Kinematics and evolution of the Northern Branch of the North Anatolian Fault (Ganos Fault) between the Sea of Marmara and the Gulf of Saros

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Kinematics and evolution of the northern branch of the North Anatolian Fault (Ganos Fault) between the Sea of Marmara and the Gulf of Saros

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Abstract

The WSW–ENE-trending Ganos Fault is a dextral strike-slip fault running parallel to and southwest of the West Marmara Trough and south of the Saros Trough. Dextral structures started evolving in the early Miocene, and at this time the Ganos fault system developed from a part of the Thrace–Eskişehir fault system. Beginning in the late Pliocene (∼3.5 Ma), the North Anatolian transform fault propagated into the Marmara region and captured the Ganos Fault. Subsequently, this fault has accommodated the westward movement of the Anatolian Block. Because of the curvature of the microplate boundary in this area, the Ganos fault system has tended to rotate counterclockwise. Farther west in the Gulf of Saros, the strike-slip motion was accommodated by a new fault on the northern margin of the gulf, rather than along the northern coast of the Gelibolu Peninsula as previously thought. This interpretation differs from previous assessments of the position of the northern strand of the North Anatolian fault (Marmara segment) in the Marmara Sea and in the Gulf of Saros. The role of the Ganos Fault proposed in this paper is considerably different from that proposed by earlier studies. While the revised orientation of the North Anatolian fault on land is about 7° different than specified by previous authors, at sea it is different by ∼32° counterclockwise and ∼23° clockwise in the West Marmara and Saros submarine depressions, respectively. The revised position of the Ganos Fault in the Marmara Sea, derived from shallow and conventional seismic reflection data, calls into question the validity of evolutionary models previously used in kinematic and stress-failure analyses. In particular, it is not possible to regard the Marmara Sea as a pull-apart basin and the Gulf of Saros as a transtensional half-graben. Furthermore, palinspastic maps taking into account the revised position of the Ganos Fault and GPS slip vectors support the idea that a dextral master fault is present to the north of the Saros Trough with a sinistral oblique fault dominated by normal offset (Gelibolu Fault) to its south. The Gelibolu Fault is reactivated in a limited region.

Keywords: Gulf of Saros; Aegean; Marmara Sea; active faulting; seismic reflection; North Anatolian Fault; Ganos Fault

1. Introduction

The portion of the North Anatolian fault between the western Marmara Sea and the Gulf of

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Saros is known as the Ganos fault system or zone (Fig. 1A) (Yaltırak, 1996). The Ganos fault system is composed of a series of faults disposed to the north and south of a master fault observed on land, that cover the western part of the Marmara Sea and the North Aegean Trough (Fig. 1B). These faults lie sub-parallel to the master fault. They are generally strike-slip and thrust faults on land and normal oblique faults at sea (Yaltırak, 1996; Yaltırak et al., 1998).

Gutzwiller (1923) was the first to notice a fault between the Gulf of Saros and the Marmara Sea. According to Sieberg (1932), the Gulf of Saros is the northernmost depression in the Aegean graben system, which is connected with the Marmara Sea depressions by the Ganos Fault. Later, Pınar (1943) proposed a hypothetical fault extending the Ganos–Eksamil Fault (Gutzwiller, 1923) westward into the Gulf of Saros, and eastward to Izmit Bay through the Marmara Sea depressions. Pfannenstiel (1944), combining the proposals of Andrussov (1890) and Sieberg (1932), defined the elements of the Ganos fault system as the western part of a west-trending rhomboidal structure and proposed that the Saros Trough represents a graben structure.

Following the identification of the North Anatolian fault as an active dextral strike-slip fault by Ketin (1948), Pavoni (1961) postulated the Ganos fault system as the northernmost branch of the North Anatolian fault, where it bifurcates into westward-trending segments. Kopp et al. (1969), based on studies in Thrace, considered the Ganos Fault an extension of a fault centred in the deep Marmara Sea troughs. Following these approaches, Dewey and Şengör (1979) considered Ganos (Işıklar) mountain as a zone of compression (restraining bend) and later Şengör (1979) took the view that the Ganos mountain is a thrust-generated uplift above the basement of the Marmara Sea. In that case, the Gulf of Saros should be considered as a NE–SW-striking graben produced by N–S extension caused by the deviation of the master fault (Şengör et al., 1985).

Early seismic reflection data available in the Marmara Sea (Barka and Gülen, 1988) supported the oblique extensional model (Barka, 1983), prompting Barka and Kadinsky-Cade (1988) to advance their well-known pull-apart model, which was discussed during the 1970s by many researchers but without sufficient seismic data for its confirmation. Meanwhile, Saner (1985) interpreted reflection data acquired in the Gulf of Saros and confirmed the strike-slip character of the Ganos Fault along the Gelibolu Peninsula; he suggested, however, that it behaved as a normal fault in the Gulf of Saros. Subsequently, Önal (1986) suggested that the structural elements on the Gelibolu Peninsula formed as a result of compression oblique to the Ganos Fault.

The extension of the Ganos Fault into the Marmara Sea was first considered in the framework of a model of strike-slip faults alternating with pull-apart basins (Erkal, 1991). However, Wong et al. (1995) and Ergün and Özel (1995) realised that their new high-resolution shallow seismic data were not consistent with the pull-apart model. They recognised five blocks, consisting of three rhombus-shaped basins and two NE–SW-trending intervening transpressional push-up structures aligned oblique to the dextral North Anatolian transform fault. In their model, the Ganos Fault forms the extension of the Marmara trough composed of these three basins, with strike-slip character on land giving way to a south-dipping normal fault at sea between Gaziköy and Kumbağ.

Yaltırak (1996), who defined the fault system to the west of the Marmara Sea and named it the Ganos fault system, proposed that this system was active in five geologic periods: Cretaceous–Palaeocene, early–middle Eocene, middle Eocene–late Oligocene, early Miocene–late Miocene, and Plio–Quaternary. In addition, the basins that were controlled by these faults were superimposed on the Saros and West Marmara troughs. This study concluded that the dextral Ganos fault system developed by separating from the Thrace–Eskişehir fault system (Sakınç et al., 1999) as a 'fishbone structure' (Bozkurt and Koçyiğit, 1996) in the early Miocene–early Pliocene and was subsequently repeatedly reactivated. This tectonic regime was superimposed on the North Anatolian transform fault regime and continues today (Yaltırak, 2002). A similar relationship is observed between the North Anatolian fault and both the Yağmurlu–Ezinepazar fault zone and Almus fault

