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Tectonic elements controlling the evolution of the Gulf of Saros (northeastern Aegean Sea, Turkey)

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Abstract

Tectonic elements controlling the evolution of the Gulf of Saros have been studied based upon the high-resolution shallow seismic data integrated with the geological field observations. Evolution of the Gulf of Saros started in the Middle to Late Miocene due to the NW–SE compression caused by the counterclockwise movement of the Thrace and Biga peninsulas along the Thrace Fault Zone. Hence, the North Anatolian Fault Zone is not an active structural element responsible for the starting of the evolution of the Gulf of Saros. The compression caused by the rotational movement was compensated by tectonic escape along the pre-existing Ganos Fault System. Two most significant controllers of this deformation are the sinistral Ganos Fault and the dextral northern Saros Fault Zone both extending along the Gulf of Saros. The most important evidences of this movement are the left- and right-oriented shear deformations, which are correlated with structural elements, observed on the land and on the high-resolution shallow seismic records at the sea. Another important line of evidence supporting the evolution of this deformation is that the transgression started in the early-Late Miocene and turned, as a result of regional uplift, into a regression on the Gelibolu Peninsula during the Turolian and in the north of the Saros Trough during the Early Pliocene. The deformation on the Gelibolu Peninsula continued effectively until the Pleistocene. Taking into account the fact that this deformation affected the Late Pleistocene units of the Marmara Formation, the graben formation of the Gulf of Saros is interpreted as a Recent event. However, at least a small amount of compression on the Gelibolu Peninsula is observed. It is also evident that compression ceased at the northern shelf area of the Gulf of Saros.

Keywords: North Aegean Sea; Gulf of Saros; Thrace Fault Zone; North Anatolian Fault Zone; escape tectonics; shallow seismic

1. Introduction

The Gulf of Saros is a neotectonic basin placed at the northeastern part of the Aegean Sea (Fig. 1). It is a basinal structure created by a strike-slip fault system at the western termination of the Ganos Fault System, which is the most significant tectonic element controlling the evolution of the area (Yaltırak, 1996a). In this study, the relationships between the northern shelf area, the Saros Trough (−700 m) and the Gelibolu High (Peninsula) will be discussed.

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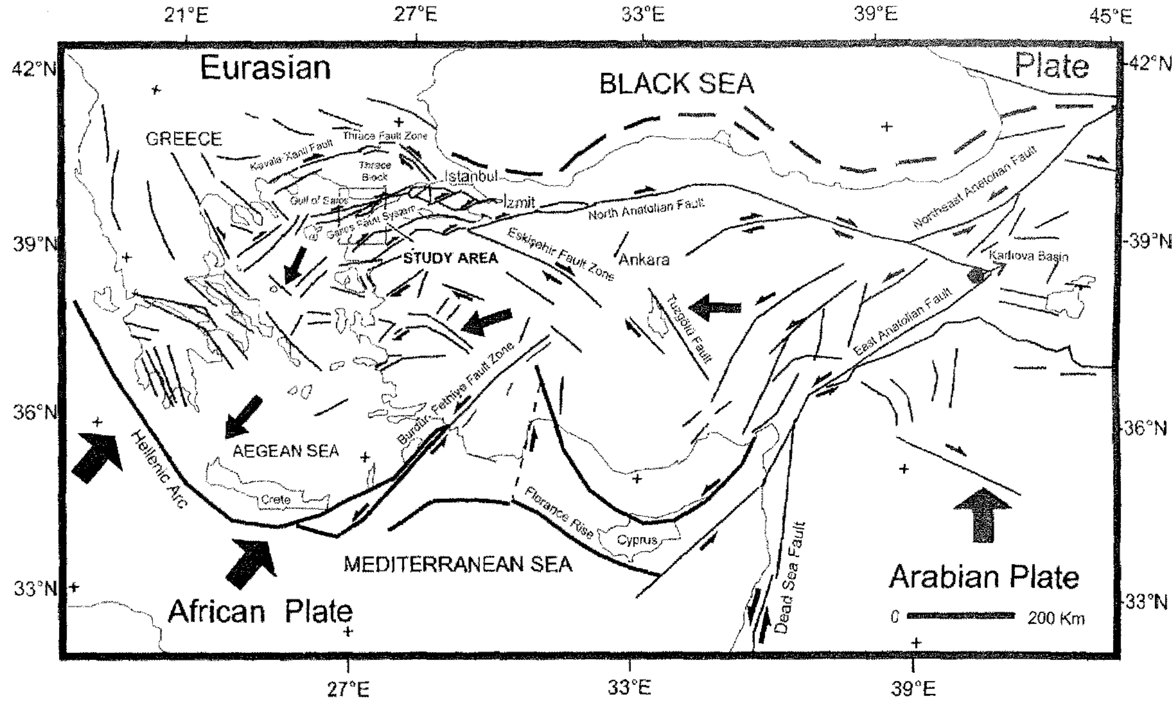


Fig. 1. Tectonic map of the study area and the eastern Mediterranean region (compiled from Bornovas and Rondogianni-Tsiambau, 1983; Jackson and Mc Kenzie, 1984; Şengör et al., 1985; Perinçek et al., 1987; Şaroğlu et al., 1987; Barka and Kadinsky-Cade, 1988; Gheshitev et al., 1989; Taymaz, 1990; Perinçek, 1991; Barka, 1992; Wong et al., 1995; Yaltırak, 1996a; Tapırdamaz and Yaltırak, 1997).

Sieberg (1932) described the Gulf of Saros as the northernmost trough of the Aegean Graben System, which is an ENE-trending depression zone. He connected this depression zone with the trough in the Marmara Sea through the Ganos Fault. He considered the Marmara and Saros troughs as parts of the major graben system that includes the Gulf of Izmit (Fig. 1), and the Gelibolu High as a horst. Pınar (1943) proposed a fault by extending the Ganos–Eksamil Fault (Gutzwiller, 1923) towards the troughs placed in the Sea of Marmara and into the Gulf of Saros (Fig. 2). However, her theory was not accepted by Pfannensteal (1944), who proposed (as Sieberg, 1932 affirmed in the past) that the Saros Trough represents a graben structure. Following these insights, the Gulf of Saros was considered to result from N–S extension that controls the evolution of the Aegean Sea, and also of the Ganos Fault System that controls the Saros Trough and were believed to have strike-slip components (Mc Kenzie, 1978). Dewey and Şengör (1979) considered the Gulf of Saros as a part of the Aegean Graben System created by N–S extension. This extension depends on the E–W compression caused by the North Anatolian Fault. This theory was improved by Şengör et al. (1985) who considered the Gulf of Saros as a NE–SW-oriented graben created by the directional change of the Ganos Fault (the northern strand of the North Anatolian Fault) during a neotectonic period of movement. Saner (1985) supported the strike-slip vector of the Ganos Fault on the Gelibolu Peninsula; however, by using conventional seismic sections, he claimed that the Ganos Fault works as a normal fault in the Gulf of Saros due to N–S extensional forces. Önal (1986) added to these claims that the structural elements were indicating a component of compression to this fault. Yaltırak (1995a) claimed that the Ganos Fault has different dip orientations between the Evreşe plain and B. Kemikli Cape. A compressional tectonic regime during the Late Miocene–Early Pleistocene controlled the uplift of the Gelibolu Peninsula and caused the Anafartalar Thrust Fault (Yaltırak, 1995b). Following these studies, Yaltırak (1996a) suggested that all of the

