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Active submarine tectonism and formation of the Gulf of Saros, Northeast Aegean Sea, inferred from multi-channel seismic reflection data

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Abstract

Active submarine tectonism and the formation of the Gulf of Saros, northeast Aegean Sea, were investigated by means of multi-channel seismic reflection data. This area is a key in understanding the development of major structures resulting from the interacting regimes of the Western Anatolia–Aegean Sea and the North Anatolian Fault zone (NAF). The major feature forming the Gulf of Saros is the Ganos fault, which is one of the main segments of the northern strand of the NAF. In this study, a total of 159 km reflection seismic data were collected, processed and interpreted in seven lines in order to map active submarine faults which were used to propose a tectonic model for opening of the Gulf of Saros. Interpretation of the seismic sections and their correlation with the geological, morphological and earthquake data indicate that there are two main fault systems in the gulf: (i) strike-slip faults with normal components which bound the Saros trough in the north and south; and (ii) normal faults located within the trough. We propose that the Saros trough was first formed as a negative flower structure in response to the southward bending of the NAF zone possibly in Plio-Quaternary, then it evolved as a dilated negative flower structure as the Aegean extension intensified in late Pliocene–Quaternary. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Gulf of Saros; Aegean Sea; North Anatolian fault; North Aegean trough; Seismic reflection

1. Introduction

The Gulf of Saros is located at the northeast Aegean Sea and is surrounded by Gelibolu Peninsula to the south and Thrace Peninsula to the north (Fig. 1). It is an E–W trending and eastward closing wedge shaped gulf with a width of 30 km and length of 55 km. The gulf is the easternmost part of the North Aegean Trough (NAT) (Fig. 1). The formation of the gulf has been intensively studied (Saner, 1985; Çağatay et al., 1998; Tüysüz et al., 1998; Saatçılar et al., 1999; Yaltırak et al., 1999). The Gulf of Saros lies in an area where two dominant regional regimes, N–S extension in the Western Anatolia–Aegean Sea and shear in the NAF zone, are interacting. The aim of this study is to investigate active submarine tectonism in the Gulf of Saros by multi-channel seismic reflection data, and furthermore to evaluate the opening and evolution of the gulf in the light of the regional regimes.

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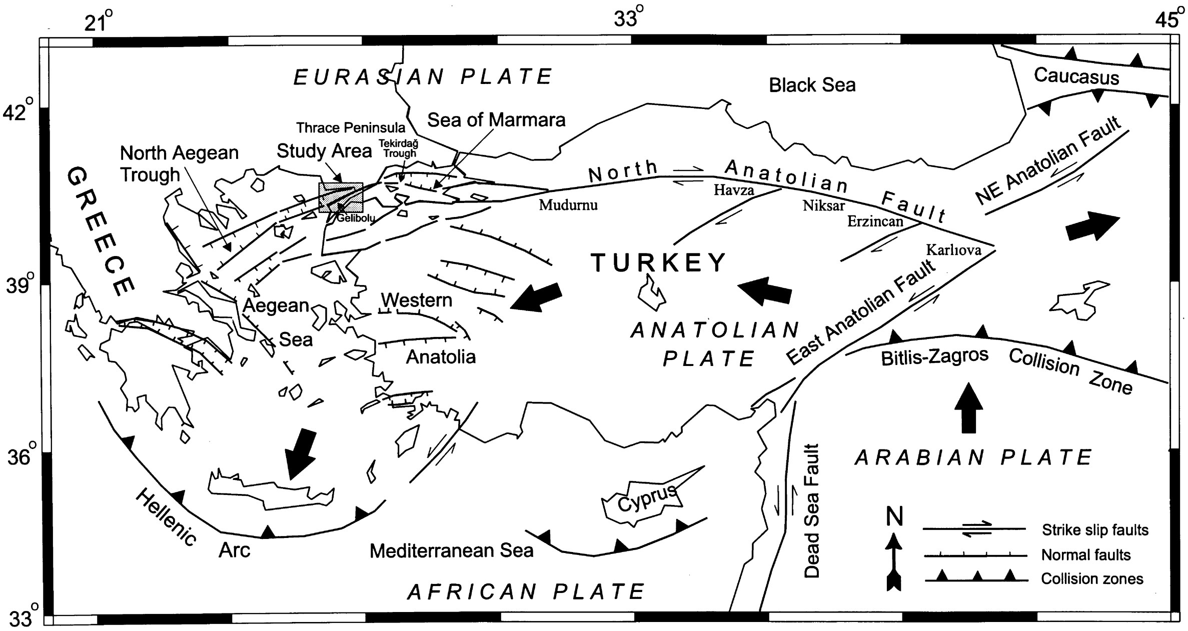

Fig. 1. Simplified tectonic map of the eastern Mediterranean region. Solid lines are strike-slip faults with arrows on each side showing direction of motion, ticked lines are normal faults with ticks on the downthrown block and lines with solid triangles are thrust faults with triangles on the overriding block. The large solid arrows show directions of motion of Arabian and Anatolian plates with respect to the African plate. Three strands of the NAF zone and main grabens in the Western Anatolia are shown. Note that the study area is located in the NE part of the NAT and it belongs to northern strand of the NAF zone. Figure was drawn from Lybéris (1985), Barka and Kadinsky-Cade (1988), Suzanne et al. (1990), Barka (1992), Wong et al. (1995), Reilinger et al. (1997), Barka and Reilinger (1997), Okay et al. (1999) and Kurt et al. (1999).

After the collision of the Arabian–African and Eurasian plates along the Bitlis-Zagros suture zone sometime during the Miocene, the Anatolian–Aegean plate started to laterally escape westward. This motion is controlled by the dextral North Anatolian Fault (NAF) and the sinistral East Anatolian Fault (EAF) since late Miocene–Pliocene (Dewey and Şengör, 1979; Şengör, 1979; Şengör et al., 1985). There are many transtensional basins along the NAF zone, such as Karlıova, Erzincan, Niksar, Havza basins, Marmara Sea, and Gulf of Saros (Fig. 1), formed mostly as a consequence of overstep and fault-bend mechanisms (Lybéris, 1985; Şengör et al., 1985; Barka and Kadinsky-Cade, 1988; Suzanne et al., 1990; Barka, 1992; Wong et al., 1995; Çağatay et al., 1998; Okay et al., 1999). The NAF splays into three branches around Mudurnu: a northernmost branch, a middle branch and a southernmost branch. The Gulf of Saros is located at the northernmost branch (Fig. 1). Another major tectonic development occurring in the whole Western Anatolia–Aegean Sea region is a N–S extensional regime (McKenzie, 1978; Dewey and Şengör, 1979; Le Pichon and Angelier, 1981; McKenzie and Yılmaz, 1991). The imprints of this extensional regime are clearly seen as generally grabens and horsts in the geology and geomorphology of the Western Anatolia–Aegean Sea region. According to the model of Dewey and Şengör (1979), extension in the Western Anatolia–Aegean Sea region might be related to the westerly escape of the Anatolian plate in reaction to the collision of the Arab–African and Eurasian plates through the Bitlis-Zagros continental collision zone. Back-arc spreading of Aegean crust in relation to Hellenic subduction as suggested by Le Pichon and Angelier (1981) as well as gravitational spreading of the Aegean crust suggested by Le Pichon and Angelier (1979) and Seyitoğlu and Scott (1991) are, however, alternative explanations for a dominant N–S extension.