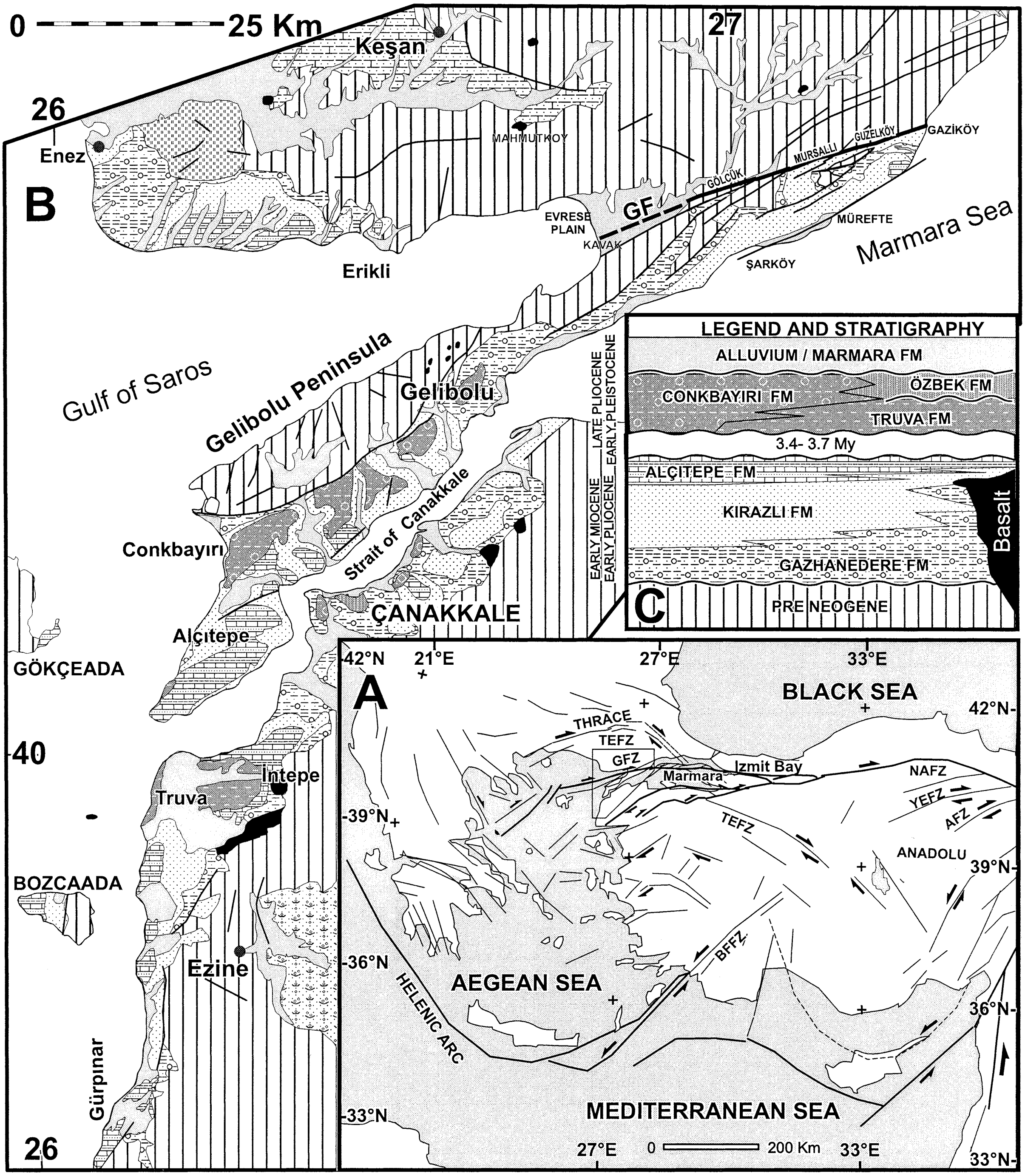
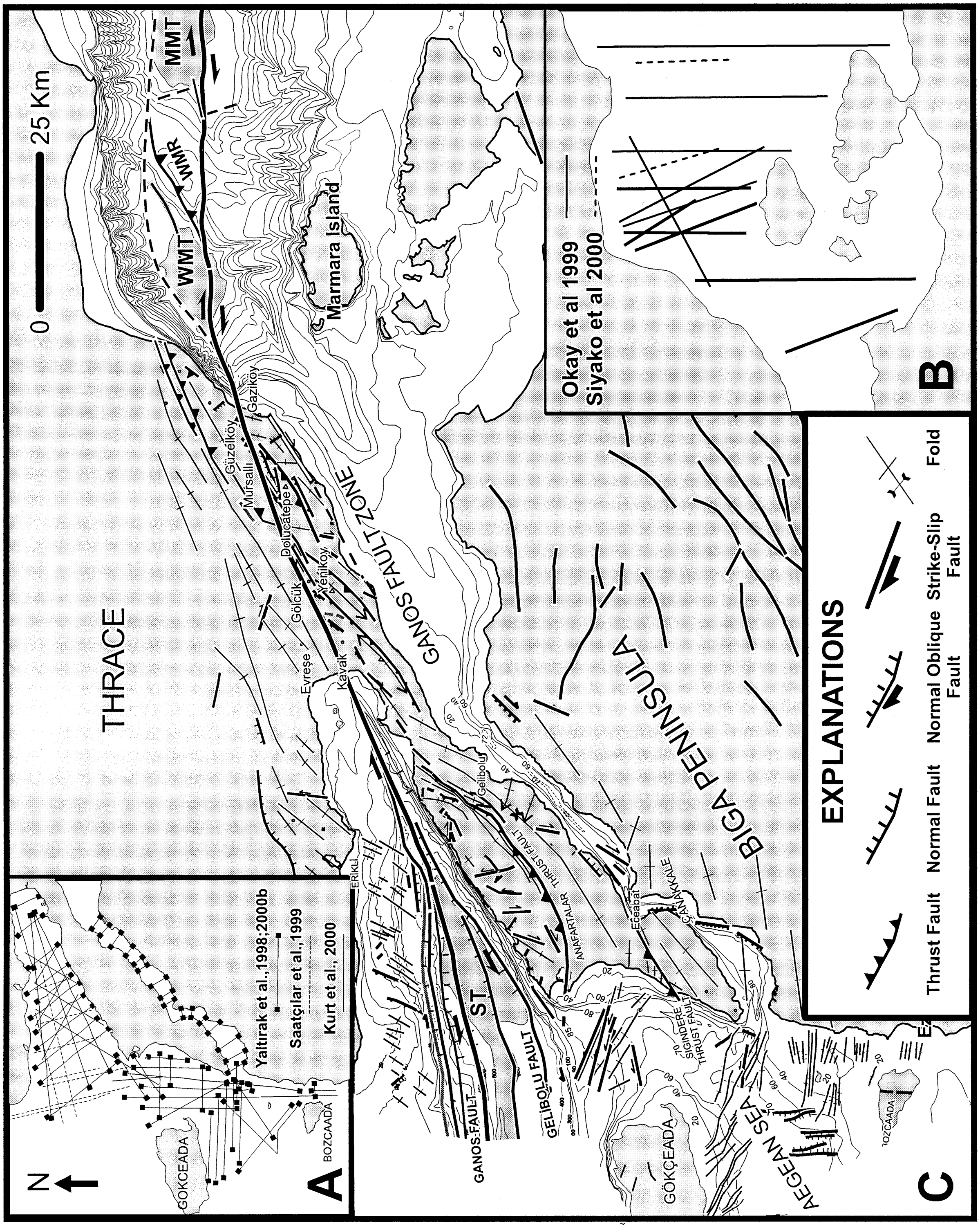


Fig. 1. (A) Tectonic setting of the eastern Mediterranean. GFZ: Ganos Fault Zone, TEFZ: Thrace–Eskişehir Fault Zone, BFFZ: Burdur–Fethiye Fault Zone, NAFZ: North Anatolian Fault Zone, YEFZ: Yağmurlu–Ezinepazar Fault Zone; AFZ: Almus Fault Zone. Figures compiled from Yaltırak et al. (1998) and Bozkurt (2001). (B) Geological map of the study area. (C) Generalised stratigraphic column of the post-Neogene units in the study area. Figures compiled from Yaltırak (1996), Yaltırak et al. (1998), Sakınç et al. (1999) and Yaltırak et al. (2000a,b).