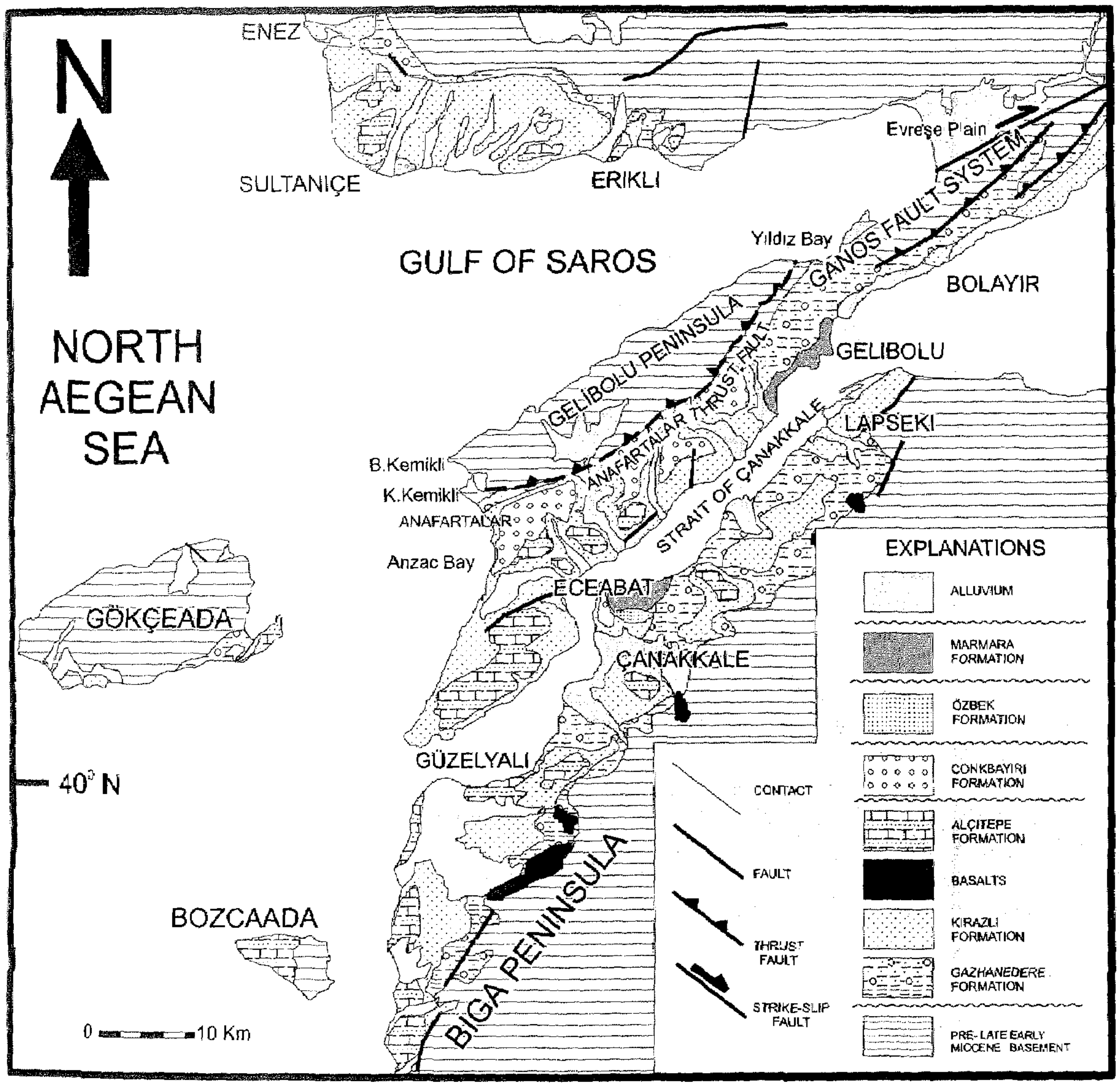


Fig. 2. Geological map of the Gulf of Saros and the study area (compiled from Ternek, 1949; Önal, 1984; Sümengen et al., 1987; Şentürk et al., 1987; Yaltırak, 1996a; Sakınç and Yaltırak, 1997; Tapırdamaz and Yaltırak, 1997).

structures between the Gulf of Saros and the Sea of Marmara are entirely controlled by the Ganos Fault itself. Late Miocene sediments on the northern coasts of the Gulf of Saros were subjected to dextral shear deformation while their equivalent strata exposed on the Gelibolu highs were subjected to sinistral shear deformations. He explained that the Saros Trough evolved by compression of the northern block. The compression was caused by the westward extrusion of the West Anatolian Block along the Ganos Fault System. According to this study, compression appears to be possible in a limited space by a sinistral movement of the North Anatolian Fault Zone (NAFZ), which followed the older tectonic lines, and the squeezed blocks created a negative flower structure (Yaltırak, 1996a). Following these studies and by using the palaeomagnetic data collected on Thrace and the Gelibolu Peninsula, Tapırdamaz and

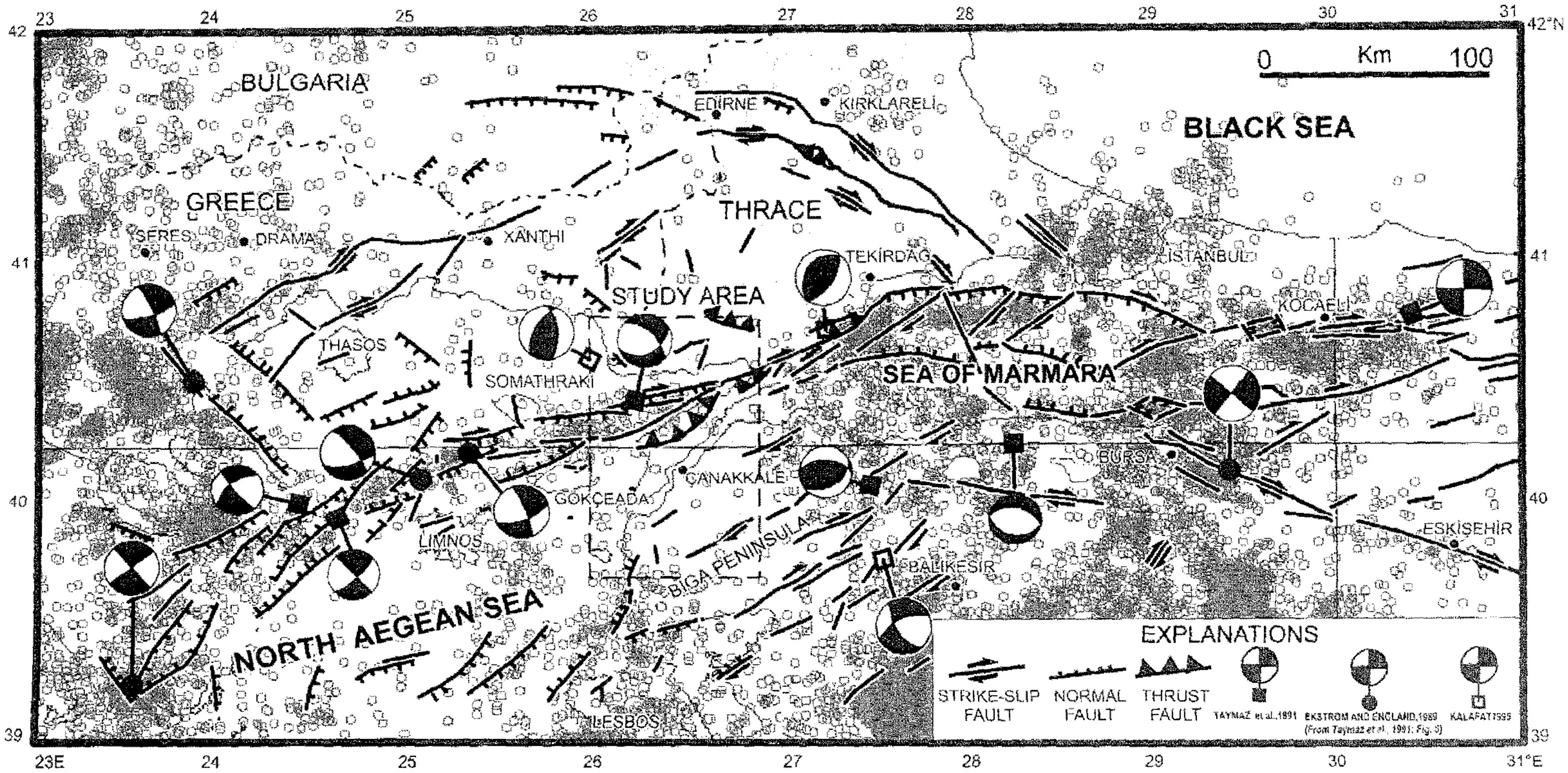


Fig. 3. Seismotectonic map of the study area and its surroundings: ISC seismicity map Cornell Univ. GIS Map and Information on services http://atlas.gen.cornell.edu; tectonic lines were compiled from Bornovas and Rondogianni-Tsiambau (1983), Barka and Kadinsky-Cade (1988), Gheshitev et al. (1989), Simeakis et al. (1989), Siyako et al. (1989), Perinçek (1991), Wong et al. (1995), Eryılmaz (1996), Yaltırak (1996a) and Tapırdamaz and Yaltırak (1997). Fault plane solutions are from Taymaz et al. (1991) and Kalafat (1995).

Yaltırak (1997) proposed an updated model. This 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. To explain the cause of these movements, the northern strand of the Ganos Fault cutting the northern shelf area of the Gulf of Saros should be dextral, while the southern strand cutting the Gelibolu Peninsula until the west of Gökçeada Island should be sinistral. The sinistral movement in the Late Miocene along the Ganos fault was also reported from Limnos Island (Simeakis et al., 1989). From previous studies on the Ganos Trough and adjacent areas, these are known to be still seismically active (Fig. 3) (Pınar, 1943; Ambraseys and Finkel, 1987; Kalafat, 1989, 1995; Taymaz et al., 1991; Sakınç and Yaltırak, 1997) due to collision of the Anatolian and Thrace blocks along the Ganos Fault (Straub and Kahle, 1994, 1995).

In summary, these studies indicate that the N–S extensional graben model of the Gulf of Saros is questionable, and that there is a different situation, at least around Gökçeada Island and Gelibolu Peninsula. In this study, structural elements that created the Saros Trough (Yaltırak, 1996a; Tapırdamaz and Yaltırak, 1997) will be correlated with the marine high-resolution shallow seismic data and the land geological information. Consequently, propounded models will be examined.