Tectonic models for the Gulf of Saros have been extensively discussed in the literature. On the basis of deep multi-channel seismic reflection data, Saner

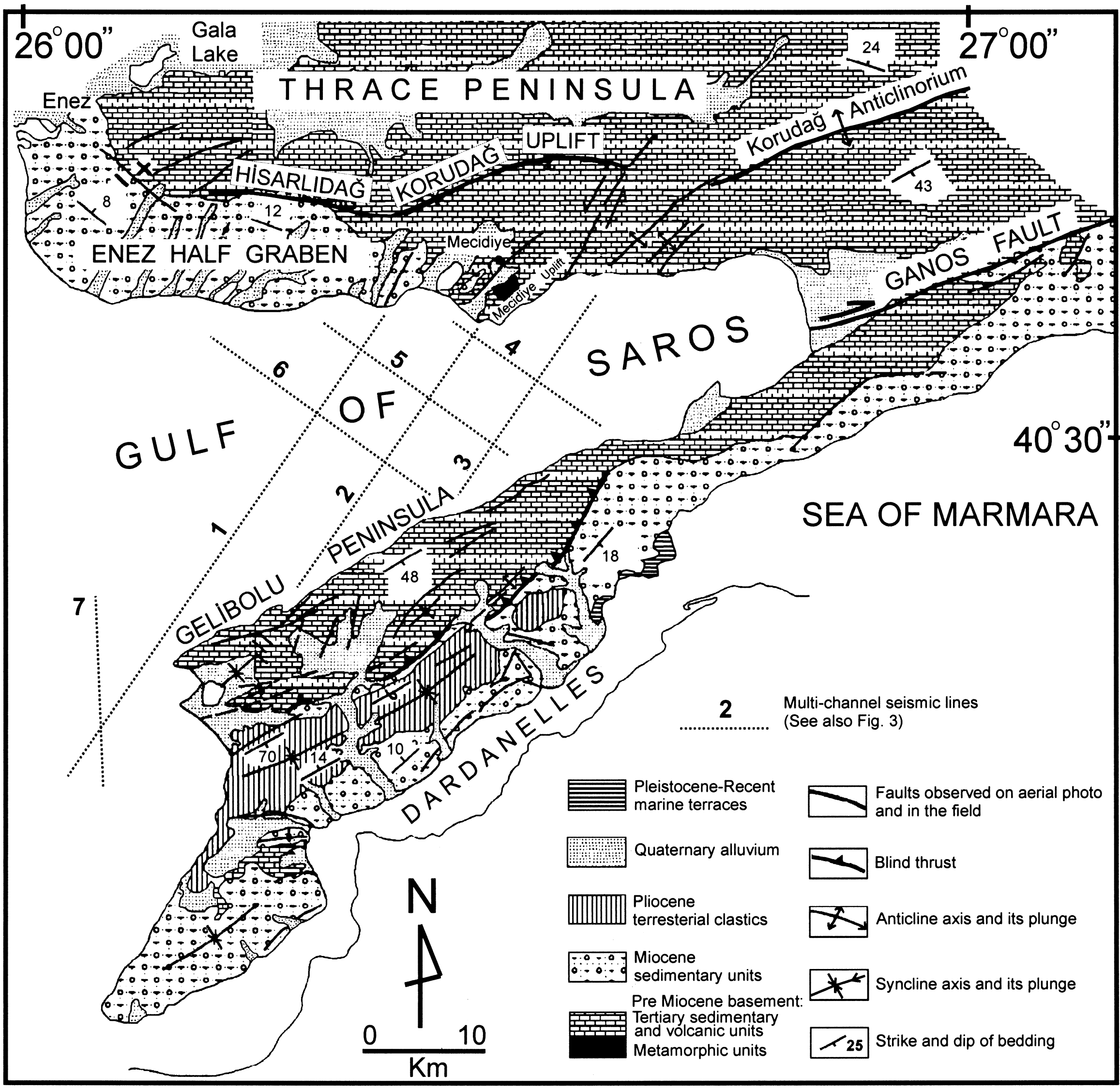

Fig. 2. Geological map of Saros area (modified from Tüysüz et al., 1998) and location of the seismic lines. Eocene–Oligocene Tertiary sedimentary and volcanic units form the Hisarlidağ–Korudağ uplift, and Miocene and younger sediments form former Enez graben. Dextral Ganos fault is extending in NE–SW and it continues along the southern coast of the gulf. Eocene–Oligocene units are exposed in the northern part of the Gelibolu Peninsula while Miocene, Pliocene and Quaternary sediments outcropped in its southern part. A blind thrust (Anafartalar thrust) trending NE–SW dipping to the north is extending throughout Gelibolu Peninsula.

(1985) suggested that release faults along the fold flanks caused synclines to evolve into graben when tensional forces were dominant in the Saros area since Miocene. Using single-channel shallow seismic reflection data and field geology, Çağatay et al. (1998) have proposed that the Gulf of Saros resulted from interactions between the NAF zone shear activity and the Aegean extensional regime. The southward bending of the NAF may have been increased over time as a consequence of concurrent extensional regime and resulted in development of new strands of the NAF towards south (Şengör et al., 1985).