THRACE
GANOS FAULT ZONE
BIGA PENINSULA
Marmara Island
0
25 Km
WMT
WMR
MMT
Güzelköy
Mürsallı
Gaziköy
Dolucatepe
Yeniköy
Gölcük
Evreşe
Kavak
Gelibolu
THRUST FAULT
ANAFARTALAR
Eceabat
ÇANAKKALE
SIĞINDERE THRUST FAULT
ST
GANOS FAULT
GELİBOLU FAULT
GÖKÇEADA
BOZCAADA
AEGEAN SEA
EXPLANATIONS
Thrust Fault
Normal Fault
Normal Oblique Fault
Strike-Slip Fault
Fold
Okay et al 1999
Siyako et al 2000
B
N
Yaltırak et al.,1998;2000b
Saatçılar et al.,1999
Kurt et al., 2000
GÖKCEADA
BOZCAADA
A
C

zone (Fig. 1A) (Bozkurt and Koçyiğit, 1996; Bozkurt, 2001).

The Ganos Fault is an active tectonic structural element, confirmed by its accommodation of the large 1912 earthquake (Ambraseys and Finkel, 1987). Palaeocurrent measurements in upper Pliocene–lower Pleistocene fluvial units on the Gelibolu Peninsula indicate that the material was transported from the direction of the Gulf of Saros (Yaltırak, 1995a). It was suggested that the reason for this is that the development of the Anafartalar thrust fault on the Gelibolu Peninsula has been constricted by the North Anatolian fault. In order to examine this new hypothesis, which contradicts the notion that the North Anatolian fault is a strike-slip fault in the Gulf of Saros with an extensional component, Yaltırak (1996) examined the kinematic features of the Ganos fault system. On the basis of fold axes and faults mapped on the Gelibolu Peninsula and along the coastal area of the Gulf of Saros, Yaltırak (1996) identified a dextral shearing mechanism for the northern coastal area of the Gulf of Saros, and a sinistral shearing mechanism starting from the town of Gelibolu on the Gelibolu Peninsula. Based on the premise that the Gulf of Saros was a pre-North Anatolian fault structure, Yaltırak (1996) proposed that the Ganos Fault extends into the Gulf of Saros as a sinistral strike-slip fault. This is a necessary condition for the development of the transpressional Anafartalar thrust fault and the west-trending folds observed on the Gelibolu Peninsula.

In order to explain the kinematics of the region, a high-resolution single-channel marine reflection survey was carried out in the Gulf of Saros. The results together with field surveys (Yaltırak et al., 1998) also support dextral shearing to the north and sinistral shearing to the south. Subsequently, the same research group carried out a similar high-resolution reflection study in the Strait of Çanakkale (Alpar et al., 1996). The Strait of Çanakkale (Dardanelles) is a narrow valley that resulted from regional uplift of the Gelibolu and Biga Peninsulas in the Pliocene. As a consequence of that uplift, the area was ruptured by N–S-trending normal faults under the influence of sinistral shearing forces (Yaltırak et al., 2000a). Taking into account this fault pattern and GPS slip vectors, Yaltırak et al. (2000a) constructed a model in which the Ganos Fault crosses the northern margin of the Gulf of Saros, rather than following the steep northern shores of the Gelibolu Peninsula. The conventional seismic reflection profiles published in Saatçılar et al. (1999) and Kurt et al. (2000) now allow us to test this hypothesis.

In summary, it has been widely assumed that the Ganos Fault runs along the northern shores of the Gelibolu Peninsula (Tüysüz et al., 1998; Okay et al., 1999; Saatçılar et al., 1999; Kurt et al., 2000). However, recent marine seismic data and regional GPS studies have brought this assumption into question. The most important of these doubts concerns the position of the Ganos Fault in the Gulf of Saros and in the western Marmara Sea (Yaltırak et al., 1998, 2000a,b; Sakınç et al., 1999) and has been discussed by Armijo et al. (1999) and Yaltırak et al. (2000b). At the root of the present disagreement are the fault patterns used in conflicting models. For example, Saatçılar et al. (1999) and Kurt et al. (2000) adopted the generally assumed fault positions in interpreting the regional significance of their seismic profiles, even though the assumed faults have not been mapped on land (Tüysüz et al., 1998; Armijo et al., 1999).

The apparent basic tectonic misconception concerning the location of major faults on land and at sea forces us to question published assessments of seismic hazards, the probability of strong shak-

Fig. 2. Tectonic and bathymetric map of the Ganos Fault System and its surrounds. WMR: West Marmara Ridge, ST: Saros Trough, MMT: Middle Marmara Trough, WMT; West Marmara Trough. The faults in the Gulf of Saros were redrawn from shallow seismic investigations of Yaltırak et al. (1998, 2000a,b) and from the conventional seismic data of Saatçılar et al. (1999) and Kurt et al. (2000). The faults in the Marmara Sea were redrawn from the conventional seismic data of Okay et al. (1999) and Siyako et al. (2000). The master fault is coloured white and outlined in black. Bathymetry data are from Yaltırak et al. (1998, 2000a) and Aksu et al. (1999).

ing, and the way in which stress is accommodated in the Marmara Sea (e.g. Nalbant et al., 1998; Hubert-Ferrari et al., 2000; Parsons et al., 2000). The discrepancies and differences between the various articles published during the last decade are, evidently, due to a lack of integrated marine and land-based studies of the structural and kinematic evolution of the region. Due to high estimates of the percentage probability (62 ± 15%) of strong shaking in the Marmara Sea within the next 30 years (Parsons et al., 2000), the region has become a natural laboratory for earth scientists (Le Pichon et al., 1999). The primary aim of the present study is to combine the results of shallow and conventional marine seismic investigations with structural elements observed on land so as to delineate actual rather than theoretical fault patterns.

2. Seismic data

Marine seismic data relevant to the evolution of the Gulf of Saros and its surroundings have been published in six papers: Yaltırak et al. (1998), Saatçılar et al. (1999), Okay et al. (1999), Yaltırak et al. (2000a), Kurt et al. (2000) and Siyako et al. (2000). These data sets were collected and processed by various institutions or groups.

Shallow reflection data used by Yaltırak et al. (1998) consist of 560 line-km of high-resolution analogue sparker (1 kJ) profiles acquired by the Department of Navigation, Hydrography and Oceanography (DNHO) in 1995–96. The profiles are located in the Gulf of Saros (15), in the area between Gökçeada (Imbros) island and the Gelibolu Peninsula (15) and in the area between Bozcaada (Tenedos) island and the Biga Peninsula (6). In Yaltırak et al. (2000a), two different data sets were considered: 270 analogue Uniboom (200 J) profiles (1240 line-km) acquired by DNHO in three legs between 1977 and 1991 along the Strait of Çanakkale, and 11 digital Sparker (1.25 kJ) profiles (260 line-km) recorded by the Marine Sciences and Management Institute of Istanbul University at the Aegean exit of the strait in 1997 (Fig. 2A,B).

We have also re-interpreted three multi-channel profiles acquired in the Marmara Sea, two of which were published by Okay et al. (1999) and the other by Siyako et al. (2000), and nine conventional 12-fold multi-channel reflection profiles which were acquired in the Gulf of Saros by the Institute of Mineral Research and Exploration (MTA) during cruises in 1996–97. These latter data were used in the studies of Saatçılar et al. (1999) (nine profiles, 275 line-km) and Kurt et al. (2000) (seven profiles, 159 line-km).

