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Geological evolution of the Gulf of Saros, NE Aegean Sea

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Abstract The Gulf of Saros is an Upper Miocene transtensional basin in NW Anatolia, formed by the interaction between the North Anatolian Fault and the N-S extensional tectonic régime of the Aegean. The present configuration of the basin evolved mainly during the Plio-Quaternary under the increased activity of the North Anatolian Fault. During the late Miocene-late Quaternary, no sedimentation took place on the shelves. After this long hiatus, an important change in tectonic style about 0.2 Ma BP allowed sedimentation to resume in the gulf.

Introduction

The Gulf of Saros is a westward-widening triangular graben in the northeastern Aegean Sea (Fig. 1). It shows an asymmetrical bathymetric profile with a 10-km-wide shelf to the north and an up to 15-km-wide deep trough to the south (Fig. 2). The shelf inclines gently toward the slope with a shelf break at a water depth of 90–120 m. The slope leading to the deep trough has a mean gradient of 8.5° and displays an irregular morphology caused by ENE faulting and sediment slumping. The deep trough starts to the southeast of Mecidiye as a wedge-shaped depression, deepening and widening toward the west. It lies below 660 m of water in the Gulf of Saros and continues towards the WSW between the islands of Bozcaada and Semadirek to join the 1000- to 1500-m-deep Anatolian Trough. It is bounded from the south by the steeply faulted (the Ganos Fault) margin of the Gallipoli Peninsula (Fig. 2).

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The purpose of this study is to reconstruct the geological evolution of the Gulf of Saros. This is important in understanding the origin of the other Neogene grabens developed in the northeastern Aegean and the Marmara Sea regions (Fig. 1). It will also shed light on both the timing and the kinematics of the opening of these seas. This construction is based on both onshore and offshore data. The onshore data were provided by the coastal geological studies, whereas the offshore data were obtained by seismic reflection studies (both conventional and high-resolution) and gravity coring, as well as from a previously drilled borehole (the Saros-1) (Fig. 2). The conventional seismic data were acquired by the Turkish Petroleum Company in 1980. By using special processing algorithms (i.e., single/multichannel predictive deconvolution), these data have been reprocessed for multiple suppression with a partial success. The high-resolution profiles were obtained during two geophysical cruises of the Turkish Navy ship T.C.G. Çubuklu in 1995 and 1996. The sparker data were recorded directly on paper and covered approximately the top 100 m of the subsurface. Positioning was provided by Trisponder (using three shore-based radio beacons) with an accuracy of about 10 m. Depths to reflectors were estimated using average sediment velocity of 1750 m s^{-1} and water velocity of 1500 m s^{-1}. The average vertical exaggeration on the high-resolution seismic sections is 13 $\pm$ 3. The results obtained from all these studies are combined here with other published geological and geophysical information to establish the Neogene to Quaternary evolution of the Gulf of Saros.