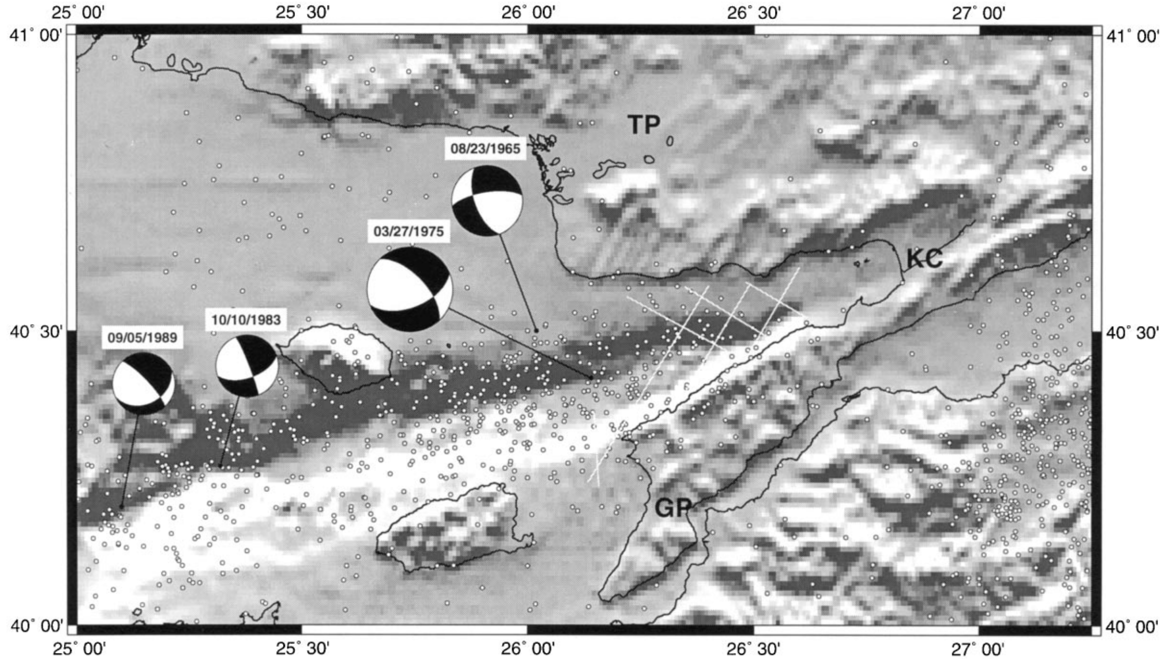

Fig. 3. Bathymetric and topographic relief, earthquake epicentral distribution, and location of seismic lines in the Saros area. In the gulf, a wedge-shaped trough is bounded by ENE trending slopes at the north and NE trending slopes at the south. This trough continues to the SW between two islands and it connects to the NAT. There exists a wide shelf area at the north in contrast to no shelf area at the south. At the northern onshore, Hisarlıdağ–Korudağ uplift is clearly observed. There exists a plain area at the eastern tip of the gulf resulted from deposits of Kavak creek and a dendritic drainage system to north. Northern shore of Gelibolu Peninsula has steep slopes and this is possibly related to the continuation of dextral Ganos fault to the west. Epicentral distribution of the earthquakes from the ISC catalogue between 1964 and 1993 shows high activity throughout the trough. Abbreviations are: TP, Trakya Peninsula; KC, Kavak Creek; GP, Gelibolu Peninsula.

According to Çağatay et al. (1998), the Saros Graben was formed between these strands. On the basis of detailed field geology, kinematic deformation modelling and seismological studies, Tüysüz et al. (1998) suggested that the Gulf of Saros was mainly formed by the activation of the NAF in northwestern Turkey. In a first stage, a transpressional regime, induced during Pliocene, resulted in the uplift of the Gelibolu Peninsula, and in a second stage, a transtensional regime through the NAF, induced opening of the Gulf of Saros as a pull-apart basin during the late Pliocene–Quaternary. Components of this activity are the well-known dextral Ganos fault (Okay et al., 1999) to the south, and some submarine dextral faults to the north. In contrast to these models, Yaltırak et al. (1999) claimed that the Saros graben was created as a consequence of the westerly escape of a middle block between two strike-slip faults, a dextral one located to the north and a sinistral one located to the south. This escape of the middle block occurred because of the NW–SE compression caused by counter-clockwise rotation of the Thrace and Biga peninsulas during middle to late Miocene. They argued that the NAF was not responsible for the onset of Saros graben, but was responsible for the evolution of the gulf when the Ganos fault system became a part of the NAF zone during late Pleistocene. Recently, Saatçılar et al. (1996 and 1999) have mapped some active submarine faults in the Gulf of Saros. Although they did not discuss basin formation mechanisms, both the geometry and the characters of active faults tend to support a transtensional basin model.

We collected, processed and interpreted multichannel deep seismic reflection data along seven lines in order to map the active fault systems in the gulf. Moreover, bathymetric and topographic relief,