In this paper, we develop a structural block diagram of the Gulf of Saros and the West Marmara Trough using all the available seismic data, and define the tectonic pattern of the Ganos fault system between these regions (Fig. 2C). To accomplish this, we have correlated deeper structures on the multi-channel data with shallow tectonic elements and then mapped them in a manner consistent with Yaltırak et al. (1998, 2000a).

3. Stratigraphy

The stratigraphy of the study area can be divided into two sectors: north and south of the Ganos Fault Zone (GFZ). Although the post-Palaeogene stratigraphy shows no important discrepancies between these sectors, the thicknesses of the deposits differ as a result of variable fault activity. The borehole data (Fig. 3) as well as lateral facies changes observed on land (Fig. 1B,C) confirm this.

3.1. Sector north of the GFZ

The oldest Neogene strata are the middle Miocene fluvial sandstones to the south of Keşan (Fig. 1) (Ünay and de Bruijn, 1984). In the region between Enez and Erikli, the stratigraphic sequence starts with lacustrine and meandering-fluviatile mudstones and terminates with upper Miocene–lower Pliocene (?) limestone layers intercalated with shallow marine clastic sediments (Ternek, 1949; Saner, 1985; Sakınç et al., 1999). The only volcanics are middle-upper Miocene basaltic layers, intercalated within the Neogene units, outcropping in the central parts of Thrace as small-scale patches (Sümengen et al., 1987; Tapırdamaz and Yaltırak, 1997). Radiometric

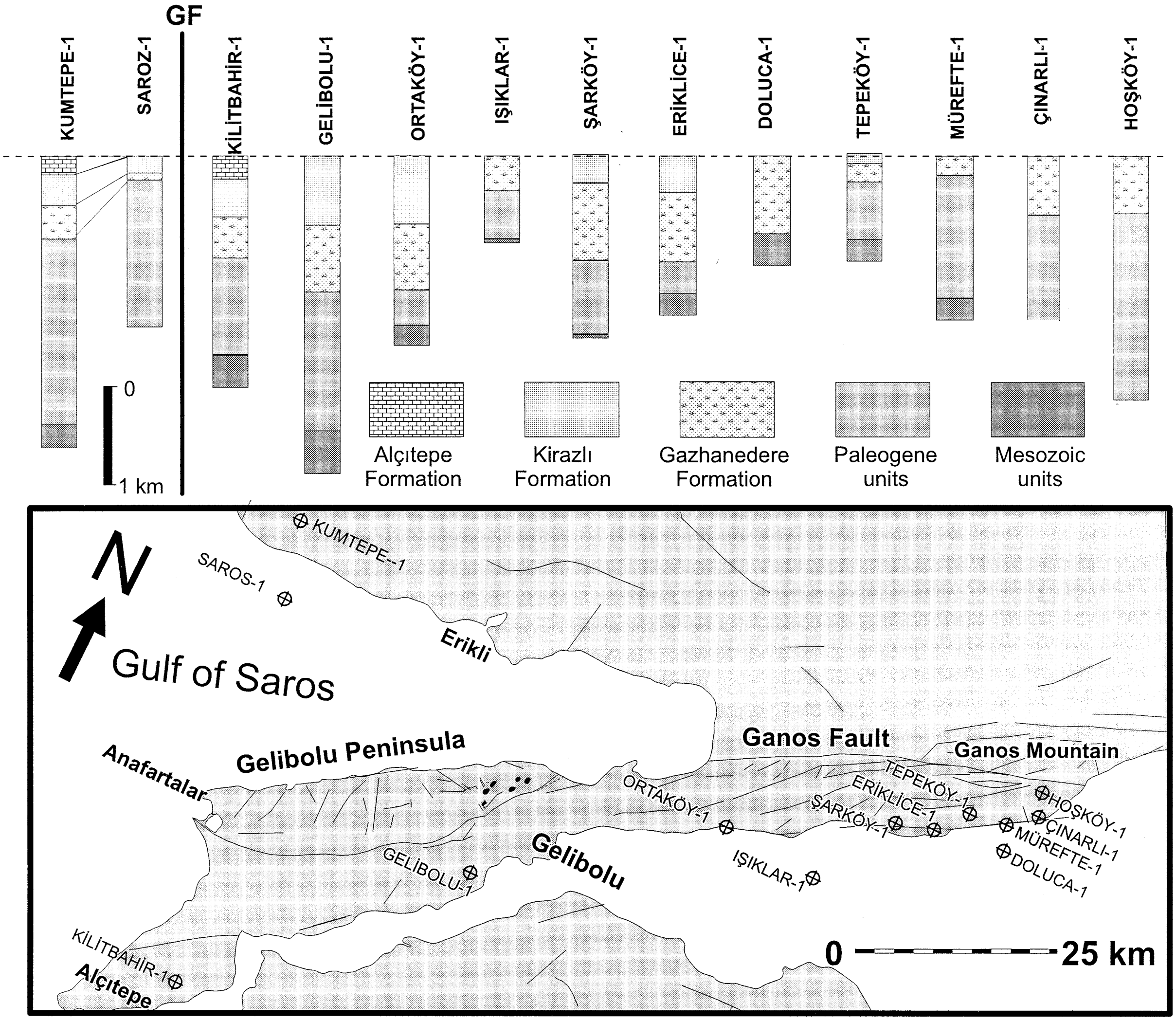


Fig. 3. The correlation of the post-early Miocene units drilled along the western Marmara Sea and Gulf of Saros (TPAO borehole data; Yaltırak, 1996; Yaltırak et al., 2000a).

dating of outcrops at Mahmutköy (Fig. 1B) gives an age of 6.7 ± 0.7 Ma (Sümengen et al., 1987). The most prominent feature of the northern sector is a period of non-deposition and denudation during the middle to late Pliocene (3.7–3.4 Ma, Yaltırak et al., 2000b). This hiatus indicates that the area started to uplift after early Pliocene. At present, even the Pleistocene units crop out tens of metres above the elevation at which they were deposited because of the uplift (Yaltırak et al., 2002).

3.2. Sector south of the GFZ

Basalts are present in the Palaeogene sequence near Yeniköy (Gelibolu) (Fig. 1B). Since these basalts supplied detritus to the widely distributed terrestrial units of the lower-middle Miocene Gazhanedere formation, they must be older. The Palaeogene units to the south of the GFZ are overlain by multicoloured meandering-fluviatile mudstones deposited in the early(?)–middle Miocene (Ünay and de Bruijn, 1984). These deposits

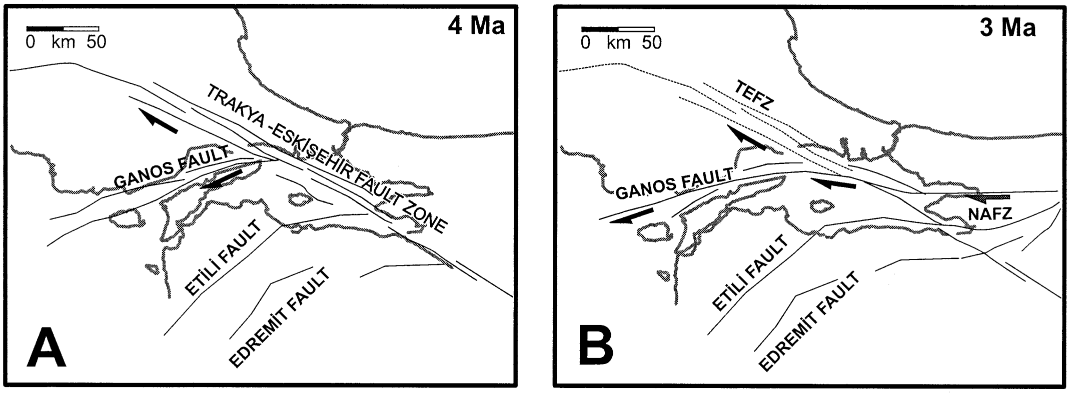


Fig. 4. The relationship between the North Anatolian fault and the Thrace–Eskişehir fault during the period 4–3 Ma.