2. Seismic data

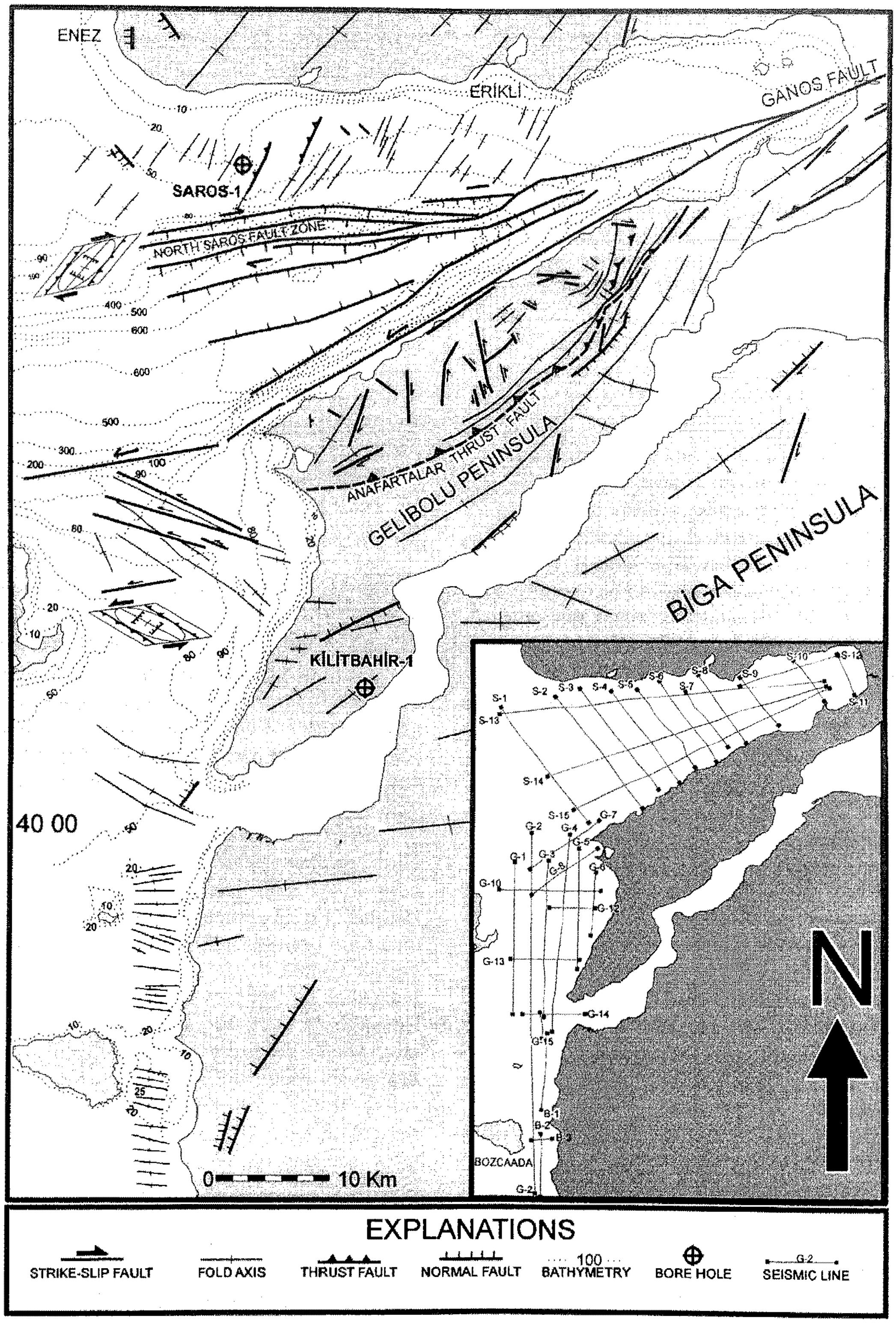
A total of 36 high-resolution analog Sparker (1000 J) seismic profiles (560 km) were recorded on board R/V *TCG-Çubuklu* of the Department of Navigation, Hydrography and Oceanography. The location of the profiles is in the Gulf of Saros, in the area between Gökçeada Island and the Gelibolu Peninsula and finally in the area between Bozcaada Island and the Biga Peninsula (Fig. 4). A Trisponder system was used for positioning with two shore-based radio beacons. It gives an accuracy of ±10 m. Data were recorded analogically for about 200 ms (two-way-time), approximately imaging about 60 m subsurface below sea bottom. The records were generally of good quality, but deteriorated in areas with steep seafloor gradients. All of the seismic sections were scanned to bit-map images; folds and faults were interpreted. The widely distributed Middle–Upper Miocene sediments in the study area, the sub-bottom structures affecting the near surface and also the acoustic basement were mapped. The continuity of these structures was explored and correlated with those observed on land.

3. Stratigraphy

In the study area, the Neogene sediments are composed of various similar-aged lithofacies with lateral and vertical transitions. These facies show some discrepancies related to the tectonic evolution of the basin (Figs. 2 and 5). These formations discordantly overlie a pre-Early Miocene basement (Ternek, 1949; Saltık, 1974; Önal, 1984; Sümengen et al., 1987; Siyako et al., 1989; Yaltırak, 1996a).

3.1. Gazhanedere Formation

The Gazhanedere Formation, as designated by Saltık (1974) at Mürefte (Fig. 2), is widely distributed on the Gelibolu Peninsula, the northern part of the Gulf of Saros and the Strait of Çanakkale (Dardanelles). In the study area, the formation consists of coarse clastics of meandering-river origin containing some coal seams and lacustrine clay deposits (Figs. 2 and 5). Around Gelibolu, it is 220 m thick and starts with fluviatile cycles of coarse clastics and reddish mudstones upwards grading into green–red-coloured clays containing some silty intercalations. The thickness of the units increases (300–330 m) towards Eceabat (Fig. 2), where it is solely formed of reddish *Unio*-bearing mudstones passing into brownish-green-coloured sandstone–siltstone with some marl intercalations. Between Çanakkale and Lapseki, the formation is made up of braided-river conglomerates, which vertically pass into reddish–greenish mudstones containing freshwater ostracods and bivalves. To the north of the Ganos Fault the sequence starts with reddish mudstones laterally passing into marl and limestone and upwards into buff-coloured sands (Fig. 5). Some bentonite lenses are also noted in the upper part of the section. To the north of the Gulf of Saros, the formation is 148 m thick overlying with discontinuous contact the Palaeogene basement (Ternek, 1949). In this region, it is repre-


ENEZ
ERİKLİ
GANOS FAULT
SAROS-1
NORTH SAROS FAULT ZONE
ANAFARTALAR THRUST FAULT
GELİBOLU PENINSULA
BİGA PENINSULA
KİLİTBAHİR-1
40 00
0 10 Km
BOZCAADA
N
EXPLANATIONS
STRIKE-SLIP FAULT
FOLD AXIS
THRUST FAULT
NORMAL FAULT
100
BATHYMETRY
BORE HOLE
G-2
SEISMIC LINE

sented by feldspathic sandstones and cyclic reddish mudstones deposited in a meandering-fluviatile environment.

The age of this formation is late Orleanian around Şarköy–Mürefte (micro-mammals fauna; Ünay and de Bruijn, 1984); Astaracian around Gelibolu (Sümengen et al., 1987); and pre-early Pannonian around Çanakkale (Şentürk et al., 1987).

3.2. Kirazlı Formation

The Kirazlı Formation, as designated by Saltık (1974), is the most widespread unit in the study area. It represents fluviatile and beach environments (Yaltırak, 1995c). Around Gelibolu, the unit starts with massive sandstone with siltstone intercalations. To the top, high-angle cross-bedding sandstone follows the massive sandstone. Some thin conglomeratic intercalations and medium-bedded sandstones are also noted. The uppermost part of the unit is formed by siltstone–sandstone alternations. The rodent faunas collected from the basal part of the formation indicate a Valesian age for the formation (Ünay and de Bruijn, 1984).

Between Gelibolu and Eceabat, the formation starts with trough cross-bedded sandstone on the variegated deposits by vertical passage (Figs. 2 and 5). There are also some variegated mudstone intercalations in the basal sands (Fig. 5). Here, fine sandstones follow the basal sands; they are, in turn, followed by 0.3–0.5 m bedded and carbonate-cemented sandstone. Later in the sequence, high-angle cross-bedded sandstone takes place. Clay–silt–sand alternation is seen above these sands. Towards the top, conglomerate intercalations containing *Mactra* fossils are also noted. The unit ends with sandstones with *Mactra* fossils. The mammal fossils collected from the unit indicate a Valesian age for the formation (Kaya, 1989).

The formation is conformable and passing laterally and vertically into the Gazhanedere Formation around Çanakkale and south of Lapseki (Fig. 5). The sequence starts with cross-stratified fine sands at the base. There are some *Unio*-bearing green mudstone and sandstone lenses within these sands. To the top the lithology turns to *Mactra*-bearing sandstones alternating with fine sands. In this locality, the sequence is about 180 m thick. Micro- and macromammal fossils found around the southern part of Çanakkale City indicate an Astaracian–early Valesian age for the lower part of the formation (Şentürk et al., 1987).

The Kirazlı Formation exhibits a similar development to the north of the Gulf of Saros (Fig. 2). Here, the sequence starts with cross-bedded sandstones. The upper part of the formation is made up of reddish-coloured fine sandstones containing abundant bivalve shells. Some gypsum lenses are also noted in these sandstones. The formation is represented by dune sands later developing into bivalve-bearing sandstones around Enez (Fig. 4), where the formation is 80–120 m thick. *Ostrea cuculata*, *O. gingensis* and *Cardium edule* constitute an acme zone in the sandstones of the middle part of the section. The marine fauna of Sarmatian–Serravallian age was found in the upper part of the formation between Erikli and Enez (Ternek, 1949; Sümengen et al., 1987).

3.3. Alçıtepe Formation

The Alçıtepe Formation, as designated by Önem (1974), lies on the Kirazlı Formation with a gradational contact (Figs. 2 and 5). It represents shallow marine and lacustrine depositional environments (Fig. 5) (Önem, 1974; Taner, 1979; Sümengen et al., 1987; Şentürk et al., 1987; Yaltırak, 1995b).

On the Gelibolu Peninsula, the Alçıtepe Formation is made up by sandy limestone, oolitic limestone, sandstone and *Mactra*-bearing limestone intercalations. To the top of this formation, it gains a regressive character. Around Alçıtepe village, the formation is intercalated with terrestrial mudstone layers (containing lens-shaped, mixed-coloured, thin coal lenses). It is about 200 m thick.