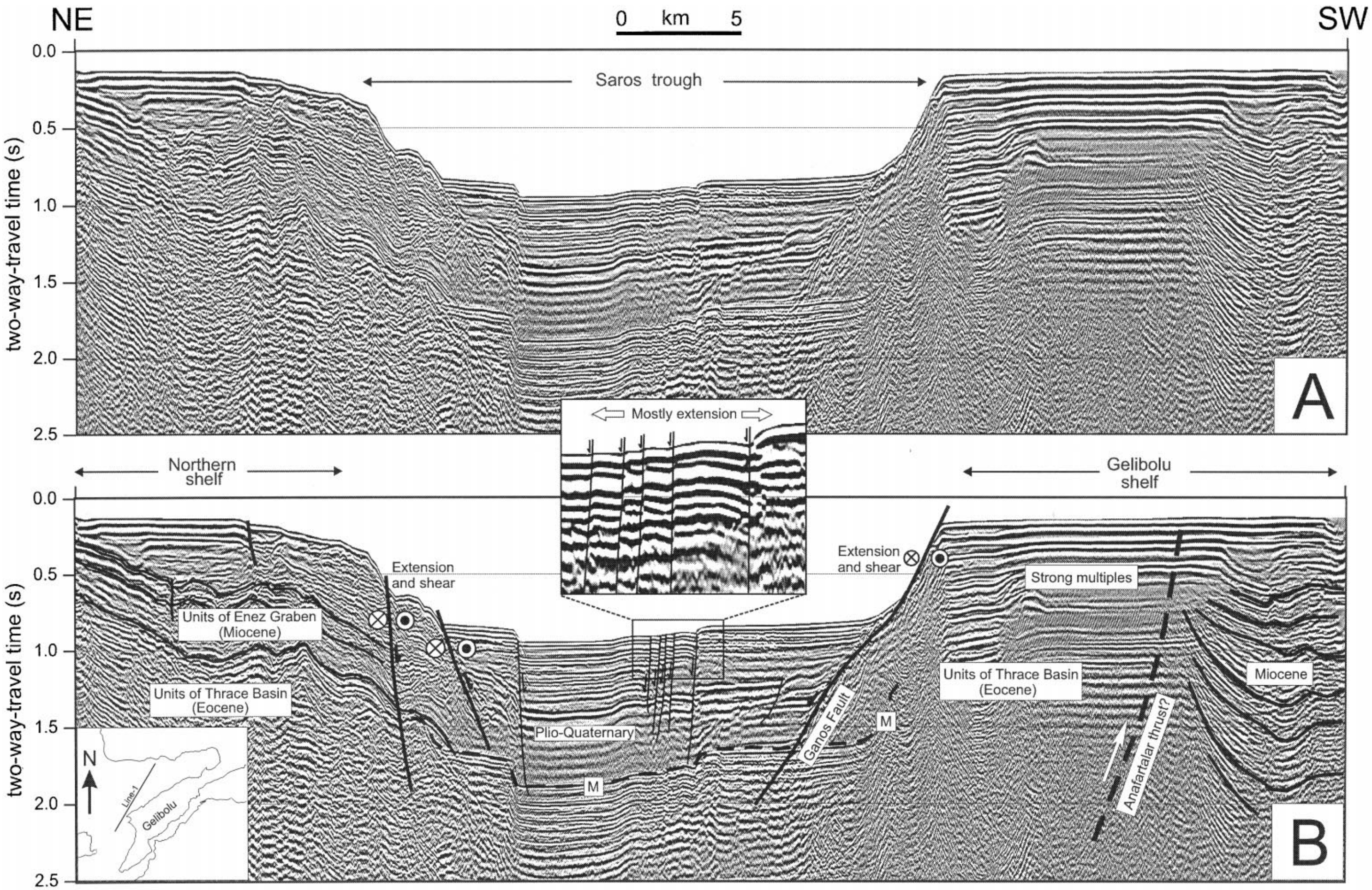

Fig. 4. (A) Time-migrated seismic section-1; (B) Interpreted section. Main feature Saros trough is bounded by faults, which have dip and strike-slip components. Blocks towards us and away from us are marked by (⊙) and (⊗), respectively. Sea bottom multiple reflection is indicated by dashed line labelled (M). Strong multiples cover the primary reflections on the Gelibolu shelf. Interpreted location of the Anafartalar thrust against folded Miocene units is marked by thick dashed line. Vertical exaggeration is about 4.5. Inset figure shows back tilting of beds due to normal faulting, i.e. rotation of both fault planes and beds, possibly caused by extensional forces.

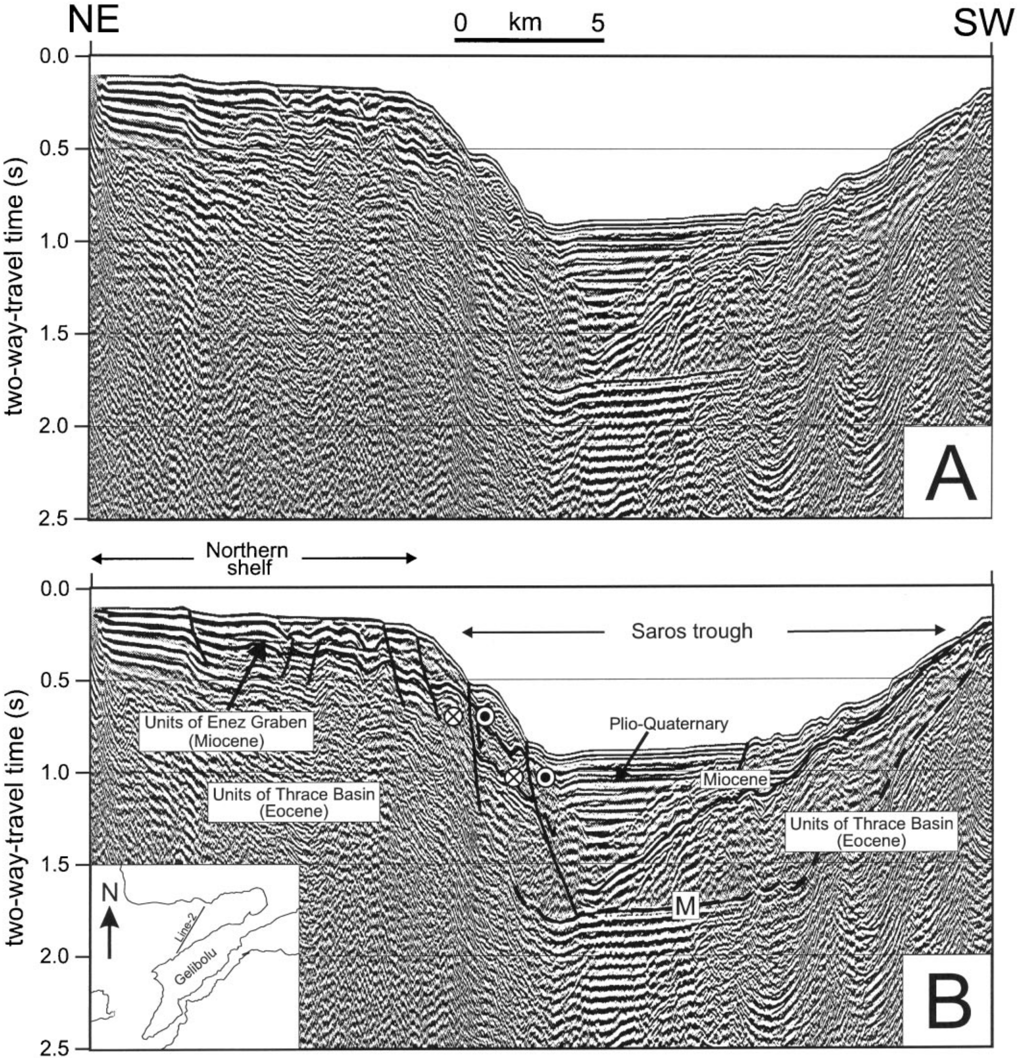

Fig. 5. (A) Time-migrated seismic section 2; (B) Interpreted section. Folded and faulted units are noticeable below the northern shelf. These units are cut by normal and strike-slip faults. In the Saros trough, horizontal bedding possibly corresponds to Quaternary deposits. The dashed line marked by (M) shows the sea bottom multiple reflection. Vertical exaggeration is about 4.5. $\odot$ = blocks moving towards us; $\otimes$ = blocks moving away from us.

earthquake distribution and focal mechanism solutions as well as onshore geology are also included in the interpretations. Two sets of fault systems can be observed from our seismic data: (i) faults showing both strike and dip-slip character delineating a trough in the gulf; and (ii) faults showing mainly the dip-slip character cutting the seabed and recent deposits only. We propose that the final shape of the Gulf of Saros has been determined by these fault systems in a two-stage evolution model.