include the well-known Gazhanedere formation. They usually lie with an angular unconformity on the older Palaeogene strata, as seen around the towns of Gaziköy, Mürefte, şarköy and Gelibolu; bedding above and below the unconformity may be parallel locally, such as near the town of B. Anafarta (Saltık, 1974; Siyako et al., 1989; Yaltırak, 1995a,b; Yaltırak et al., 1998, 2000b; Sakınç et al., 1999). On top of these mudstones, with lateral and vertical transitions, rests the Kirazlı Formation, made of massive and semi-consolidated sandstone representing beach and back-beach lithofacies of the late Miocene (Saltık, 1974; Siyako et al., 1989; Yaltırak, 1995a,b; Yaltırak et al., 1998, 2000b; Sakınç et al., 1999). The Kirazlı Formation is conformably overlain by the Alçıtepe Formation, which is made of cross-bedded calcareous sandstones and gravels, representing shallow-marine and lacustrine depositional environments (Önem, 1974; Yaltırak, 1995a,b; Yaltırak et al., 1998, 2000b; Sakınç et al., 1999). Above the Alçıtepe formation are upper Miocene–lower(?) Pliocene, *mactra*-bearing limestones, deposited in marine to lagoonal depositional environments (Taner, 1979; Yaltırak, 1995a). In the vicinity of the transpressional Anafartalar Thrust Fault, the middle Miocene–lower Pliocene (?) sequence is overlain at a parallel-to-angular (sub-parallel) unconformity by upper Pliocene–lower Pleistocene alluvial-fan deposits widely distributed on the Gelibolu Peninsula. This, the Conkbayırı Formation, is made up of mudstone–sandstone–pebblestone intercalations with an increasing grain size upward and containing polygenic pebbles (Saltık, 1974; Sümengen et al., 1987; Yaltırak, 1995a; Yaltırak et al., 1998, 2000b; Sakınç et al., 1999). Finally, the Özbek and Marmara formations, made up of fossiliferous siliciclastics, unconformably overlie the Conkbayırı formation. These were formed in a coastal environment during the late Pleistocene and are presently found between the towns of Çanakkale and Gaziköy (Fig. 1B,C) (Sakınç and Yaltırak, 1997; Yaltırak et al., 2000a,b).

Based on stratigraphical and structural evidence, Armijo et al. (1999) proposed that alluvial-fan deposits of the Conkbayırı formation show lateral transitions into the shallow-marine to lagoonal deposits of the Alçıtepe formation. They also claimed that both formations were deposited atop an angular unconformity above the Kirazlı Formation following Messinian desiccation. However, there is no unconformity at this stratigraphic level (Sakınç et al., 1999; Yaltırak et al., 2000b). Our detailed field observations have indicated that the apparent angular discordance is in fact an illusion.

4. Structural framework

In the study area, all structures developed above the axis of the modern Ganos Fault have been subjected to inversion tectonics. The inversion has also affected the distribution of depositional environments and morphology of the terrain. These structures are related to the North Anatolian fault only for the last 3.5 million years. However, the Thrace–Eskişehir fault previously affected these deposits, from the beginning of the neotectonic period at the end of the early Miocene (Sakınç et al., 1999). This implies two different neotectonic periods in which the Ganos fault system interacted first with the Thrace–Eskişehir fault and subsequently with the North Anatolian fault (Yaltırak, 2002, this volume). These can be defined as early and late neotectonic periods. The early neotectonic period covers the early Miocene-early Pliocene, when the Ganos Fault was a branch of the Thrace-Eskişehir fault, while the late neotectonic period covers late Pliocene-Present, when the Ganos Fault was a branch of the North Anatolian fault (Yaltırak, 2002). The Ganos fault system was first activated as a part of the Thrace–Eskişehir Fault Zone in the form of a 'fishbone structure' (Fig. 4A). In the late Pliocene, when the North Anatolian transform fault reached the Marmara Sea region, the Ganos fault system was captured by the North Anatolian fault system (Fig. 4B).

4.1. Ganos Fault, its position and features

The Ganos Fault is the main element of the Ganos fault system (Fig. 2). The Ganos Fault is believed to have affected and shaped all the strata to its north and south (Yaltırak, 1996). The Ganos Fault starts in the West Marmara Trough, passes through the towns of Gaziköy and Evreşe, the Gulf of Saros, and reaches Samothraki Island in the northern Aegean Sea.

4.1.1. The West Marmara Trough

The Ganos Fault strikes east into the western Marmara Sea (Fig. 2). The fault passing along the southern edge of the West Marmara Trough represents a typical negative flower structure on seismic sections (Fig. 5). The contemporaneous Plio–Quaternary strata on both sides of the Ganos fault have different seismic character. They show releasing seismic character to the north (greater subsidence), while compressional seismic character is dominant to the south. At first glance this structural difference may seem odd. The compression observed on the southern block can be explained by dextral shearing along the curved Ganos Fault. The releasing seismic character observed on the northern block could have been generated by oblique extension, which is dominant in a limited region in the West Marmara Trough due to the WSW-oriented migration of the southern block. In other words, the folding observed to the south of the master fault is due to a 7° counterclockwise rotation of the Ganos Fault as it approaches the town of Gaziköy (Fig. 2). Okay et al. (1999) have identified a compressional structure on the multi-channel reflection profiles, which is oblique to the master fault and positioned somewhere on this curved fault segment; they interpreted this to coincide with the Ganos Fault. Therefore, they concluded that the Ganos mountain was uplifted on a NW-striking thrust. This inferrred thrust is of small scale, having an aspect ratio of ~1:18, comparable to the greater size of the Ganos mountain (Okay et al., 1999; Figs. 2 and 8A).

The master fault starts from the deepest end of a submarine depression and extends to the town of Gaziköy. The orientation of the West Marmara Trough fault segment is N57°E in the studies of Barka (1992), Ergün and Özel (1995), Wong et al. (1995) and Armijo et al. (1999). However, the seismic sections published in the studies of Okay et al. (1999) and Siyako et al. (2000) indicate that this segment strikes N89°E (Figs. 2 and 5).

