

Reilinger, R.E., S.C. McClusky, M.B. Oral, R.W. King, M.N. Toksoz, A.A. Barka, I. Kınık, O. Lenk, and I.Şanlı, Global Positioning System measurements of present-day crustal movements in the Arabia-Africa-Eurasia plate collision zone, *J. Geophys. Res.*, *102*, 9983-9999, 1997.

Rockwell, T., A. Barka, K. Thorup, and S. Akyüz, Paleoseismology of the Gaziköy-Saros segment of the North Anatolian Fault, northwestern Turkey: Implications of regional seismic hazard and models of earthquake recurrence, Paper presented at International Symposium on Recent Developments on Active Fault Studies, İstanbul Techn. Univ., İstanbul, 1997.

Sakınç, M., and C. Yaltırak, Marine Pleistocene deposits and Pleistocene paleogeography of the southern Thrace (in Turkish), *Maden Tetkik Arama Ens. Derg.*, *119*, 43-62, 1997.

Sanderson, D.J., and W.R.D. Marchini, Transpression, *J. Struct. Geol.*, *6*, 449-458, 1984.

Şaroğlu, F., Ö. Emre and İ. Kuşçu, Active fault map of Turkey. Gen. Dir. of the Miner. Res. and Explor., Ankara, Turkey, 2 sheets, scale 1: 2, 000, 000, 1992.

Şengör, A.M.C., The North Anatolian transform fault: Its age, offset and tectonic significance, *J. Geol. Soc. London*, *136*, 269-282, 1979.

Şengör, A.M.C., and Y. Yılmaz, Tethyan evolution of Turkey: A plate tectonic approach, *Tectonophysics*, *75*, 181-241, 1981.

Şengör, A.M.C., N. Görür, and F. Şaroğlu, Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study, in *Strike-Slip Deformation, Basin Formation, and Sedimentation*, edited by K.T. Biddle and N. Christie-Blick, *Spec. Publ., Soc. Econ. Paleontol. Mineral.*, *37*, 227-264, 1985.

Şentürk, K., and A.I. Okay, Blueschists discovered east of Saros Bay in Thrace, *Bull. Miner. Res. Explor. Ins. Turk.*, *97/98*, 72-75, 1984.

Seyitoğlu, G., B.C. Scott, and C.C. Rundle, Timing of Cenozoic extensional tectonics in west Turkey, *J. Geol. Soc. London*, *149*, 533-538, 1992.

Smith, A.D., T. Taymaz, F. Oktay, H. Yüce, B. Alpar, H. Başaran, J.A. Jackson, S. Kara, and M. Şimşek, High-resolution seismic profiling in the Sea of Marmara (northwest Turkey): Late Quaternary sedimentation and sea-level changes, *Geol. Soc. Am. Bull.*, *107*, 923-936, 1995.

Straub, C., and H.-G. Kahle, Active crustal deformation in the Marmara Sea region, NW Anatolia, inferred from GPS measurements, *Geophys. Res. Lett.*, *22*, 2533-2536, 1995.

Straub, C., and H.-G. Kahle, Recent crustal deformation and strain accumulation in the Marmara Sea region, NW Anatolia, inferred from repeated GPS measurements, in *Active Tectonics of Northwest Anatolia: The Marmara Poly-project*, edited by C. Schindler and M. Pfister, pp. 417-447, Hochschulverlag AG an der ETH, Zürich, 1997.

Sümengen, M., and İ. Terlemez, Stratigraphy of the Eocene sediments from the southwestern Thrace (in Turkish), *Maden Tetkik Arama Ens. Derg.*, *113*, 17-30, 1993.

Sylvester, A.G., Strike-slip faults, *Geol. Soc. Am. Bull.*, *100*, 1666-1703, 1988.

Taymaz, T., J. Jackson, and D. McKenzie, Active tectonics of the north and central Aegean Sea, *Geophys. J. Int.*, *106*, 433-490, 1991.

Turgut, S., M. Türkaslan, and D. Perinçek, Evolution of the Thrace sedimentary basin and its hydrocarbon prospectivity, in *Generation, Accumulation, and Production of Europe's Hydrocarbons*, *Spec. Publ. Eur. Assoc. Pet. Geoscientists.*, vol. 1, edited by A.M. Spencer, pp. 415-437, Oxford Univ. Press, New York, 1991.

Tüysüz, O., A. Barka, and E. Yiğitbaş, Geology of the Saros Graben: Its implications on the evolution of the North Anatolian fault in the Ganos-Saros region, NW Turkey, *Tectonophysics*, *293*, 105-126, 1998.

Üçer, B., H. Eyidoğan, C. Gürbüz, A. Barka, and Ş. Barış, Seismic investigations of the Marmara region, in *Active Tectonics of Northwestern Anatolia: The Marmara Poly-project*, edited by C. Schindler and M. Pfister, pp. 89-100, Hochschulverlag AG an der ETH, Zürich, 1997.

Ünay, E., and H. de Bruijn, On some rodent assemblages from both sides of the Dardanelles, Turkey, *Newsl. Stratigr.*, *13*, 119-132, 1984.

Wong, H.K., T. Lüdmann, A. Uluğ, and N. Görür, The Sea of Marmara: A plate boundary sea in an escape tectonic regime, *Tectonophysics*, *244*, 231-250, 1995.

Woodcock, N.H., The role of strike-slip fault systems at plate boundaries, *Philos. Trans., R. Soc. London*, *Ser.* A, *317*, 13-29, 1986.

Yaltırak, C., The tectonic history of the Ganos fault system (in Turkish), *Türk. Petrol Jeologları Derneği Bülteni*, *8*, 137-150, 1996.

Yazman, M., Western Turkey poses exploration challenges on/offshore, *Leading Edge*, *June 1997*, 897-899, 1997.

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