2. Data acquisition and processing

Seismic reflection data with 96 channels were collected on seven lines (total of 159 km) by MTA *Seismic-1* research vessel in August 1996 in order to investigate the expected ENE–WSW oriented active tectonism in the Gulf of Saros (Figs. 2 and 3). The energy source was a 7-gun source array with a 750 and 870 (only for line-1) cubic inch volume. Receiver group interval, shot interval, and near offset values

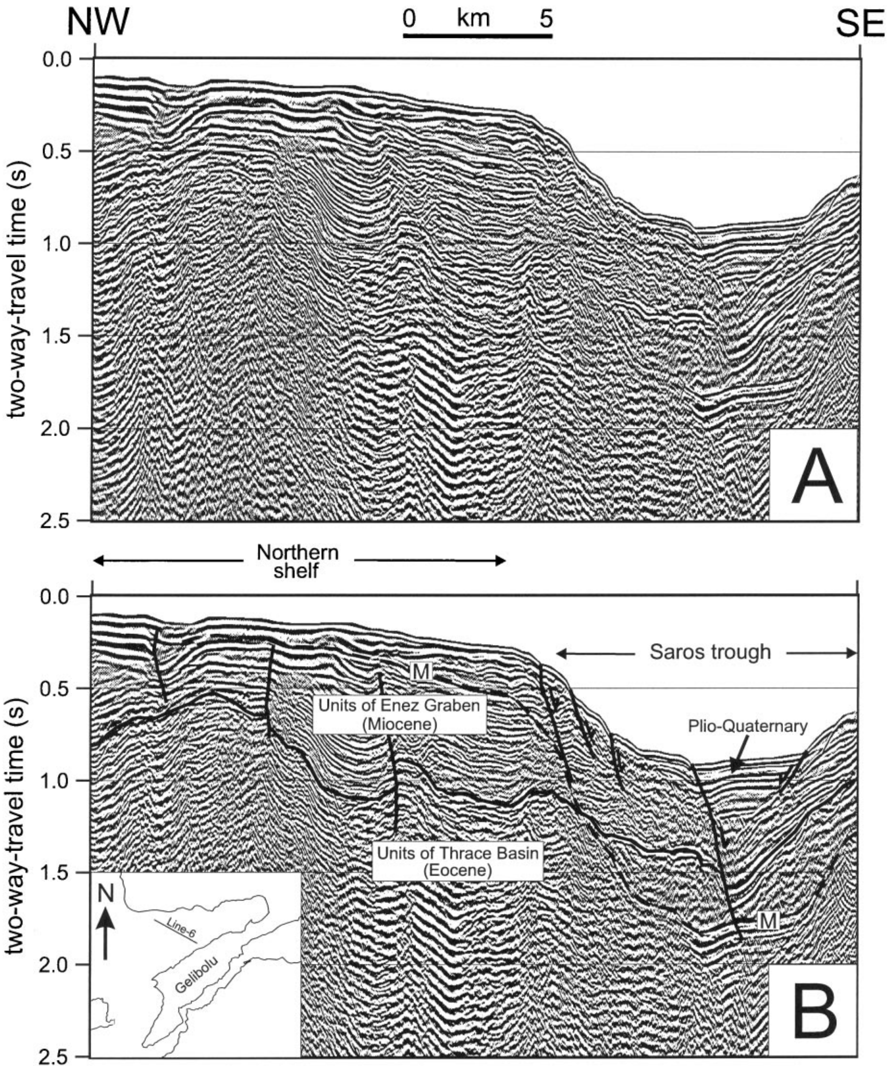

Fig. 6. (A) Time-migrated seismic section-6; (B) Interpreted section. On the northern shelf, units of former Enez graben are interpreted on the basis of field geology. These units are folded and faulted and some of the faults also cut Eocene Thrace basement. Northern border of the Saros trough is faulted stepwise. Vertical exaggeration is about 4.5.

are 12.5, 50 and 237.5 m, respectively. These parameters provided 12-fold common-depth-point (CDP) data. Sampling interval and record length were selected as 2 and 5120 ms while real time 8–218 Hz band-pass filtering was applied to raw data before recording. Although a Differential Global Positioning System (DGPS) was operated during recording, most of the lines were positioned only by GPS mode.

The data were processed in the Department of Geophysics, İstanbul Technical University (İTÜ). A conventional seismic data processing flow was applied to the data: data transcribing, in-line geometry definition, editing, sorting, gain correction, band-pass filtering, velocity analysis, normal-moveout correction, muting, stacking, bandpass filtering, automatic gain control, and post-stack finite-difference time migration. Unfortunately, sea bottom multiples were strongly imprinted degrading the interpretation although some attempts were made to attenuate the