4.1.2. Gaziköy–Evreşe segment

Starting from the east, the fault first passes from the north of Gaziköy village to the southern foot of the Ganos mountain where it is delineated by a definite contact between Eocene basement and the overlying Miocene strata (Fig. 1B). Young valleys between Mursallı and Gaziköy villages are the only places where direct detailed field observations of the fault plane are possible. Offsets measured on the fault cutting the young deposits in these valleys are of the order of 1–5 m. Similar offsets were also observed along the roads to Mursallı and Güzelköy villages. These offsets are the result of the most recent (1912) earthquake. A reverse component was observed along

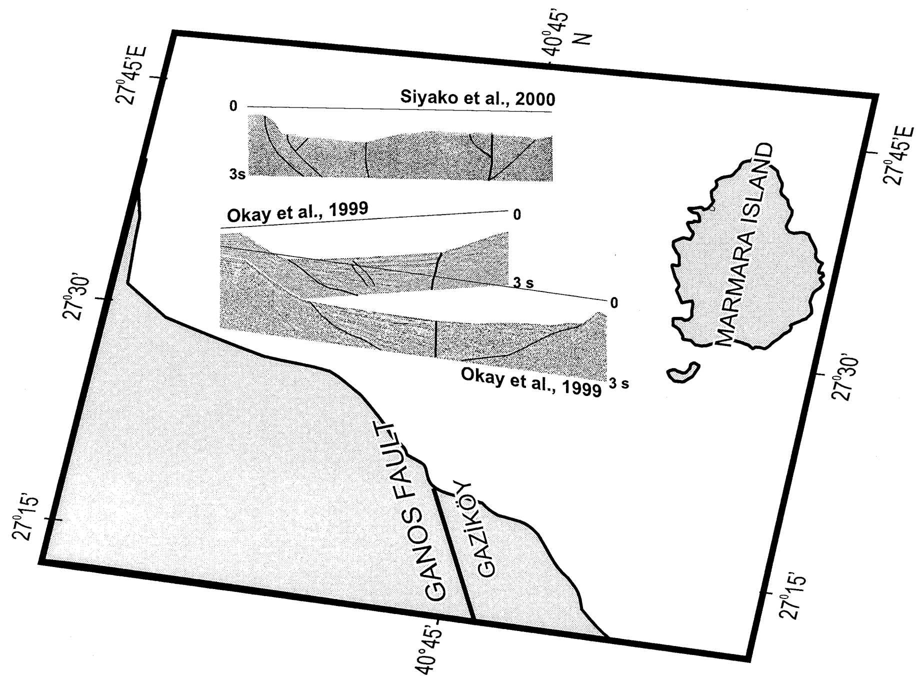


Fig. 5. Re-interpreted seismic profiles at the western Marmara Sea. Seismic lines are from Okay et al. (1999) and Siyako et al. (2000).

the open fault surface between Mursallı and Gaziköy villages. The orientation of these surfaces is 055°/87NW and 060°/85NW. The width of the shear zone between Mursallı and Güzelköy is 10 m. The fault bifurcates at the town of Gölcük, forming a pressure ridge. Young alluvial deposits, which can be observed near the dammed lake along the road going to the Evreşe plain from Yeniköy village (Fig. 1B), are a few tens of metres from the Ganos Fault. These westward-dipping deposits are on the southern block. At this locality, marine deposits of the Upper Pleistocene Marmara formation have been uplifted about 30 m above their original position (Sakınç and Yaltırak, 1997). Farther west, the Ganos Fault reaches Kavak village (Fig. 2), displacing the Kavak creek in a right-lateral sense. The results of a trench study at this locality (Rockwell et al., 1997) indicated that the southern block was uplifted and thrust a little northward.

Sakınç and Yaltırak (1997) proposed that the basement of the Gulf of Saros was uplifted under compression, citing evidence of the uplifted terraces around the gulf. The Gelibolu uplift is a compressive block between the Anafartalar and Gelibolu faults. The other effect of this compression is the westward motion of the Saros Block forming Saros Trough between the Gelibolu and Ganos faults (Fig. 6). Sığındere Thrust Fault (Fig. 2C) is a further structural element that resulted from this compression. Other faults, with similar characteristics, pass from the northern and southern foot of the Doluca Tepe mountain to the north of Mürefte (Fig. 2C) (Yaltırak, 1996).

4.1.3. *Saros Trough*

The Ganos Fault runs through the Evreşe plain and enters the Gulf of Saros approximately at the mouth of the Kavak creek (Fig. 2). In previous studies, the western extent of the Ganos Fault in the gulf was drawn solely according to bathymetry and morphology (Tüysüz et al., 1998; Okay et al., 1999; Armijo et al., 1999). An alternative approach was proposed by Yaltırak et al. (2000a), who tried to determine the position of the Ganos Fault in the gulf and to explain its sinistral strike-

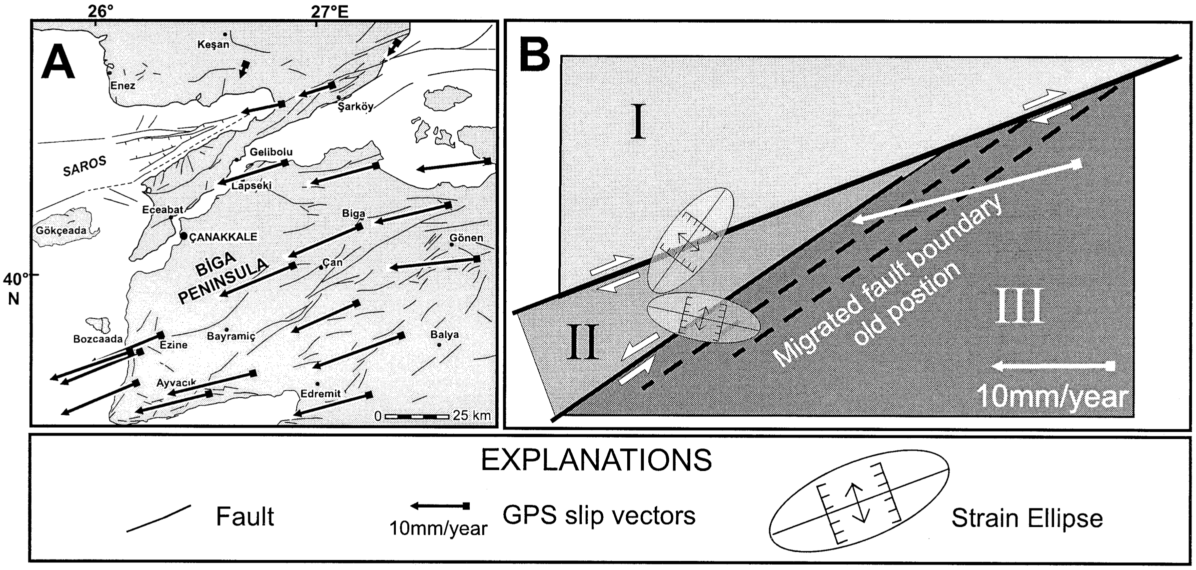


Fig. 6. Tectonic evolution model of the Western Marmara Sea and Gulf of Saros. (A) GPS slip vectors (Straub and Kahle, 1997). (B) Kinematic model in which the Ganos Fault forms the boundary between block I and blocks II and III, while the Gelibolu Fault migrates westward as the northwestern boundary of block III. During this migration, the northern boundary of the triangular block II moves dextrally while the southern boundary moves sinistrally. The normal faults observed on the Gelibolu Peninsula and its western extension are oriented N–S, while the fold axes are E–W (Fig. 2). These orientations confirm the deformation indicated on the strain ellipses. In addition, the folds parallel the Anafartalar and Sığındere thrust faults (Fig. 2), and corroborate compressional movement given by the GPS slip vectors in the region, parallel to the master fault, but oblique to the Gelibolu Fault. The sediments in front of the Gelibolu Fault (see Fig. 7B,C) and their dips show a pattern consistent with compressional inversion of a normal fault. The sinistral movement attributed to the Gelibolu Fault is also consistent with the compression of the Gelibolu Peninsula. There is harmonious agreement between the tectonic evolution model and the geometric setting of folds and faults, which show dextral movement to the north and compression to the south.

slip activity using kinematic data. Other researchers realised that seismic data would be of value, had the Ganos Fault crossed the northern continental slope. Therefore, they proposed a wedge model squeezed by two rulers oblique to each other to explain evolution of the Ganos Fault (Fig. 6). In this model, the GPS slip vectors (Straub and Kahle, 1997), which are parallel to the fault bounding the northern side of the Gulf of Saros, suggest that the Anafartalar Thrust Fault developed in a transpressional regime (Yaltırak et al., 1998).