At the east of the Strait of Çanakkale, the Alçıtepe Formation starts with transgressive cross-bedded sandstone–pebblestone at the base that gradually passes upward into sandstone, shelly and oolitic

Fig. 4. Bathymetric and structural map of the Gulf of Saros and study area (compiled from Tapırdamaz and Yaltırak, 1997; Yaltırak, 1996a; and this study). Seismic lines are presented in a small map.

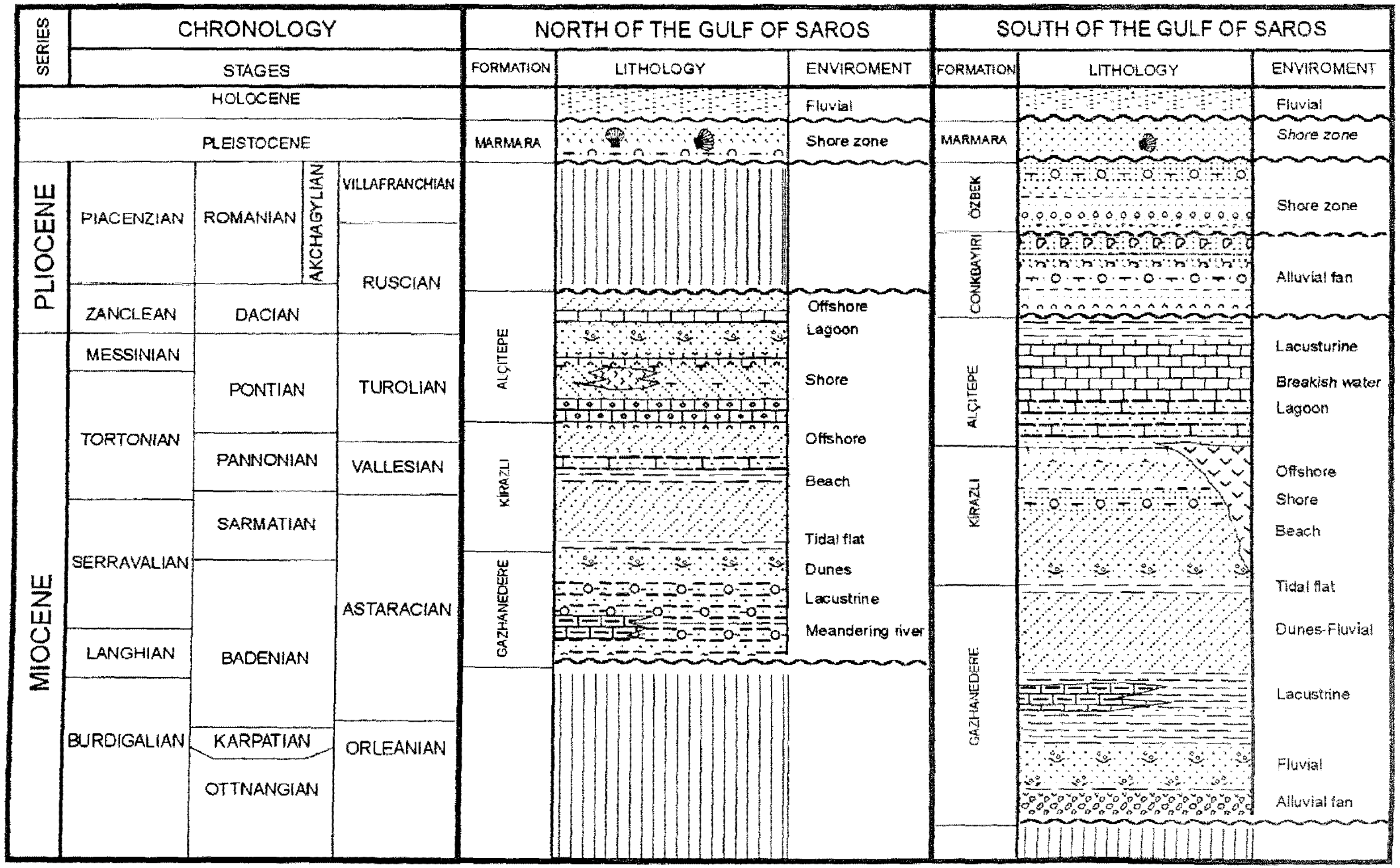


Fig. 5. Generalized stratigraphic columnar section of the study area, (simplified from Yaltırak, 1996a).

limestones. These abundantly marine-bivalve-containing levels correspond to the marine sediments encountered at the north of the Gulf of Saros. On top of these intercalations, *Mactra*-bearing limestone, with silty–clayey and laminated-sandstone intercalations, is added to the formation. The upper part of this section is completed by alternations of conglomerate and sandstone.

The marine bivalves at the north of the Gulf of Saros were dated as Tortonian by Ternek (1949). In addition, the age of the uppermost level of the Alçıtepe Formation may be considered as Early Pliocene since it contains similar fossils as found in the units deposited during the Seres transgression in Greece (Karistineos and Georgiades-Dikeoulia, 1986). On the Gelibolu Peninsula, around the Alçıtepe village, the Alçıtepe Formation contains Pannonian marine ostracods and the uppermost terrestrial sediments indicate that these are of Turolian age (Şentürk et al., 1987; Kaya, 1989). On the other hand, Taner (1979) dated the bivalves collected from the lacustrine levels as Pontian. These ages of the Alçıtepe Formation dated by different fossil groups agree with the terrestrial and marine stages. This formation is dated as Tortonian by fish fossils (Erdogan, 1978), as early–middle Pannonian by ostracods, as Pontian by *Mactras* (Erguvanlı, 1955), and as Vallesian–Turolian by mammal fossils at top levels (Şentürk et al., 1987).

3.4. Conkbayırı Formation

The Conkbayırı Formation, as designated by Kellog (1973), is widely distributed on the Gelibolu Peninsula and characterized by the alluvial fan deposits matured with the Anafartalar Thrust Fault (Yaltırak, 1995b) (Figs. 2 and 5). It is conformable to the Upper Miocene deposits at the eastern part of the area while it lies with an angular unconformity on them at the western part. The sequence starts with mudstone at the base and later continues with sand- pebblestone intercalations. The dominant palaeo-current direction is northwest to west. Its age is either Akchagylian by means of freshwater molluscs collected in the disconformable levels on the Alçıtepe Formation around southwest of Gelibolu or Late Pliocene by means of spores and pollens analyzed (Önal, 1984).

3.5. Özbek Formation

The Özbek Formation is discordant on the Miocene units around Özbek, north of Çanakkale City. It is composed of well-rounded pebbles and carbonate sands with carbonate cement (Figs. 2 and 5) and placed about 85–115 m above the present mean sea level. Stratigraphic and palaeontological data give its age as Late Pliocene–Early Quaternary (Erol and Nuttal, 1973; Şentürk et al., 1987; Görür et al., 1997).

3.6. Marmara Formation

The Marmara Formation is angularly discontinuous on the Miocene units at Gelibolu and Çanakkale. It consists totally of detritic material and generally terminates with beachrock facies. Its thickness varies between 2 and 36 m, depending on the morphologic characteristics of the shoreline. The coastal sediments placed along the coasts of the Sea of Marmara, the Strait of Çanakkale and the Gulf of Saros were named as marine terraces. They were initially thought of as the shore facies of an uplifted formation, which continues to the sea and dated as middle to Late Pleistocene (Sakınç and Yaltırak, 1997).

4. Tectonic setting

The structural elements in the study area were developed around the Ganos Fault. They are morphotectonic structures of the Gelibolu High and the Saros Trough. These structures affected the Middle Miocene–Early Pliocene formations placed at the north and south of the Gulf of Saros.

4.1. North of the Gulf of Saros and the northern shelf area

The orientation of fold axes at the north of the Gulf of Saros is NE–SW, and they plunge into the gulf. They were cut by the northwest-trending normal faults with slip vectors not more than a few metres. The most typical one of them can be seen at the southwest slope of Hisarlidag hill. A series of Quaternary alluvial valleys were placed parallel to the fold axes (compare Figs. 2 and 4). These structures can be followed on the shallow seismic horizons of the Middle Miocene–Early Pliocene series and their existence in the northern shelf area is confirmed by a previously drilled borehole (Yazman, 1997) (Saros-1 in Fig. 4). According to the map (Fig. 4) prepared from the structural correlation of NW–SE-oriented seismic sections (e.g. section S-6 in Fig. 6) with the E–W-oriented seismic section (e.g. S-13 in Fig. 6), the fold on the northern shelf area, with an amplitude of 5–10 km between the North Saros Fault and the coastline, seems to be an extension of the folds on land. Normal faults and thrust faults are in a relative position suggesting a dextral movement (Fig. 4). The strike of the young thrust fault observed on the sections S-13 (Fig. 6) and S-4 (Fig. 7A) is NE–SW. Furthermore, there are no young sediments on the horst which shows an anticlinorium structure at the west side of this thrust fault (see S-13 in Fig. 6). These facts may pronounce that the area is still rising today. The folds observed on all of the NW–SE-oriented seismic sections in the Gulf of Saros support this hypothesis. The fault planes usually run parallel to NW–SE-oriented sections (Figs. 4 and 7), hence numerous faults observed on the E–W-oriented sections are scarce on the NW–SE-oriented sections.