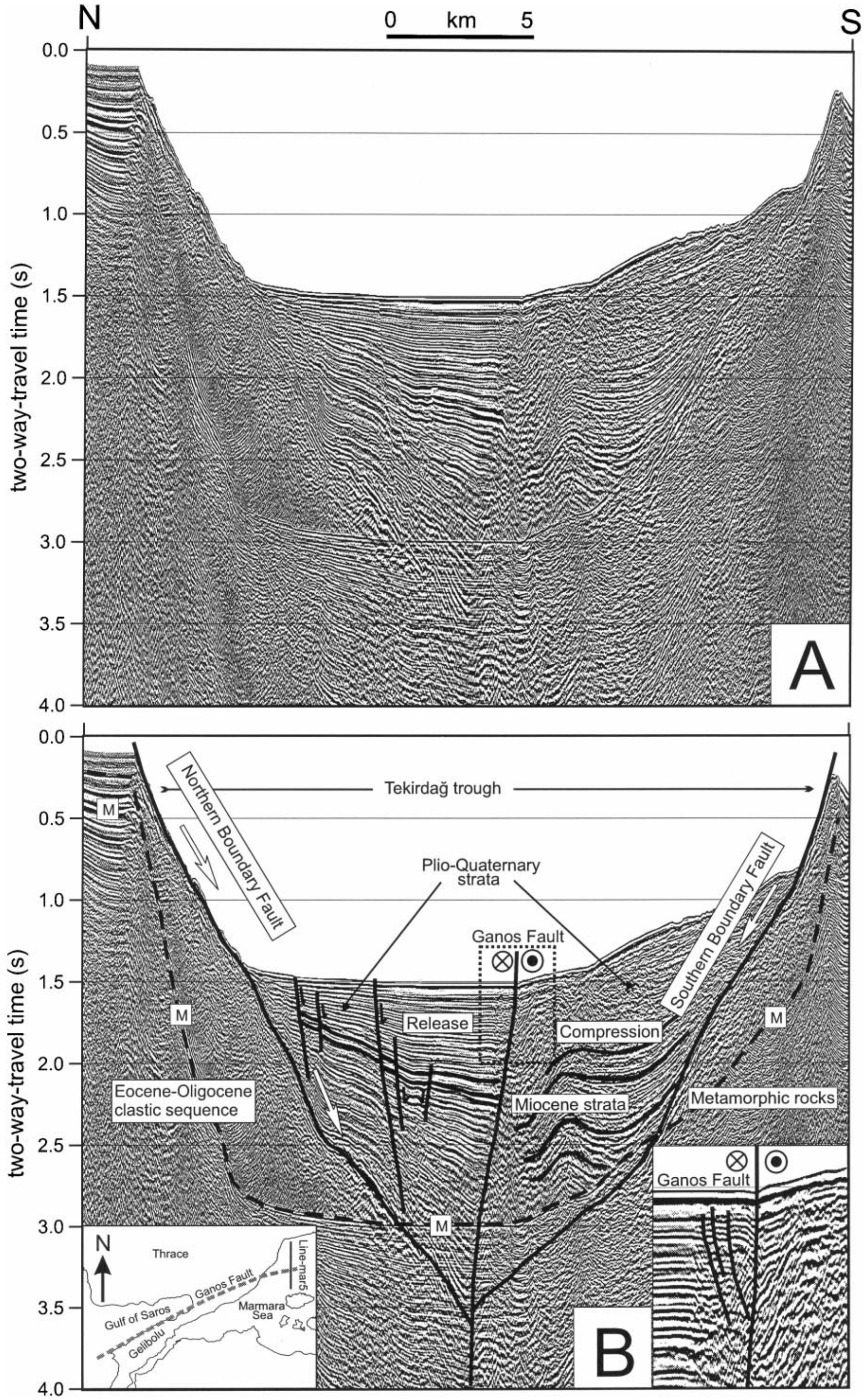

Fig. 7. (A) Time-migrated seismic section from the Sea of Marmara; (B) Interpreted section. Dextral Ganos fault through Tekirdağ trough in the Marmara Sea shows a clear strike-slip character in this seismic section. In the Tekirdağ trough, the Plio-Quaternary strata to the north of Ganos fault shows releasing seismic character while southern side shows compressional seismic character. Blocks towards us and away from us are marked by (⊙) and (⊗), respectively. Dashed line labelled (M) marks multiple reflections. Inset figure shows a minor negative flower structure developed in the uppermost part of the main fault (stratigraphic dating is from Okay et al., 1999). Vertical exaggeration is about 4.5.

multiples during repeated velocity analyses and post-stack predictive deconvolution.

3. Bathymetric and topographic relief of the Saros area

A relief map of the Saros area (Fig. 3) was prepared by using data sets from different sources. The bathymetry data were obtained from bathymetry charts of the Turkish Navy, "International Bathymetric Chart of the Mediterranean" prepared by the "Intergovernmental Oceanographic Commission" and "Geophysical Data System Worldwide Marine Geophysical Data" (GEODAS). Topographic data were obtained from a "Global Land One-km Base Elevation" (GLOBE) model of "the USA Department of Commerce National Geophysical Data Center" (NGDC). Echo-sounder depths along the seismic lines in this study were also included. All of these data sets were combined to produce the relief map shown in Fig. 3 by using Generic Mapping Tools (GMT) (Wessel and Smith, 1995).

The bathymetry relief shows a wedge-shaped trough, extending more or less parallel to the shorelines of Gelibolu and Thrace Peninsula (Fig. 3). This trough initiates within the gulf and elongates towards WSW to become the northeastern part of the NAT (Fig. 1). A wide shelf (about 10 km) exists at the northern gulf and it is bounded by faults most of which make significant steps at the sea bottom (Figs. 3–6). On the contrary, steeply dipping sea bottom along the shores of Gelibolu Peninsula is observed in Figs. 3 and 4. This morphology has been related to the dextral Ganos fault which is the western extension of the northernmost branch of the NAF zone according to Barka (1992), Çağatay et al. (1998), Tüysüz et al. (1998) and Okay et al. (1999). We interpret that these steep slopes seen along the northern coast of the Gelibolu Peninsula can be correlated to the imprints of the Ganos fault on land further northeast. A direct connection of these two morphological features however cannot be observed due to alluvial cover from Kavak creek and a dendritic drainage system located at the northeastern part of the gulf (Fig. 3). Further, the Gelibolu Peninsula shows an asymmetric morphology having a watershed located close to the northern shores and extending in NE–SW.

4. Structural and stratigraphic interpretation of seismic data

Most of the seismic lines from previous investigations are perpendicular to the main structural trend (Saner, 1985; Saatçılar et al., 1996, 1999; Yaltırak et al., 1999). The new seismic lines were routed oblique to the shorelines in order to get more information from the shelf areas.

Two major fault systems can be observed in the seismic sections (Figs. 4–6): (i) Faults showing both shear and extensional features. These faults show strike-slip and dip-slip components and they are the main features bounding the Saros trough. (ii) Faults with possibly only dip-slip. These faults develop only in the central part of the Saros trough and they cut the latest deposits.

Steeply dipping sea bottom and basement reflections on southwest indicate the western continuation of the Ganos fault (Fig. 4). The seismic line crosses the fault zone obliquely; therefore, the fault plane slope should be steeper than it appears. This fault system bounds the Saros trough from the south and the fault plane can be followed at least down to 2 s two-way-travel (twt) time. The Ganos fault has widely been studied and described as one of the major segments of the northernmost branch of the NAF (Barka and Kadinsky-Cade, 1988; Tüysüz et al., 1998; Okay et al., 1999). A seismic section across the Sea of Marmara just east of the Gulf of Saros reveals the characteristics of the Ganos fault (Fig. 7). This line was also collected with the same data acquisition parameters as Saros data by the same research group in September 1997. A major vertical discontinuity shows the Ganos fault. Note that folded Miocene strata to the south implies compressional characteristic, and normal faulting as well as divergent bedding to the north imply extensional characteristic (Fig. 7). A relatively flat sea bottom morphology just over the main fault indicates no significant vertical motion. Moreover, converging secondary faults to the main fault tend to initiate a minor negative flower structure (see the inset figure). In addition, the Ganos fault was observed as a dextral fault along with its transpressional features onshore (Okay et al., 1999). An earthquake focal mechanism solution also indicates thrust fault mechanism possibly related to transpressional features in onshore

(Kalafat, 1996). All evidences tend to substantiate that the Ganos fault, which extends from western Marmara Sea to the Gulf of Saros, is a major dextral segment with its secondary structural features.