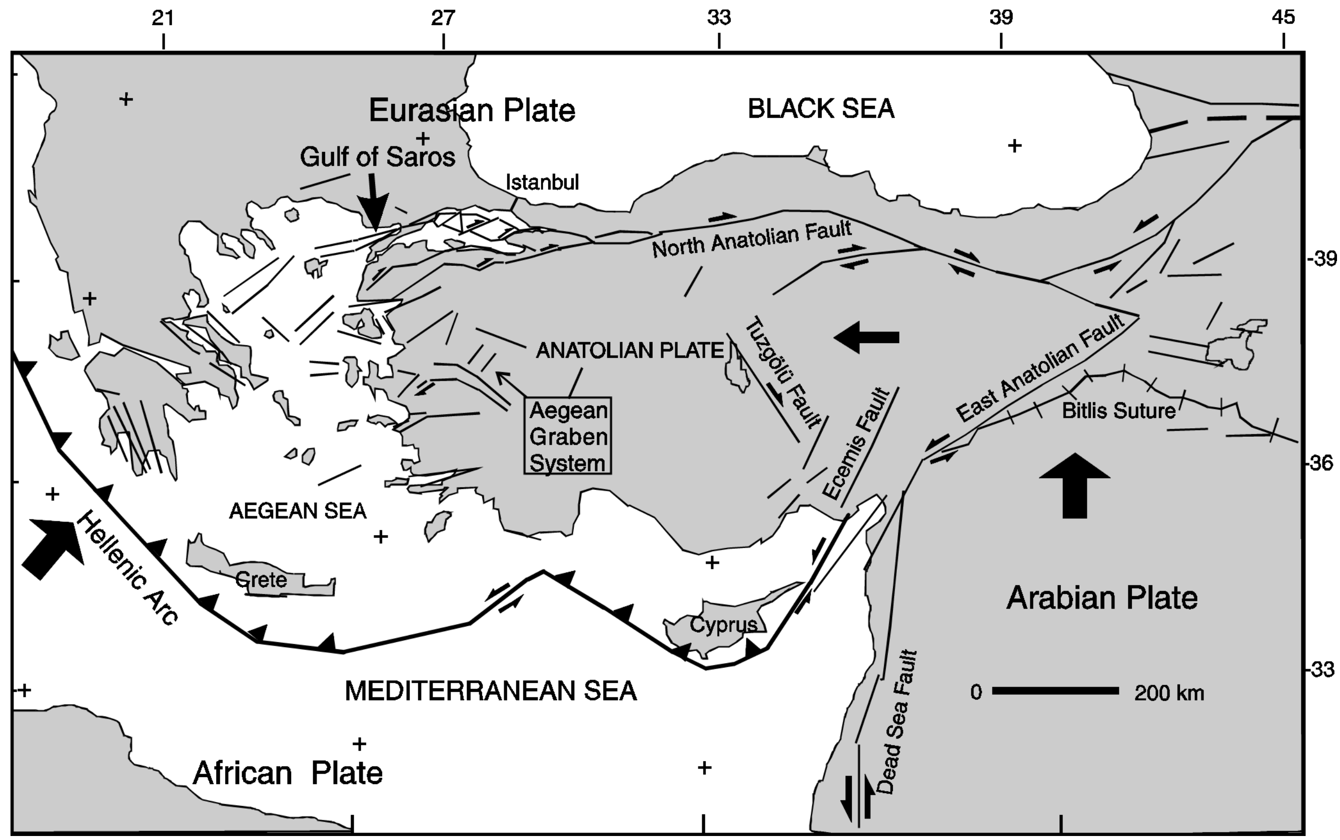

Fig. 1 Location and tectonic setting of the Gulf of Saros (modified from Şengör et al. 1985)

Tectonic setting

The Gulf of Saros is located in a region where the North Anatolian Fault and the N–S extension of western Anatolia interact. The North Anatolian Fault formed in the late–middle Miocene with an original concave southward curvature in this region (Şengör et al. 1985). It splits into several NE–SW-trending strands in the vicinity of the Marmara Sea (Fig. 1). One of them is the Ganos Fault, which is still active and forms the southern margin of the Gulf of Saros. The origin and the time of initiation of the N–S extension are disputable (Berckhemer 1977; Dewey and Şengör 1979; Le Pichon and Angelier 1979, 1981; Şengör et al. 1985; Seyitoğlu and Scott 1991; Görür et al. 1995). Whatever the causative mechanism and the timing of the extension might have been, continuous N–S stretching accentuated the original curvature of the North Anatolian Fault in the Marmara region and led to the formation of southward migrating new strands with narrow and NE–SW-oriented graben complexes, including the Gulf of Saros.

Stratigraphy

Widespread Neogene to Quaternary rocks crop out on both the northern and the southern margin of the Gulf of Saros (Fig. 2). These rocks are also encountered in the borehole Saros-1. On the basis of these outcrop and the borehole data, together with the seismic information, the stratigraphy of the gulf is summarized below:

The infill of the Gulf of Saros is divided into two depositional sequences separated by an angular unconformity. In descending order, these are the Quaternary and the Miocene sequences. Pliocene rocks are absent on the northern shelf, although they may be present in the deep trough. In the Marmara region, Pliocene sediments occur locally, showing an unconformable relationship with the underlying formations. In the Gallipoli Peninsula, the Pliocene sediments consist mainly of brownish red and coarsening-upward clastic rocks, comprising locally cross-bedded and channeled conglomerate, sandstone, and shale in part with coal seams (the Conkbayırı formation). Here, these sediments are up to 350 m thick and dip southward.

The Quaternary sequence is well developed, particularly on the northwestern shelf and the eastern gulf areas, as a result of the high sediment input by the Meriç River (about 13×10^6 t yr^{-1}) and the Kavak creek (about 0.3×10^6 t yr^{-1}). It is subdivided into three seismostratigraphic units: units 1, 2, and 3 (Figs. 3–6). The units are