4.2. Saros Trough

The Saros Trough, with a maximum water depth of 700 m, is bounded by strike-slip faults at its northern and southern margins and matured during the evolution of the present Gulf of Saros. Away from the axis of the main tectonic discontinuity, the sea bottom slope becomes gentler (Fig. 4). To the south, along the Gelibolu Peninsula there is no shelf area, but a fault-controlled deep trough. The steeply dipping topography at the northern shores of the Gelibolu Peninsula continues on the seafloor. The elevation difference between the highest and deepest points reaches 1100 m. From a bathymetric point of view, the Saros Trough has a shape of a right triangle. Typical normal faults were observed on the conventional seismic sections recorded over this triangle-shaped area (Saner, 1985). A study of an earthquake which occurred in the northern shelf area indicated that it was dextral and oblique to the trend of the fault (Taymaz et al., 1991). On the shallow seismic sections, from the northern shelf break to the Gelibolu Peninsula, there are many normal faults (Fig. 7A). The slopes of the layers in the Saros Trough are towards the centre of the basin, and these slopes are paradoxical with the expected (theoretical) movements of the fault blocks. Between the normal faults observed on the sections, the folds and positive structures (Fig. 7A), which also influence the bathymetry, indicate that the faults, bounding the northern border of the Saros Trough, are strike-slip in character. The position of the folds and faults in the northern shelf area indicates that most of the faults are oblique dextral (Fig. 4).

4.3. Gelibolu High

The ENE–WSW-oriented Gelibolu High forms a ridge with its 200-m-high cliffs (max. 444 m) along the coasts of the Gulf of Saros (about 34 km). On these sharp and high cliffs, the architecture of the peninsula can be deciphered by the Ganos Fault. The Gelibolu High is in the shape of a dome-type anticline which is divided into two parts. There is a system giving either dextral or sinistral movements, which make an angle of 20–40° to the main fault, in the units of pre-Miocene on the basement; nevertheless these movements are in the same direction (Fig. 4). The dextral ones of these faults are N30°W, N85°W and the sinistral ones are S80°E, N10°E. Dextral faults should be rotated counterclockwise (with a sinistral movement) when they become perpendicularly closer to the main fault. On the other hand, NNE-trending folds on the eastern part of the Gelibolu Peninsula create an undulating structure between the Anafartalar Thrust Fault and the Ganos Fault. A locally overturned cylindrical fold is placed at the border of this undulating structure and the Anafartalar Thrust Fault is of a blind thrust character and placed along this fold axis (Fig. 4). The anticline of Gelibolu High (with a NW-trending, E-plunging axis) can also be estimated to be a semi-dome type open fold bounded by the Ganos Fault. The Anafartalar Thrust Fault, which forms the eastern boundary of the Gelibolu High, covers this semi-dome structure in the shape of a bow between K. Kemikli Cape and Yıldız Bay. To the east of the Anafartalar Thrust Fault, the Neogene units are at the surface from K. Kemikli Cape to Tayfur Stream (Fig. 2) along the formation boundary, while the

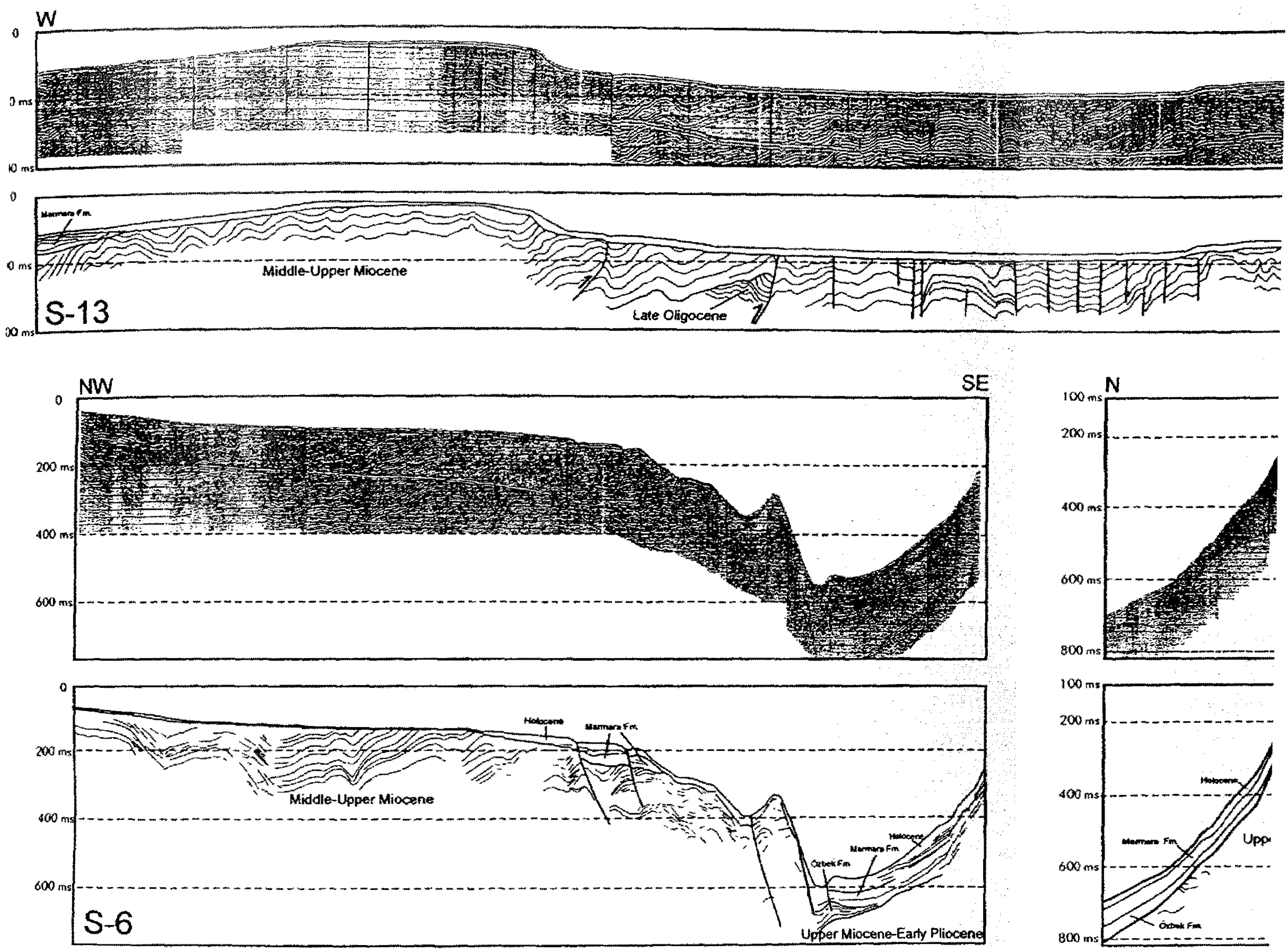
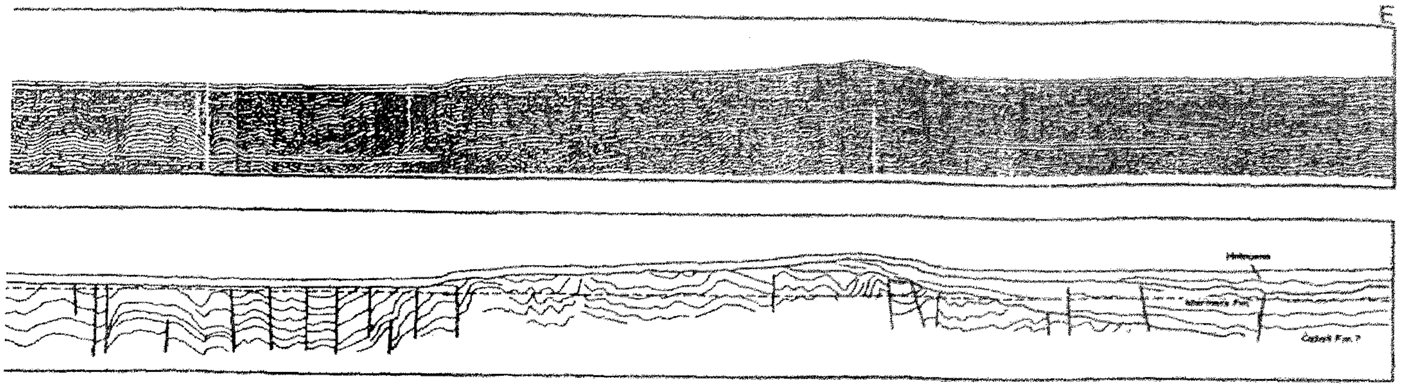
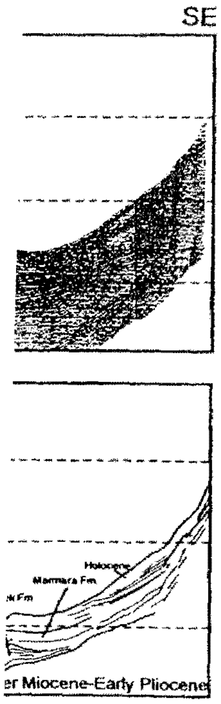


Fig. 6. Examples of seismic profiles and their interpretation.


E
Holocene
Marmara Fm.
Özbek Fm.?