Saros trough is bounded by stepwise faults to the north (Figs. 4–6) with an observed vertical throw of approximately 375 and 150 m in section-1 (Fig. 4) which can be correlated to the bathymetry in Fig. 3. Although it is not possible to figure out the mechanism of these faults from seismic sections, fault plane solutions of two major earthquakes (1965 and 1975) by Taymaz et al. (1991), Eyidoğan (1988) and McKenzie (1978) indicate a dextral component. Strike-slip characteristics of this fault zone are still recognised to the west as shown by focal mechanism solutions from recent earthquakes in 1983 and 1989 (Taymaz et al., 1991). Moreover, the epicentral distribution of earthquakes, compiled and mapped from the ISC catalogue between 1964 and 1993, shows high earthquake activity in and around the Saros trough (Fig. 3).

Active normal faults cutting the seabed and the recent sediments are observed within the trough (Fig. 4). Vertical throw of these features is about 75 m. An analysis of these recent faults reveals the following: faults are normal in character and display rotation of beds and fault planes (inset of Fig. 4). Tilted fault blocks within the trough are typical elements of the extensional mechanism as pointed out and modelled by Wernicke and Burchfiel (1982) and Jackson (1987). These evidences show that the faults within the trough are formed possibly in reaction to the N–S extension.

Besides active tectonics, paleotectonic features are also observed in the seismic sections. The former Enez graben is detected on the northern shelf (Figs. 2, 4 and 6). Units of this graben are well seen onshore (Saner, 1985; Tüysüz et al., 1998; Yaltırak et al., 1999) and its submerged section below the northern shelf was proposed by Saner (1985) on the basis of multi-channel seismic data. This graben had been created on the former Thrace basin during Miocene and filled by continental sediments in its lower part and transgressive marine sediments in its upper part (Tüysüz et al., 1998).

A NE–SW trending and NW dipping blind thrust zone on the Gelibolu Peninsula has been inferred by Saner (1985), Tüysüz et al. (1998) and Yaltırak et al. (1999) (Fig. 2). Cenozoic sedimentary and volcanoclastic units from the northern peninsula are overthrusted on Miocene sedimentary units of the southern peninsula. To the south, a NE–SW trending synclinorium is observed on the peninsula. Along its southern flank, there are many antiforms and synforms trending parallel to this feature. Towards the thrust, folds are asymmetric and tight, dips of the beds reach up to 90° and in some places they are overturned (Tüysüz et al., 1998). The submerged southern flank of this feature is interpreted in the seismic sections 1 and 7 (Fig. 4).

5. Discussions on the origin of the Gulf of Saros

It has been widely accepted that basement involved strike-slip faulting induces important geological and geomorphological features along its path where major faults experience oversteps and/or bends (Wilcox et al., 1973; Mann et al., 1983; Woodcock and Fischer, 1986; Sylvester, 1988). Field observations are also well documented from different regions (Sylvester and Smith, 1976; Ben-Avraham et al., 1979; Crowell, 1979; Aydin and Page, 1984). A variety of transtensional and transpressional features are observed and studied specifically along the NAF zone (Barka and Kadinsky-Cade, 1988; Suzanne et al., 1990; Barka, 1992; Ergün and Özel, 1995; Wong et al., 1995; Okay et al., 1999).

The Gulf of Saros is one of the major features seen in the NAF zone and it has possible genetic relation with the Ganos fault (Fig.1). Multi-channel seismic data from this survey show two sets of faults in the gulf: (i) faults showing both strike-slip and dip-slip and delineating the Saros trough; and (ii) faults showing mainly dip-slip character, and cutting across the recent sediments and the seabed within the trough. A fault line sketch map constructed from the interpreted seismic sections in this study and from the seismic sections in Saatçılar et al. (1996 and 1999) is shown in Fig. 8.

The faults bounding the Saros trough are the first set of faults responding to shear as well as extensional forces. As discussed in the previous section, these faults have strike-slip as well as dip-slip components (McKenzie, 1978; Eyidoğan, 1988; Taymaz et al., 1991). We also observe from mapping (Fig. 8) that

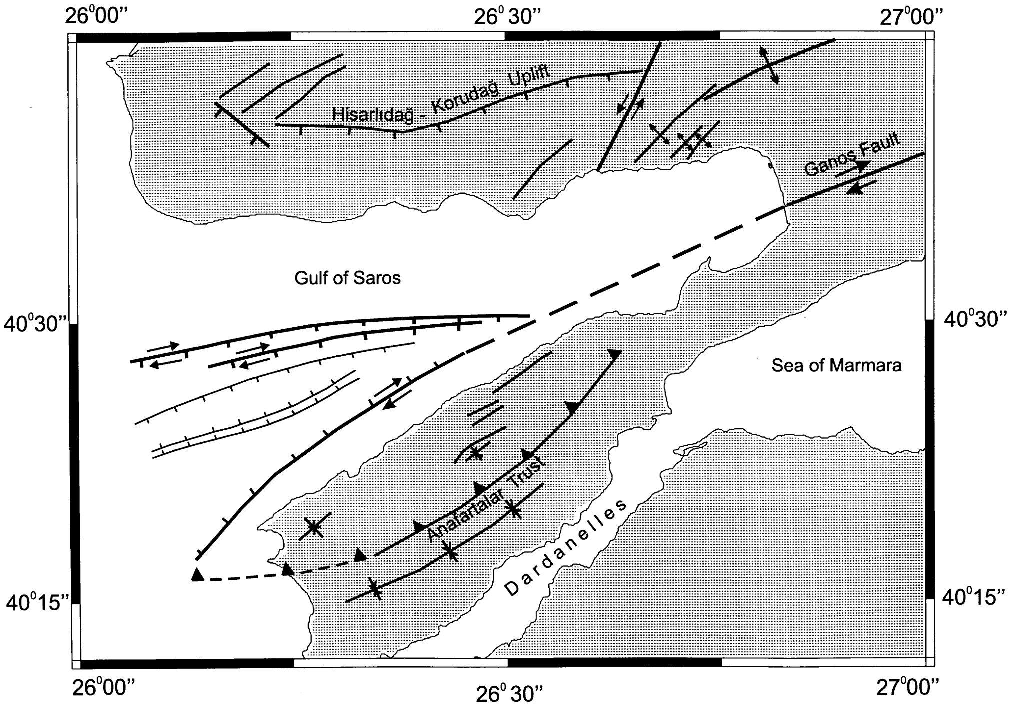

Fig. 8. Fault line sketch map constructed from the interpreted seismic sections in this study and from the seismic sections in Saatçılar et al. (1996 and 1999). Major faults in the gulf are shown in bold lines. These bounding faults are the set of faults responding to shear forces as well as extensional forces. Thin lines show the second set of faults cutting the seabed and the recent deposits and possibly responding to extensional forces of the Western Anatolia–Aegean extension. Note that the faults bounding the Saros trough from north converge to the main fault, the Ganos fault, towards east. The structural features on land are drawn from Tüysüz et al. (1998).

these faults converge to the main fault, Ganos fault, towards east. Negative flower structure is a typical feature of strike-slip faults, a transtensional feature that develops in divergent strike-slip systems as pointed out by Woodcock and Fischer (1986). We interpreted the first set of these faults as the main features created by the interacting shear forces of the North Anatolian Fault and the extensional forces in the Western Anatolia–Aegean Sea area.