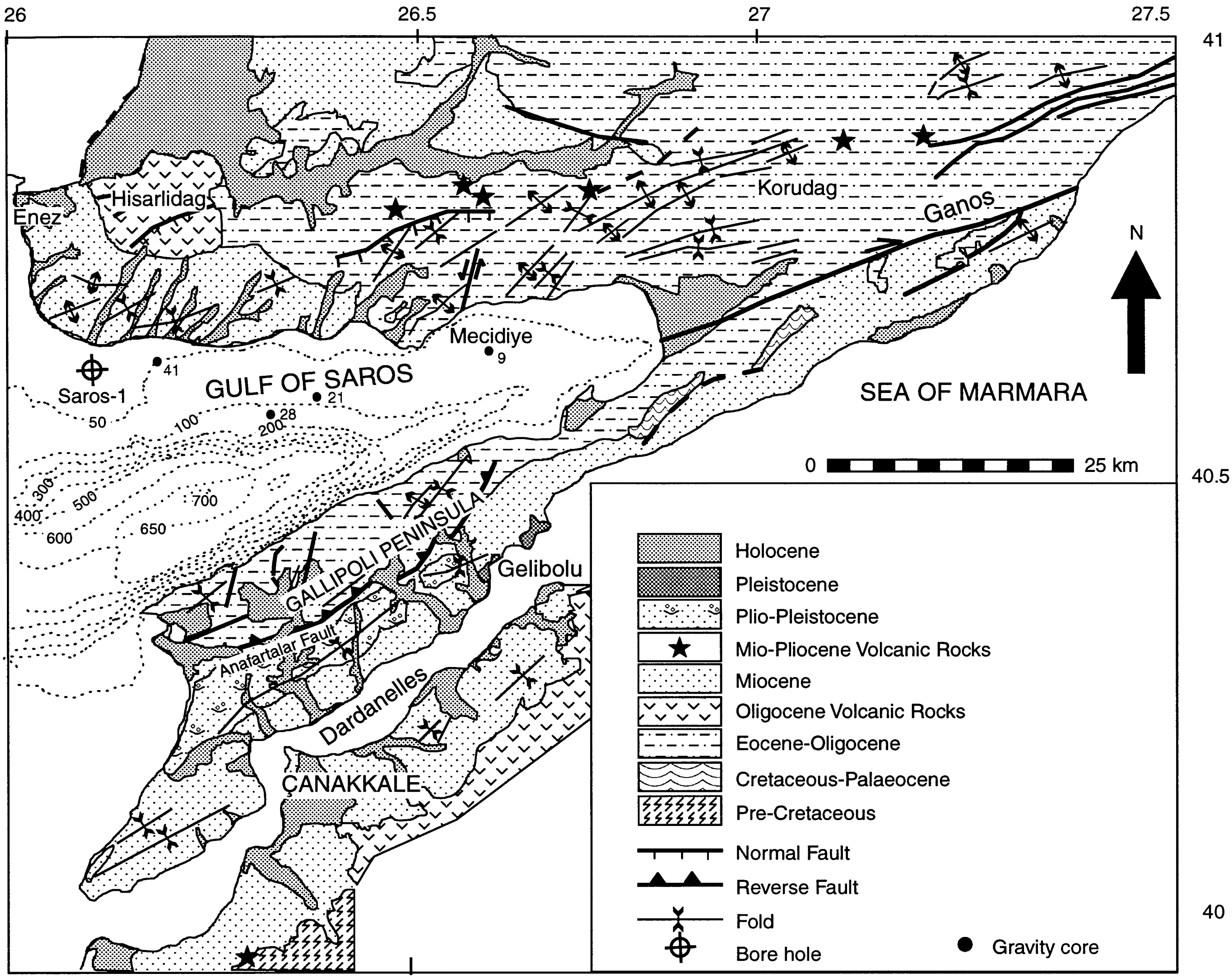

Fig. 2 Simplified geological and bathymetric map of the Gulf of Saros (geology modified from Sümengen et al. 1987)

separated from one another by a disconformity characterized by a strong reflector. The offshore Miocene sequence could not be subdivided further because of the absence of continuous cores and inadequate seismic data. However, on the shore it is subdivided into two formations, the Sultaniçe and the Göztepe formations. The basement for the infill of the gulf is formed from the Eocene to Oligocene rocks of the Thrace Basin.

The Quaternary sequence

Unit 1 forms the top of the sequence and consists of a thin sediment blanket characterized by weak and internally parallel reflectors. It is up to 20 m thick, mostly less than the dominant length of the seismic wavelets coming from the sea bottom. The maximum thickness is encountered in the far northwestern shelf and the eastern part of the gulf (Figs. 3 and 5). Core data and its reflection characteristics show that unit 1 consists mainly of green to grey, sandy and silty mud with interbeds of sand and shells. The shells are represented mostly by bivalves, gastropods, ostracods, and echinoids. On the basis of ^{14}C dates (Çağatay and Eastoe, unpublished data), the unit 1 is a Holocene post-transgression unit deposited during the most recent high stand of sea-level.