SE
Holocene
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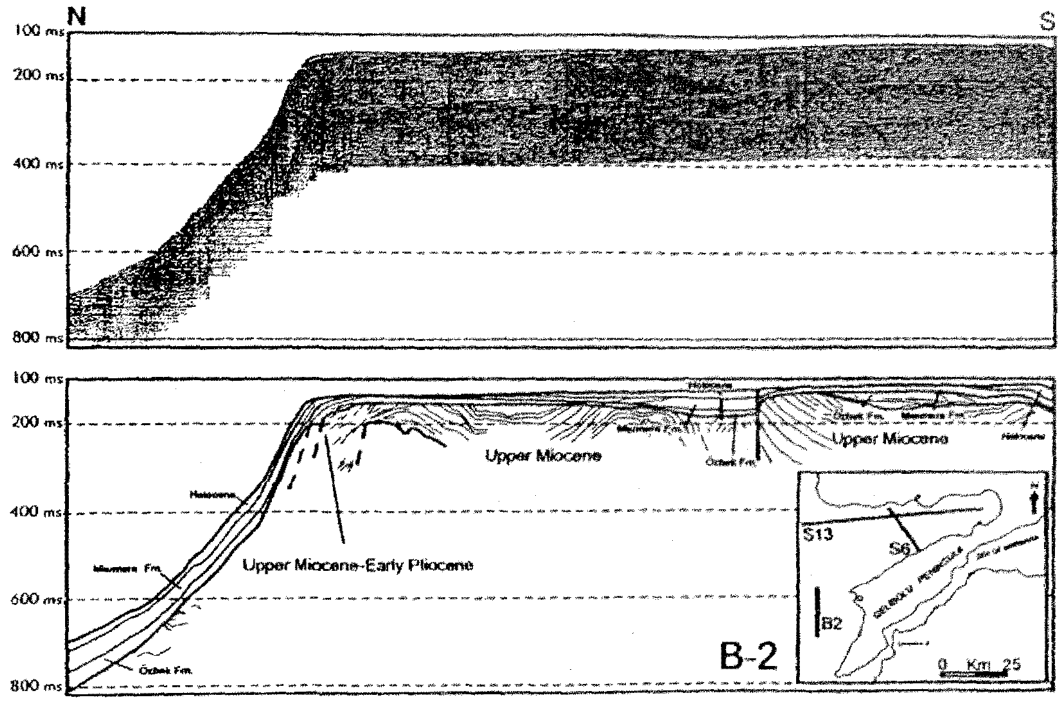

N
S
100 ms
200 ms
400 ms
600 ms
800 ms
Holocene
Marmara Fm.
Özbek Fm.
Upper Miocene
Upper Miocene-Early Pliocene
S13
S6
B2
B-2
0 Km 25

aeogene units (folds are developed inside these its) are at the surface towards the north. The folds the Neogene units are open folds parallel to the ngitudinal axis of the peninsula and also to the nafartalar Thrust Fault (ATF). Closer to the ATF, e Neogene units become steeper and occasionally erturned. In these layers there are some oblique acks and small-scale reverse faults which devel-ed by WSW–ENE-oriented compression. Besides, the area from Anzac Bay to the southernmost part the Gelibolu Peninsula, there is another group of 3–20° east-dipping folds. These folds can also be oserved on the seismic sections between Gökçeada land and Gelibolu Peninsula (see section B-2 in igs. 6 and 7). The angle between the folds and e strike-slip faults which are bounding the WNW–SE-oriented folds traced on the N–S sections is be-ween 10 and 20°. The angle between all these struc-ures and the ENE–WSW-oriented Ganos Fault is etween 30 and 45°, indicating that WNW-trending tructures were caused by a sinistral movement. Sim-lar folds can be seen between the western coasts of he Biga Peninsula and the Bozcaada Island (Fig. 4). According to the correlation of the N–S-oriented seismic profiles, the folds are approximately in the W–E direction (Fig. 7A). These folds turned to the Ganos Fault as a result of a sinistral shear deformation progression. The structural elements imaged by the seismic data represent Early to Late Miocene successions corresponding to the ones with a thickness of 1057 m in the borehole 'Kilitbahir-1' (see Fig. 4) (Yazman, 1997).

5. Geological evolution

In the vicinity of the study area, the Rhodop–Pontid Block collided with the Sakarya Zone in the Oligocene (Okay and Görür, 1995; Şengör, 1995). The Early Miocene was a non-depositional period in Thrace and the Gelibolu Peninsula (Keskin, 1974; Yaltırak, 1996a).

The tectonic movements are stationary in the Gulf of Saros and its surroundings during the late-Early Miocene and Middle Miocene. In this period, meandering fluviatile and lacustrine sedimentation regimes were dominant (Gazhanedere Formation; Fig. 5). With the activation of the dextral Thrace Fault Zone in this period, the area of non-depositional environments (Early Miocene) in Thrace was broken into pieces and supplied material in the Thrace Basin along the positive flower structures (Perinçek, 1991; Sakınç et al., 1995). Consequently, the coarse-grained sandstones (Kirazlı Formation) were dominant along the Ganos Fault System, indicating the beginning of a new tectonic regime. At the end of the Middle Miocene and the beginning of Late Miocene, marine depositional conditions started to prevail from the south and became effective to the west of Biga Peninsula and to the north of the Gulf of Saros. The eolian environment continued to be deposited on the Gelibolu Peninsula, while the Kirazlı Formation was deposited in a beach environment in the northern Gulf of Saros. In congruence with the transgression, lacustrine and marine environments (Alçıtepe Formation) became dominant on the Gelibolu Peninsula. The Gelibolu Peninsula turned into a coastal plain and was locally covered with small lakes during the Turolian (uppermost part of the Alçıtepe Formation; Fig. 5), while these environments were laterally displaced by tectonic activity on the Gelibolu and west of the Biga peninsulas. The Turolian period is the beginning of the uplift in the area. This regressive period caused by the tectonic uplift, gained acceleration at the end of the Late Pliocene. Due to tilting of the Gelibolu Block, the formations (Gazhanedere, Kirazlı and Alçıtepe) deposited on the hangingwall of the Anafartalar Thrust Fault started to move onto the footwall. Thus, the alluvial fan units (Conkbayırı Formation) with a thickness of up to 300 m were deposited at the eastern part of the Anafartalar Thrust Fault. In this period, the Conkbayırı Formation was turned over and folded along the Anafartalar Thrust Fault. The only deposition in this period was in the Saros Trough (see Fig. 6; seismic lines S-6 and B-2). The receding sea, because of the tectonic uplift, affected the region in a short time with the influence of the transgression starting in the Piacenzian (Karistineos and Georgiades-Dikeoulia, 1985, 1986). Because of the continuation of the tectonic uplift, the sea receded again up to Çanakkale to the south (Özbek Formation). An erosional regime was dominant in the whole region in the beginning of the Pleistocene. On the other hand, in the northern shelf area, the land area uplifted by folding, started

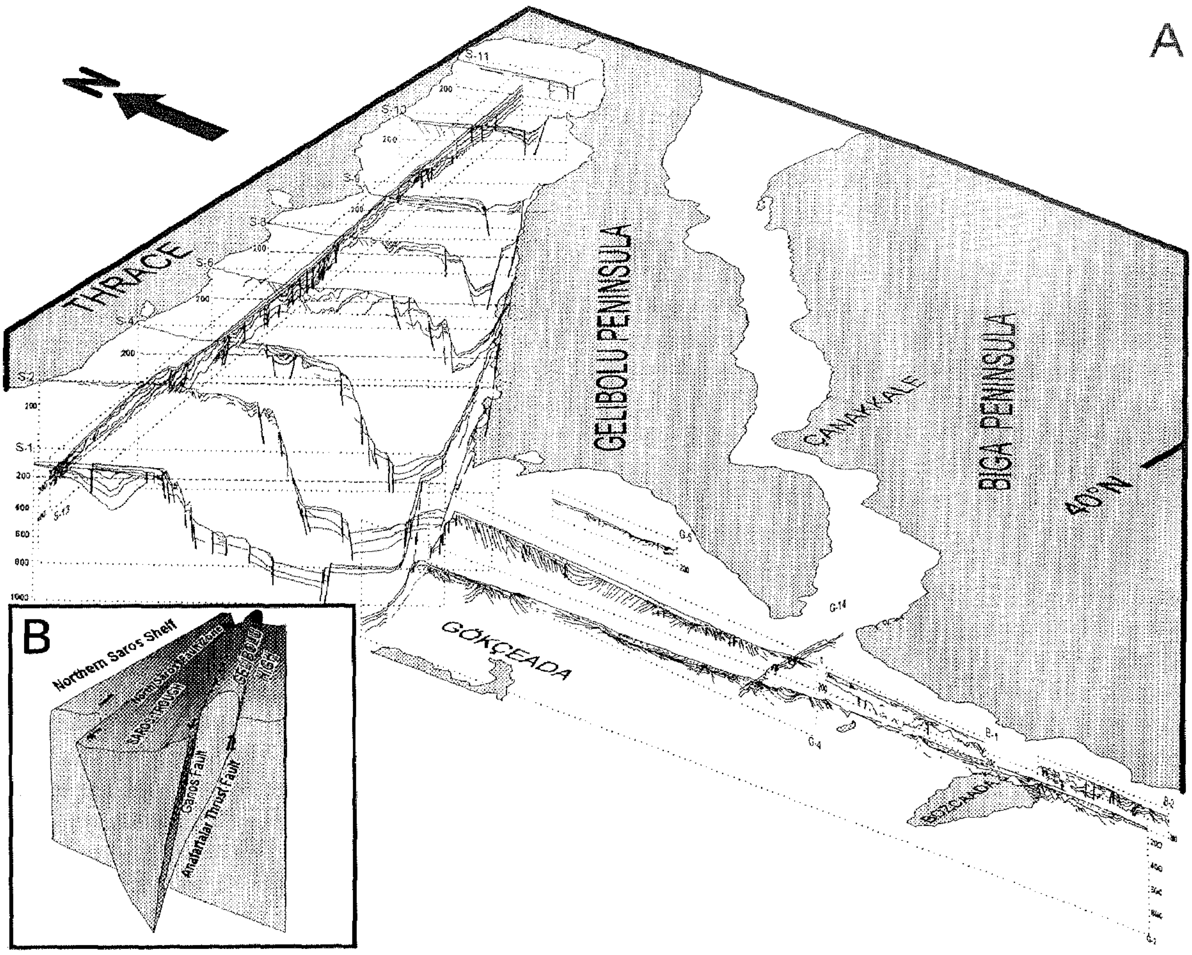


Fig. 7. (A) Structural block diagram of the Gulf of Saros and the west of Biga–Gelibolu peninsulas. Looking direction is from southwest towards northeast. All sections were reduced to the same temporal and spatial scale. (B) A block model diagram of the Gulf of Saros and Gelibolu Peninsula.