Recent papers on the Gulf of Saros, the northern Aegean Sea and the Marmara Sea, continue to draw the Ganos Fault in the direction N58°E, even though all of our shallow seismic studies together with recently published new multi-channel seismic data contradict that interpretation. Shallow seismic interpretation (Yaltırak et al., 1998), kinematical models (Yaltırak et al., 2000a,b) and GPS slip vectors (Straub et al., 1997) all indicate that the true strike is N81°E (Fig. 2). This trend is also evident on the block diagram (Fig. 7) produced from the multi-channel reflection data of Saatçılar et al. (1999) and Kurt et al. (2000). Contrary to what is widely proposed, the structural element bounding the Gelibolu Peninsula to the north seems to be a normal fault on the seismic data. This is not the Ganos Fault, but another fault which terminates in the neighbourhood of Gökçeada island with a similar slope to that of the Anafartalar Thrust Fault (Fig. 8A,B). Therefore, it should be renamed and we have called it the Gelibolu Fault. This fault was initiated by the re-activation of a normal fault which had started to evolve in the Eocene–Oligocene period. Around the crossing point of two seismic sections at the western end of the Gelibolu Pen-

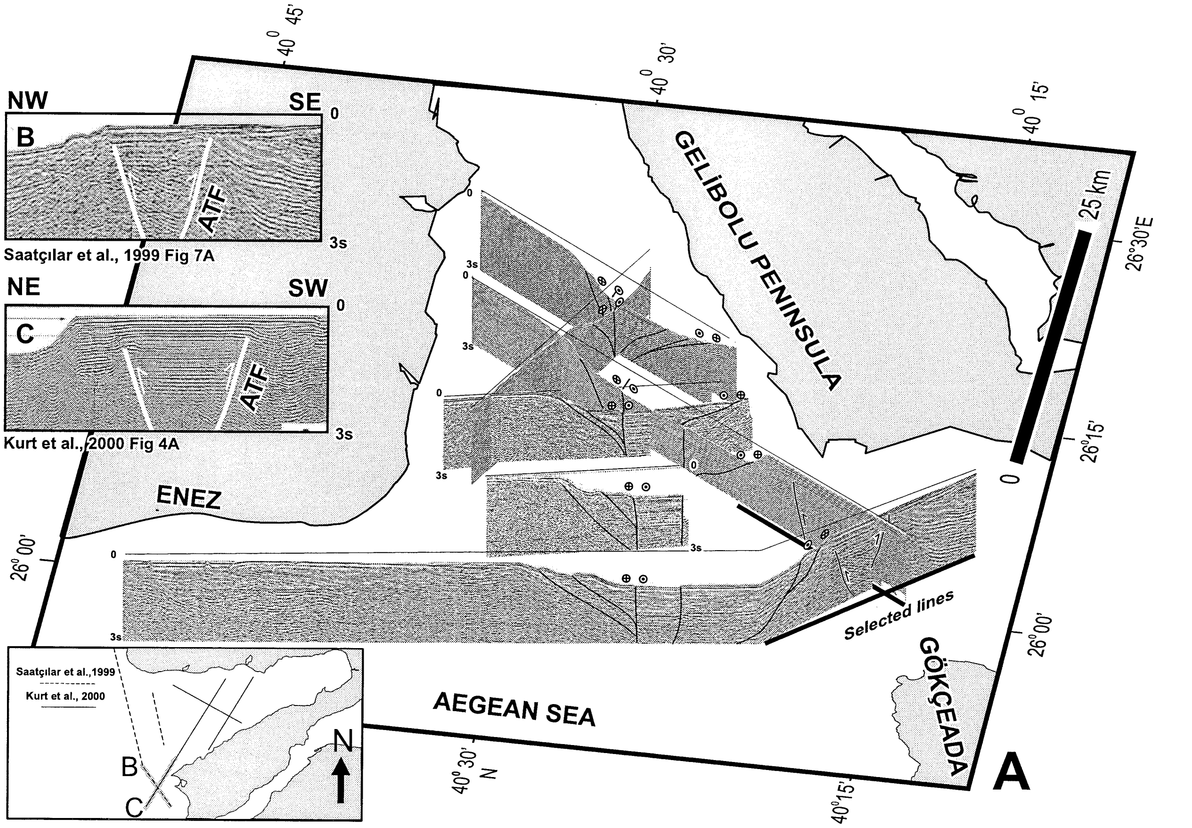


Fig. 7. Re-interpreted seismic profiles in the Gulf of Saros. Seismic lines are from Saatçılar et al. (1999) and Kurt et al. (2000). (A) A fence diagram showing the position of the North Anatolian fault in the Gulf of Saros. Two insets (B and C) show the Anafartalar Thrust Fault at different angles in detail. Also shown in an inset are the locations of the seismic lines shown in A–C.

insula, there is a blind thrust to the southwest of the Gelibolu Fault that was pushed forward into the Gulf of Saros (Fig. 7A). The sedimentary units wedge toward the Gelibolu Fault. The units dip northwest toward the fault (Fig. 7B,C), contrary to the expected geometry for normal faults. When the North Anatolian fault started to affect the region, the Anafartalar Fault gained a thrust character, the dip of the Gelibolu Fault became steeper and some slumps and folds occurred in the sediments in front of the Gelibolu Fault (see Saatçılar et al., 1999, fig. 4; Kurt et al., 2000, figs. 4, 5 and 6). These events were the result of oblique compression applied to the Gelibolu Peninsula by the Anatolian Block. In addition, the dip of the Anafartalar Thrust Fault, which is well-known on land (Yaltırak et al., 1998, 2000b) and demonstrated on the seismic sections by Kurt et al. (2000; see Fig. 4), was shown to be toward the south-west by Saatçılar et al. (1999). However, toward the south-west the structure is not a fault but rather an unconformity zone which developed by regional compression between the Palaeogene and Neogene. In this study, we recognise a thrust fault located just north of the seaward extension of the Anafartalar Thrust Fault, extending towards the NW edge of the Gelibolu Peninsula (Fig. 7). This implies that the northern coast of the Gelibolu Peninsula is associated with a thrust fault, and the Gelibolu Fault corresponds to a normal fault developed in front of the thrust.