Unit 2 underlies unit 1 and is defined by a sigmoid to oblique and seaward progradational pattern with toplap and bottomlap terminations. On the northwestern shelf, it is about 30 m thick around the shelf break and exhibits sigmoid and southward prograding reflectors dipping with low angles (Fig. 3). In these areas, the upper parts of the unit consist of pebbly and shelly sand and silty mud in the gravity cores, and they are dated by the ^{14}C method to be 16–11 ka (Çağatay and Eastoe, unpublished data). Towards the east, where the profile F is taken (Fig. 4), this and the underlying unit 3 pinch out. Here the Miocene rocks are overlain by thin (less than 1 m) sediments of unit 1. However, farther east in the gulf, unit 2 occurs again on the shelf and consists of up to 77-m-thick westward prograding clinoforms (Fig. 5). To the west of the

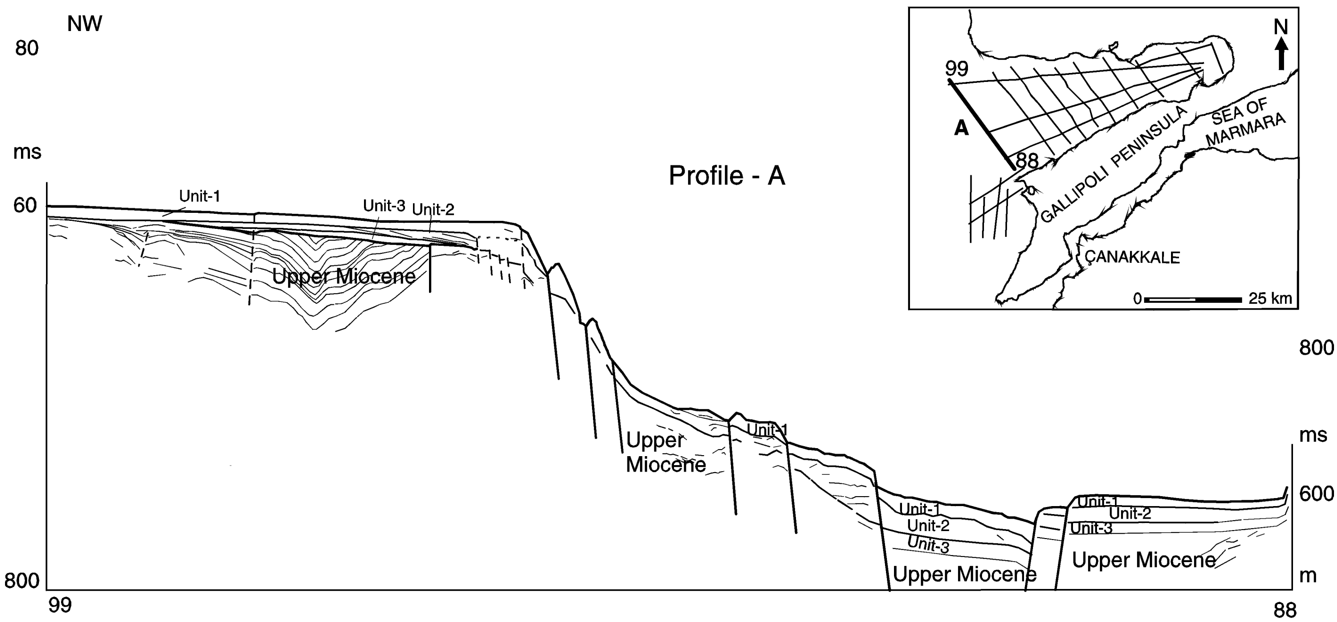

Fig. 3 High resolution seismic profile A and its interpretation

Gallipoli Peninsula, this unit is about 40 m thick and is represented by northward prograding, gently dipping reflectors (Fig. 6). It gradually thins towards the north and pinches out 400 m south of the shelf break at a depth of 112 m. At the shelf break, it reappears with a sigmoid oblique and northward prograding configuration. Unit 2 is interpreted to have been deposited as a prograding deltaic sequence during a sea-level lowstand. The foreset–topset transition of this unit at the shelf break suggests that the sea level was lowered between −95 and −120 m. The prograding character of unit 2 suggests that it is comparable with progradational units mapped by Piper and Perissoratis (1991) on the north Aegean and by Aksu and Piper (1983) on the western Anatolian shelves.