A second set of faults indicated by thin lines in Fig. 8 are located within the trough and cut the recent sediments as well as the seabed. From the seismic sections, these faults may only affect the sediments filling the trough and therefore may not be basement involved features. In other words, this second set shows mainly normal faulting in character and they have been possibly created within the unconsolidated sediments in response to Aegean extension.

We may argue that the interaction between the shear and extensional regimes in the northwestern Anatolia–Aegean Sea may have activated to shape the Gulf of Saros. The extensional model of the Western Anatolia–Aegean Sea by Dewey and Şengör (1979) and Şengör et al. (1985) offers that the westerly escape of the Aegean–Anatolian plate is mainly provided by the dextral NAF zone and the sinistral EAF zone, since the late Miocene–Pliocene. Moreover, Jackson and McKenzie (1988) have proposed that the rate of extension in the Aegean has increased through time in Plio-Quaternary. Hence, if the Western Anatolia–Aegean Sea extension was initiated as a consequence of the tectonic escape of the Anatolian plate and increased in relation to the subduction in the Hellenic Arc, the evolution of the Gulf of Saros could be viewed in two phases. In a first stage, southward bending of the NAF zone (Şengör et al., 1985) caused divergent faulting from the main feature, the Ganos fault (Fig. 9(a)). This structure may

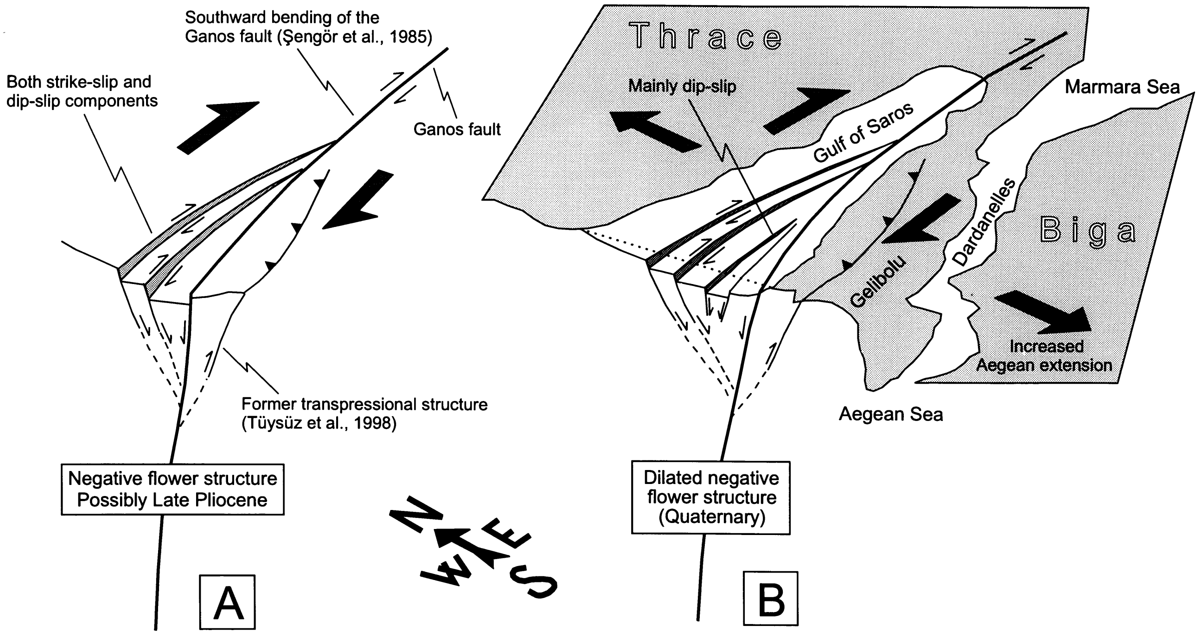

Fig. 9. Block diagram of evolution of the Gulf of Saros. (A) In a first stage, southward bending of the NAF caused divergent faults to develop which were possibly convergent to the Ganos fault in the vertical section in Pliocene–Quaternary. This structure may be evaluated as a negative flower structure, which constituted the nucleus of the gulf. (B) In a second stage, increased Western Anatolia–Aegean Sea extension possibly in late Pliocene–Quaternary caused the already formed faults, i.e. the first set of faults, to respond to the extensional forces as well as the shear forces of the NAF zone. Increasing extension might have caused development of a new fault system, i.e. the second set of faults, especially in the unconsolidated Quaternary deposits of the trough and dilated the negative flower structure.

have been a negative flower structure and the nucleus of the gulf. In a second stage, an increasing Western Anatolia–Aegean Sea extension phase, possibly in late Pliocene–Quaternary, induced the already existing faults to react to extension as well as to shear from the NAF. Increasing extension might have induced development of new fault systems, especially within the weak unconsolidated trough deposits (Fig. 9(b)). After all, the Gulf of Saros started to create as a negative flower structure and evolved later as a dilated flower structure along with a newly developed fault systems located within the trough during Western Anatolia–Aegean Sea extension intensification in late Plio-Quaternary.

6. Conclusions

Multi-channel seismic reflection data were collected, processed and interpreted in the light of field geology, morphology and earthquake mechanism solutions in the Saros area. The dextral Ganos fault, one of the main components of the northern strand of the NAF, seems to play an essential role in forming the Gulf of Saros. Data show the presence of a wedge-shaped trough within the gulf bounded by the Ganos fault to the south and divergent branches to the north. The Ganos fault and divergent branches, as well as the recent normal faults observed within the trough are seen as main structural elements of the Gulf of Saros. This gulf was created in two phases: in a first stage, southward bending of the NAF had led to divergent faults to form a negative flower structure. In a second stage, possibly in late Pliocene–Quaternary, increasing Western Anatolia–Aegean Sea extension induced an additional extension while the shear forces were still active. Increasing extension might have caused development of a new fault system, especially within the unconsolidated trough deposits.

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