to be eroded along the valleys settled parallel to the fold axes. During the Mediterranean transgression in the middle to Late Pleistocene, the valleys and broad coastal plains of the Gelibolu Peninsula, the Gulf of Saros and the Sea of Marmara, warm sea conditions prevailed. In this period, the Marmara Formation, which comprises shore facies deposits, is deposited along the varying coastal lines (Sakınç and Yaltırak, 1997). However, with the continuation of tectonic activity, the Marmara Formation attained a regressive character in a short period and tectonically uplifted 5–35 m above present sea level and eroded. In this period, the Özbek and Marmara formations, which were partly eroded in the northern shelf area and western part of the Gelibolu Peninsula because of the sea level falls during the glacial periods (Yaltırak, 1996b), continued their deposition only in certain areas: in the deepening Saros Trough, at the eastern part of the northern shelf area and around some limited areas between Gökçeada Island and Gelibolu Peninsula.

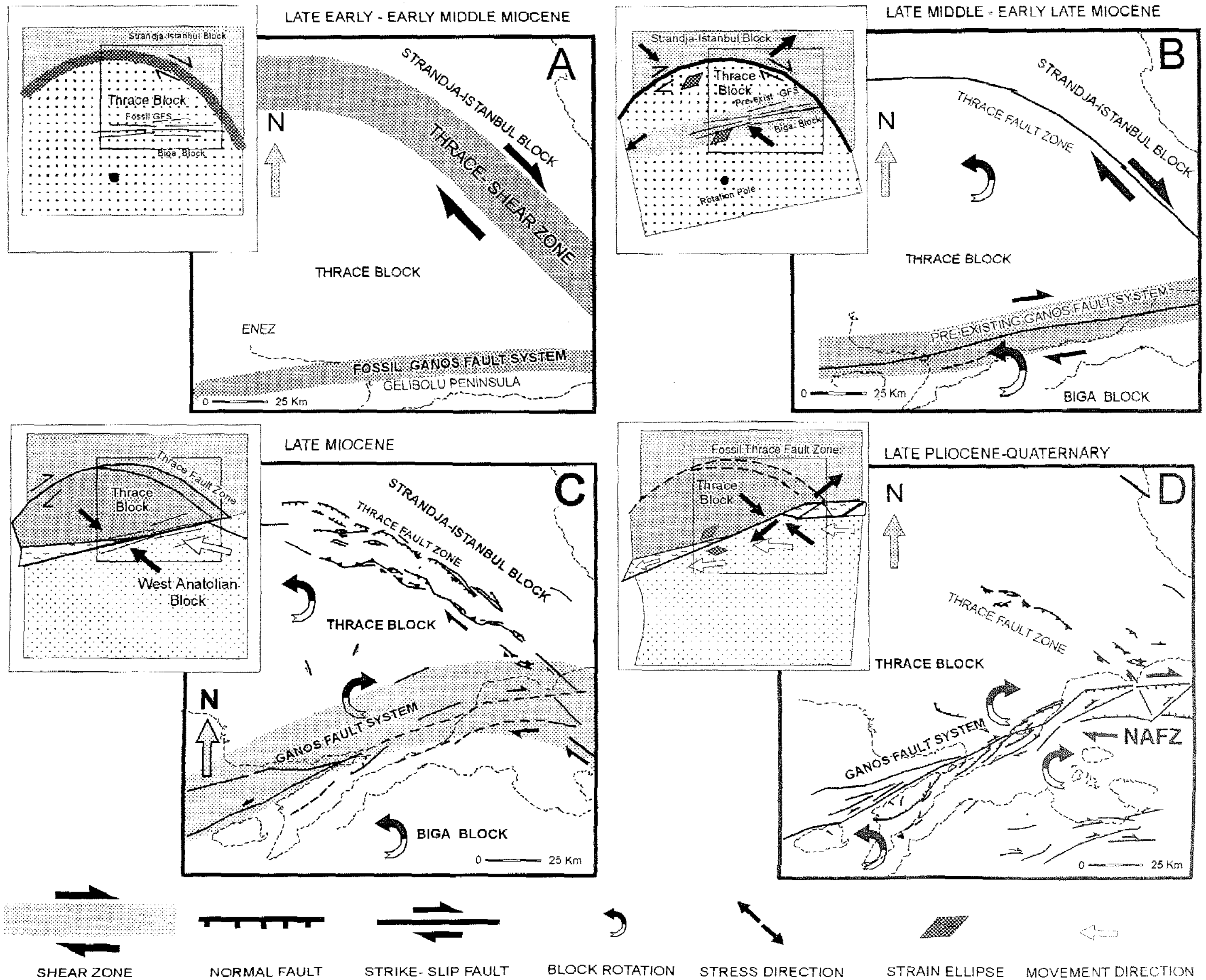
6. Discussion

The tectonic elements forming the Gulf of Saros indicate two shear deformations oriented in different directions. They are placed in the south (on land)

and the north (at sea) of the Saros Trough (Fig. 4). These deformations are dextral in the north and sinistral on the Gelibolu Peninsula and also in the east of Gökçeada Island. These deformations interrupted the deposition of pre-Early Miocene basement and overlying the late-Early Miocene–Early (?) Pliocene sedimentary sequences and then caused them to be folded. The only sequences not affected by these folds are the young deposits in the Saros Trough (Fig. 7A). The Özbek and Marmara formations were partly protected by the sea northeast of Bozcaada and northeast of the Gulf of Saros, even though they highly eroded on land at both sides of the Gulf of Saros depending on the uplift (see sections B-2 and S-13 in Fig. 6). On the seismic profiles, the units of the Marmara Formation in the north of the Gulf of Saros are also folded similar to the Neogene series, indicating that they were affected by the dextral movement. Therefore, the dextral movement occurred during the Late Pleistocene in the northern shelf area. On the Gelibolu Peninsula, taking into account that the marine deposits of the Marmara Formation were tectonically uplifted 5–35 m and 90% of them were eroded (Sakınç and Yaltırak, 1997), one can say that the compressional regime was still operative during this period. Two shear deformation forces in opposite directions caused the formation of the Saros Trough (Fig. 7B). The Thrace Fault Zone, which is responsible for these deformations, was activated during the Middle Miocene (Perinçek, 1991) (Fig. 8A). Tapırdamaz and Yaltırak (1997) reported that the counterclockwise movement of the Thrace Fault Zone along the Xanti–Kavala Fault (Fig. 1) caused a NW–SE compression on the pre-existing Ganos Fault System (Fig. 8B). The dextral deformation on the Ganos Fault System, which is caused by this pair of forces (Yaltırak, 1996a), indicates the opening of the Saros Trough in the Late Miocene to be a right-triangle-shaped area (Fig. 8C), similar to the Karliova Basin in the eastern end of the NAFZ (see Fig. 1) (Şengör et al., 1985). As a result of the combination of this system with the WNW–ESE compression, caused by the westward escape of the Anatolian Block along the NAFZ in the Pliocene–Quaternary, the escape tectonics in the Gulf of Saros continued up to the end of the Late Pleistocene. The trajectories of displacement derived from GPS measurements in the study area indicate that the compressional effect of the Anatolian Block is still active on the Ganos Fault (Fig. 9A) (Straub and Kahle, 1994, 1995). Yaltırak (1996a) proposed that the Ganos Fault System continued to use the old positive and negative flower structures (grown-up in palaeotectonic periods) during the neotectonic period and that this eased the opening of the Gulf of Saros. All of these structural interpretations indicate that the Gulf of Saros has not started to open as a result of the tensional tectonics. The normal faults on the seismic sections were possibly developed after the deposition of the Marmara Formation. This is because of the westward escape of the broken basement of the Saros Trough (Fig. 8D). The space created by the escapes of these blocks during the post-Pliocene was compensated by normal faults (Fig. 8D). The most effective factors responsible for the opening of the Gulf of Saros are the dextral and sinistral faults. Depending on failure stress analysis based on the topography and slip vectors on the segments of the Ganos Fault System, Barka (1997) proposed that the present topography could have been formed only if the compressional component of the strike-slip faults in the three segments was 50% (Fig. 9B). According to this interpretation, there is extensional deformation in the Saros Trough and compressional deformation around Gelibolu Peninsula and Enez (Fig. 9B). This stress model is not in contradiction with the idea that the negative flower structure, which belongs to the palaeotectonic period (Yaltırak, 1996a), along the Ganos Fault in the Gulf of Saros could be relatively faster than the Anatolian Block during its westward escape. Moreover, this model supports the idea that the extension occurring in the space created by the escaped block was compensated by the shallow oblique normal faults. The escape regime has recently been changed (Late Pleistocene?) into an oblique extensional regime which may cause a downward vertical movement of maximum 0.7–0.9 km within a distance of 10 km.