Unit 3 forms the basal part of the Quaternary sequence and is distinguished by parallel to subparallel internal reflectors, which exhibit downlap terminations. In the shelf areas it overlies the Upper Miocene and the basement

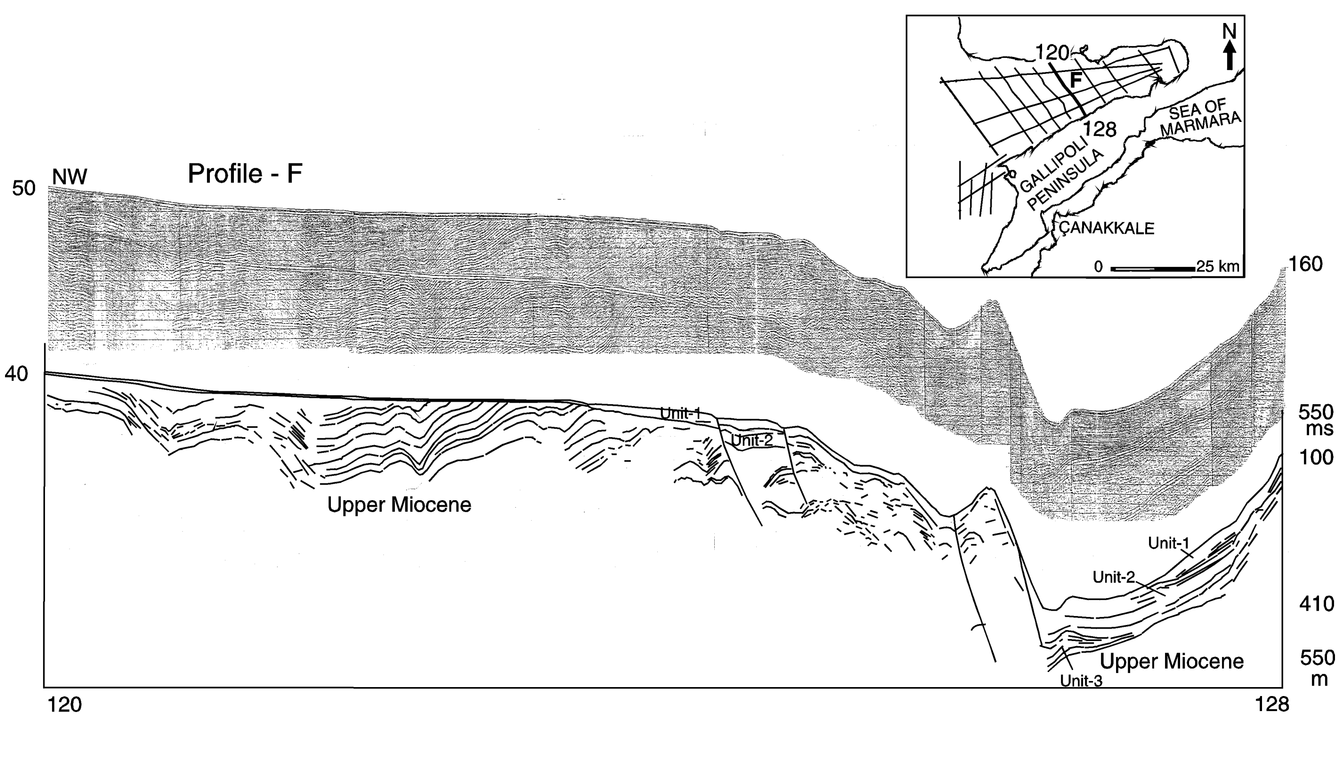

Fig. 4 High resolution seismic profile F and its interpretation

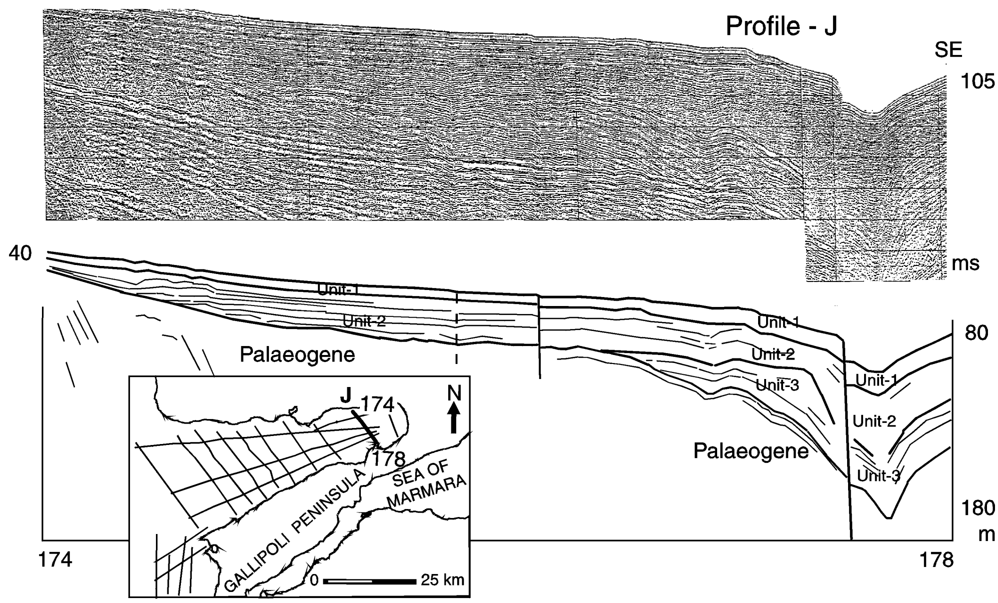

Fig. 5 High resolution seismic profile J and its interpretation

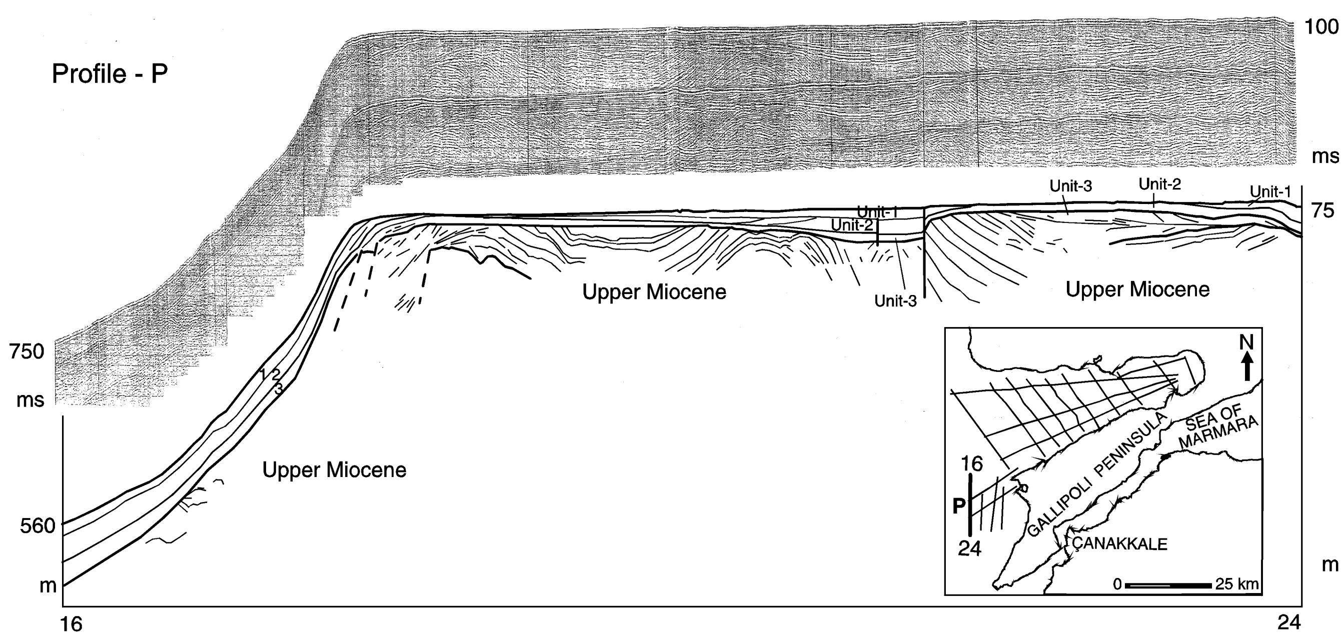

Fig. 6 High resolution seismic profile P and its interpretation

rocks above a transgressive erosion surface. Regional considerations, the age of unit 2, and the thickness of unit 3 imply an age of 0.2 Ma for this unconformity. On the northwestern shelf of the Gulf, unit 3 is about 15 m thick and seems to thin both southwards and eastwards (Fig. 3). In the east of the gulf, it is up to 50 m thick and displays baselap on the basement rocks (Fig. 5). On the southwestern shelf area, west of the Gallipoli Peninsula, the 22-m-thick unit 3 sediments rests on the smooth erosional basement surface. At the shelf break it starts dipping basinward (i.e., northward) (Fig. 6). On the basis of its reflection characteristics and the stratigraphic position, this unit is interpreted as a basal transgressive marine sediment. This sediment can be correlated with the Pleistocene marine deposits exposed on the coasts (the Marmara Formation) (Yaltırak, 1996). On the northern coast, i.e., in Enez and Hisarlıdağ areas, the Pleistocene deposits are represented by marine terraces at an elevation of about 24 m. The terraces consist mainly of conglomerates and sandstones, rich in *Ostrea edulis* shells.