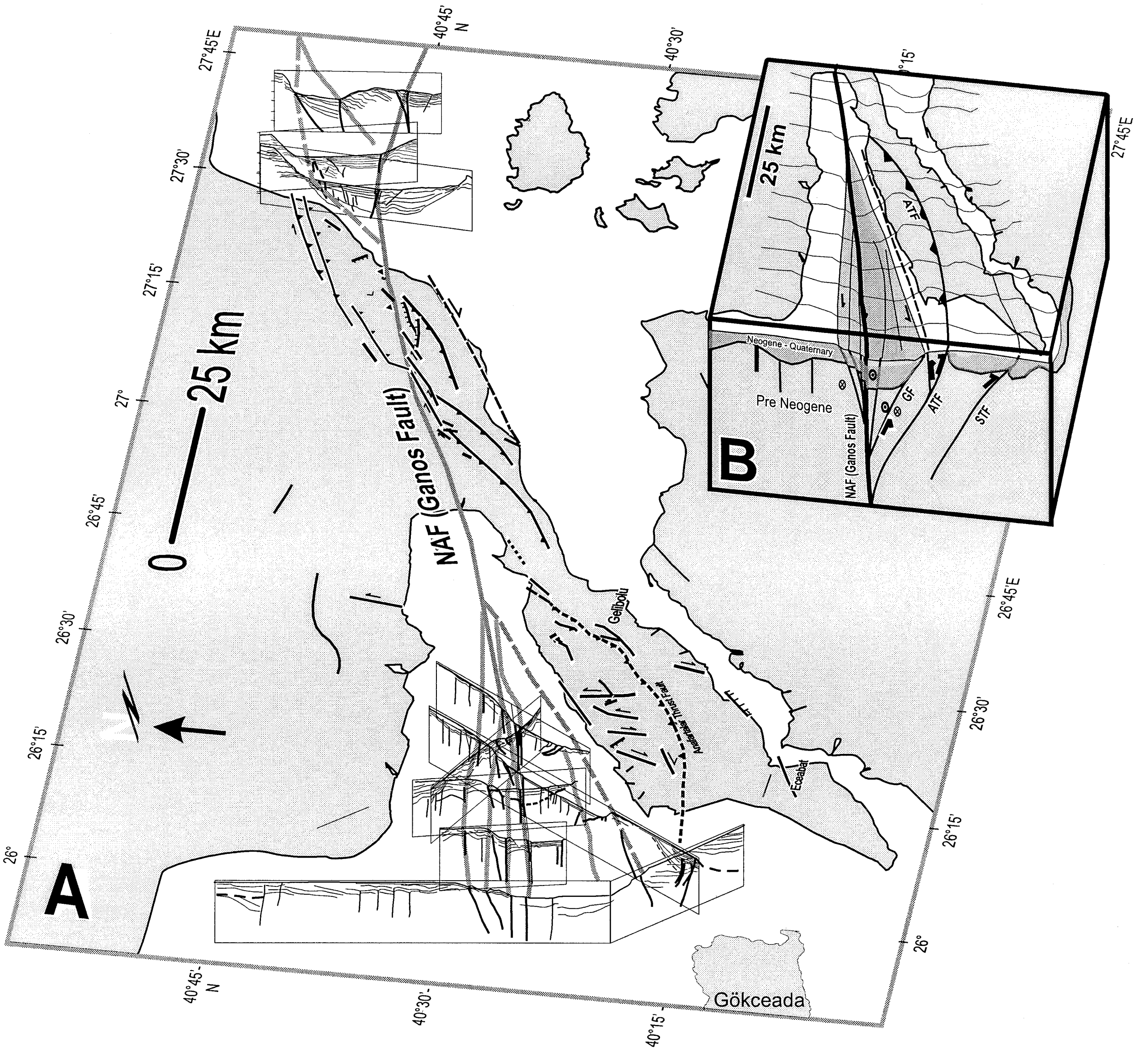


Fig. 8. (A) Fence diagram constructed from interpreted line drawings. (B) Block diagram of the Gulf of Saros. View is looking east; north is to the left. Horizontal curves represent topographic profiles. STF: Sığındere Thrust Fault, ATF: Anafartalar Thrust Fault, GF: Gelibolu Fault, NAF: North Anatolian Fault.

5. Discussion and conclusions

The Ganos fault system was initially a part of the Thrace–Eskişehir fault and subsequently became a part of the North Anatolian fault (Fig. 4). This structure can be considered as a 'horsetail' like those encountered along other strike-slip faults. It presents as a positive flower structure on blocks along the Ganos fault system to the east of the Gulf of Saros, a positive flower structure on the Gelibolu Peninsula, and a negative flower structure in the Gulf of Saros and in the Marmara Sea, east of Gaziköy (Fig. 8B). Thus, the western end of the Ganos fault system represents an example in which both positive and negative flower structures interact. Furthermore, as proposed first in Yaltırak (1996), the relatively faster movement of the Saros Block within the dextral shearing zone gives rise to a sinistral fault (Fig. 8B). The substantial marine seismic data which support this interpretation were released only in 1999 (Fig. 7). These data and the kinematic model have generated a new discussion of the trend of the Ganos Fault, which constitutes the northern strand of the North Anatolian fault (Figs. 2, 7 and 8). The Ganos Fault is an approximately ENE–WSW-trending structure (Fig. 2). Therefore, the angular difference between the trends of the Ganos Fault and the fault on which tectonic evolution and deformation analyses have been executed in Armijo et al. (1999) is about 14° clockwise (Fig. 2). While the difference in orientation is about 7° on land, it increases to $\sim$32° counterclockwise and $\sim$23° clockwise in the West Marmara and Saros submarine depressions, respectively. This revised position of the Ganos Fault in the Marmara Sea, as derived from the shallow and conventional seismic reflection data, calls into question the validity of the evolutionary models used in previously published kinematic and stress-failure analyses. The most important effect of this difference is on the tectonic models explaining the evolution of the Marmara Sea. The stress-transfer analyses applied to the Marmara Sea depend on the location of faults (commonly hypothetical faults) in these models. The westward extension of the master fault in the Marmara Sea along the southern edge of the Ganos depression is evident on seismic data (Fig. 5) (Okay et al., 1999; Kurt et al., 2000; Siyako et al., 2000). Detailed field studies have clearly defined its western extension on land between the town of Gölcük and the Marmara Sea (Fig. 2) (Yaltırak, 1996). Until now, relying solely on morphology, researchers have assumed that the master fault was located where the Evreşe plain ended. In their trenching studies, Rockwell et al. (1997) showed that the master fault lies farther north than its previously postulated position (Fig. 2). This trend corresponds to the extension of the canyon in the bathymetry map given in Yaltırak et al. (1998) (Fig. 2). In this same study, faults were observed along the northern margin of the Gulf of Saros on the seismic sections, while there are apparently no active faults along the southern margin. Therefore, based on the previous studies and also on the steep morphology along the continental slope, the main fault was thought to be closer to the northern coast of the Gelibolu Peninsula than is actually the case (Yaltırak et al., 1998).

Contrary to the findings of previous studies, it is now plain that the Ganos Fault neither shows southward bending nor follows the northern shore of the Gelibolu Peninsula (Fig. 8B). Seismic sections (Fig. 7) given by Saatçılar et al. (1999) and Kurt et al. (2000), detailed field observations (Yaltırak, 1995a,b, 1996; Tapırdamaz and Yaltırak, 1997; Sakınç et al., 1999; Yaltırak et al., 2000b), marine seismic studies (Yaltırak et al., 1998, 2000a) and GPS studies (Straub et al., 1997) now more clearly show the North Anatolian fault pattern from the Marmara Sea into the northern Aegean Sea (Figs. 2 and 7). The master fault is in the shape of a large-radius arc striking almost WSW–ESE. This appearance may explain why the GPS slip vectors in the southern Marmara Sea point more or less westward (Fig. 6). The almost E–W trend of the master fault proposed in this paper requires that stress-transfer analyses (i.e. Nalbant et al., 1998; Hubert-Ferrari et al., 2000; Parsons et al., 2000) be reconsidered. Furthermore, this proposed trend supports the existence of the Great Marmara fault (Le Pichon et al., 1999; Aksu et al., 2000; Yaltırak, 2002), a single buried fault crossing the Marmara Sea, compared to pull-apart or en echelon fault models suggested for the Marmara Sea.

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