7. Conclusion

The structural data obtained in this study put forward some new sights for the Ganos Fault System, Thrace Fault Zone, North Anatolian Fault Zone and Sea of Marmara. The North Anatolian Fault Zone is



LATE EARLY - EARLY MIDDLE MIOCENE
A
Strandja-Istanbul Block
Thrace Block
Fossil GFS
Biga Block
N
STRANDJA-ISTANBUL BLOCK
THRACE- SHEAR ZONE
THRACE BLOCK
ENEZ
FOSSIL GANOS FAULT SYSTEM
GELIBOLU PENINSULA
0 25 Km
LATE MIDDLE - EARLY LATE MIOCENE
B
Strandja-Istanbul Block
Thrace Block
Pre-exist. GFS
Biga Block
Rotation Pole
N
STRANDJA-ISTANBUL BLOCK
THRACE FAULT ZONE
THRACE BLOCK
PRE-EXISTING GANOS FAULT SYSTEM
BIGA BLOCK
0 25 Km
LATE MIOCENE
C
Thrace Fault Zone
Thrace Block
West Anatolian Block
STRANDJA-ISTANBUL BLOCK
THRACE FAULT ZONE
THRACE BLOCK
N
GANOS FAULT SYSTEM
BIGA BLOCK
0 25 Km
LATE PLIOCENE-QUATERNARY
D
Fossil Thrace Fault Zone
Thrace Block
N
THRACE FAULT ZONE
THRACE BLOCK
GANOS FAULT SYSTEM
NAFZ
0 25 Km
SHEAR ZONE
NORMAL FAULT
STRIKE- SLIP FAULT
BLOCK ROTATION
STRESS DIRECTION
STRAIN ELLIPSE
MOVEMENT DIRECTION

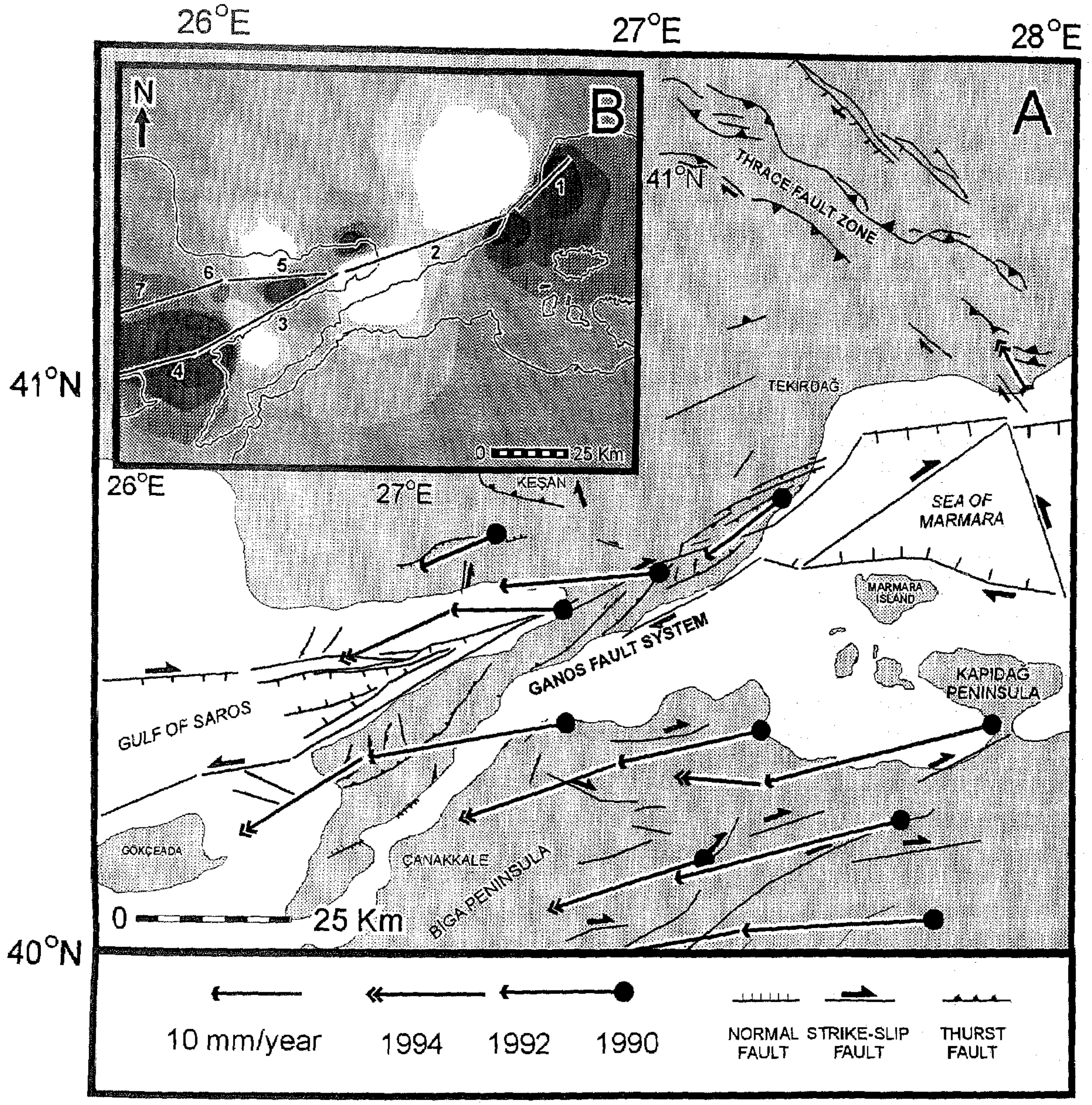


Fig. 9. (A) Trajectories of displacement derived from GPS measurements in 1990, 1992 and 1994 in the study area: the displacements are given relative to the reference site in Istanbul. Compiled from Straub and Kahle (1995); tectonic lines were modified from Siyako et al. (1989), Perinçek (1991), Wong et al. (1995) and Yaltırak (1996a). (B) Boundary element modelling of fault kinematics in the Saros–Ganos region. The areas in white, representing compressional regions, coincide with the uplifted areas while the black areas, representing dilatational regions, coincide with the basins. In order to obtain this modelling, 50% thrust components were added to segments, 1, 2 and 3. (Redrawn after Barka, 1997.)

Fig. 8. Kinematic and tectonic model map of northwest Turkey, redrawn using models of Perinçek (1991), Wong et al. (1995), Yaltırak (1996a) and Tapırdamaz and Yaltırak (1997).

not the structural element responsible for starting the formation of the Gulf of Saros. The Gulf of Saros, placed at the western end of the Ganos Fault System, was shaped by the block rotation realized along the Thrace Fault Zone during the Middle–Late Miocene (Yaltırak, 1996a; Tapırdamaz and Yaltırak, 1997). The palaeomagnetic rotations (37° counterclockwise) in Thrace (Tapırdamaz and Yaltırak, 1997) fit the movement direction of the Thrace Fault Zone in the Late Miocene. A NNW–SSE compression in the Gulf of Saros in the Late Miocene is a result of this movement. This compression activated the older faults which had formed a negative flower structure in the Saros Trough during the palaeotectonic period (before late-Early Miocene) (Yaltırak, 1996a). Based on palaeomagnetic data, the structural relationship between the North Anatolian Fault Zone and the Ganos Fault System started in the Late Pliocene in the western part of the Sea of Marmara and in the Gulf of Saros (Tapırdamaz and Yaltırak, 1997). This event is concordant with the onset of movement along the Anafartalar Thrust Fault (Late Pliocene; Yaltırak, 1995a). The proposed ages for the Anatolian part of the North Anatolian Fault System are generally not older than Pliocene (Ketin, 1948, 1969; Seymen, 1975; Tatar, 1975, 1978; Koçyigit, 1989, 1990; Barka, 1992; Koçyigit et al., 1995). The dextral effect of the North Anatolian Fault System on the Ganos Fault can be observed in the Late Pliocene and later (Yaltırak, 1995b,c, 1996a). This is another important indication that the Northern Anatolian Fault System is not responsible for the evolution of the Saros Trough during the Late Miocene–Early Pliocene. It is kinematically impossible to claim that the Thrace Fault Zone is related with the North Anatolian Fault System (Yaltırak, 1996a) (since the angle between them is greater than 45°, see Figs. 1, 3 and 8C). Hence, in order to evaluate the dextral Thrace Fault Zone, another strike-slip fault system, instead of the North Anatolian Fault Zone, should have existed in western Anatolia. This is probably, considering its position, the Eskişehir Fault Zone (see Figs. 1 and 3). Further studies will indicate if the neotectonic period and the westward escapement of the Anatolian Block started independently before activation of the North Anatolian Fault System in western Anatolia and Thrace. The events controlling the opening of the Gulf of Saros indicate that the neotectonic period started before the development of the North Anatolian Fault in this region.

Based on the type and spatial geometry of the deformations interpreted from the shallow seismic sections, the tectonic escape model (Yaltırak, 1996a; Tapırdamaz and Yaltırak, 1997) is more functional than the graben model created by N–S extension in the Late Miocene (Önal, 1984; Saner, 1985) or a transtensional basin related to the Ganos Fault System (Şengör, 1979; Le Pichon et al., 1984; Şengör et al., 1985; Sarı et al., 1995; Çagatay et al., 1997; Barka, 1997). The recent earthquakes in the northern part of the Saros Trough indicate that the dextral movement is still going on in the area (Fig. 3) (Taymaz et al., 1991; Kalafat, 1995). However, there are no large-magnitude earthquakes indicating any sinistral movement taking place on the Gelibolu Peninsula and its western part. For this area, Ambraseys and Finkel (1995) proposed an average repeat time of 570–800 years for earthquakes. They also think that sinistral movement probably ended in the Pleistocene and the Ganos Fault started a dextral movement along the Gelibolu Peninsula. According to this study, the data which include the N–S extensional and transtensional graben models should be related with the recent tectonics.

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