They rest on the Miocene rocks above an angular unconformity and are covered disconformably by the Holocene shallow-marine sands, containing *Cardium* sp. and *Murex* sp. On the southern coast, the Pleistocene marine terraces crop out in a few localities with a maximum elevation of 14 m and are formed from loosely cemented and poorly sorted conglomerates and shallow-marine sandstones with common *Ostrea edulis*. Electron-spin-resonance dating carried out on these terraces around the Sea of Marmara, as well as their fossil content, indicate an age span of Milazzian to Tyrrhenian for these sediments (Erol and Çetin 1995; Yaltırak 1996).

The Miocene sequence

The Miocene sequence is examined from the outcrops on the northern coast of the Gulf of Saros, as well as from the cuttings of the Saros-1 well. The widespread Miocene rocks cropping out within the interior of the Gallipoli Peninsula are not studied here, because these rocks contain abundant fossils of the Paratethyan affinity (mainly *Mactras*) and thus belong to a completely different depositional realm (Görür et al. 1997). The Miocene sequence on the northern coast can be subdivided into lower and upper units. The lower unit (the Sultaniçe Formation) comprises sandstone, siltstone, claystone, and subordinate conglomerate with common ripple-, trough-, and planar-type cross-beddings. This unit also contains some local lignite, bentonite, and evaporite layers toward the top. The latter was encountered only in the borehole, where the unit is unconformably covered by about 15-m-thick late Quaternary sediments. On land, the lower unit passes upwards and laterally into the upper unit (the Göztepe Formation), consisting of up to 5-m-thick oyster banks, alternating with bivalve-bearing sandstones.

The facies characteristics and the fossil content of the Miocene sequence indicate a deltaic to shallow-marine environment of deposition for these sediments. Their ostracod fauna yields a Tortonian to Messinian age (Sümengen et al. 1987).

Structural geology

As seen in the outcrops and the offshore seismic sections, NE-trending folds and faults represent the main geological structures in both the basement rocks and the Miocene infill of the Gulf of Saros (Fig. 2). The folds are north plunging, and mostly have wavelengths of about 2 km and amplitudes of 200 m. In the basement, they appear to be dominantly asymmetrical with steeper northern limbs (Figs. 7 and 8). The basement folds have a different origin than those in the Miocene basin fill. Regional geology indicates that the former is palaeotectonic, whereas the latter is neotectonic structures. The basement folds were created during the late Oligocene to early Miocene time by syn- and postcollisional compression of the Thrace Basin (Saner 1985; Turgut et al. 1991; Görür and Okay 1997). In contrast, the origin of the folds in the Miocene fill appear to be related to the North Anatolian Fault. They probably formed in the transpression zones on the margins of the gulf during the Pliocene–early Pleistocene, after the present westward escape-tectonic regime of Anatolia

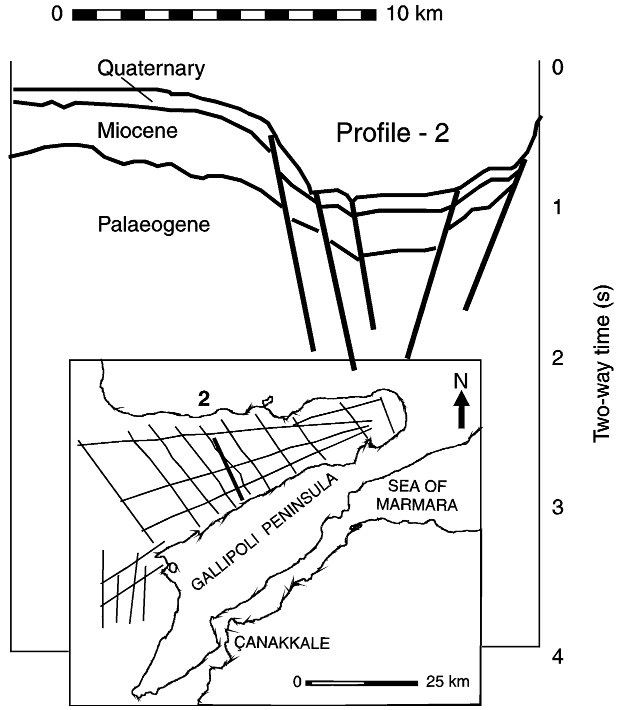

Fig. 7 Interpretation of conventional seismic profile 2

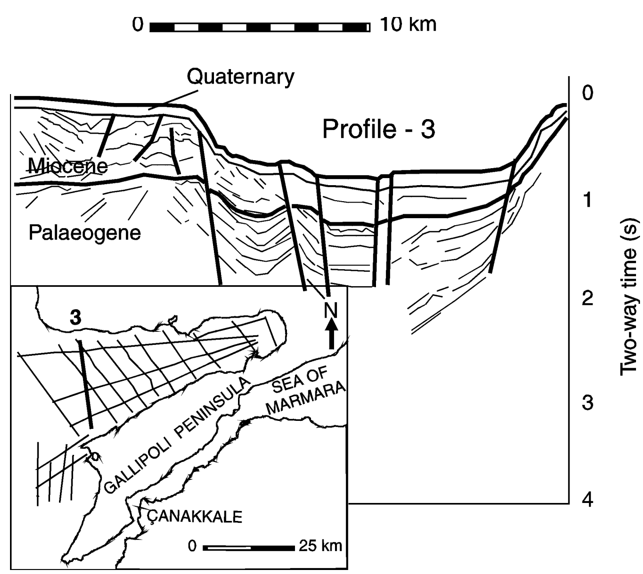

Fig. 8 Interpretation of conventional seismic profile 3

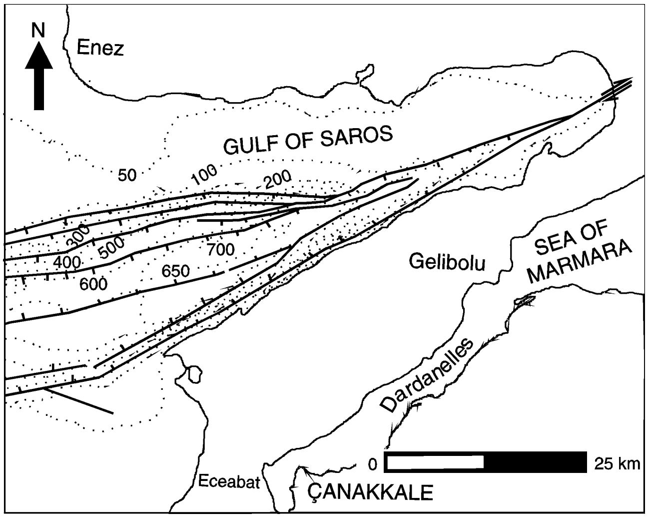

Fig. 9 Fault map of the Gulf of Saros

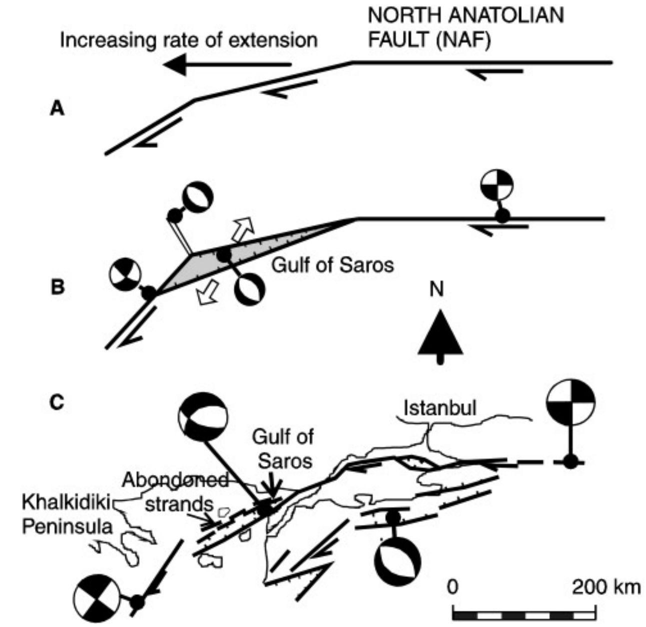

Fig. 10 Kinematic model for the formation of the Gulf of Saros. **A**: Hypothetical course of the North Anatolian Fault (NAF) before onset of the Aegean extention. **B**: Geometry of the NAF immediately after extention. **C**: Geometry and kinematics of the Marmara and the north Aegean regions (modified from Şengör et al. 1985; fault plane solutions from Taymaz et al. 1991)

started in the late Miocene (Dewey and Şengör 1979; Şengör et al. 1985).

Another important structural element of the Gulf of Saros is the strike-slip dominated oblique faults with normal displacement. In the northern margin of the gulf, they are more abundant and downthrow to the south, whereas in the southern margin they are few and downthrow to the north, indicating that the gulf has a graben structure with an asymmetrical profile (Figs. 3, 4, 8, 9). Quite a number of faults in the northern shelf do not cut the Quaternary deposits and are therefore inactive (Fig. 8). In contrast, in both the graben floor and the southern margin they are active and cut the Quaternary sediments (Figs. 3, 4, 7, 8). This distribution indicates that the fault activity in the gulf migrated southward through the time. The largest active fault in the southern margin is the Ganos Fault (Taymaz et al. 1991). All the faults, including the Ganos, represent the splays of the North Anatolian Fault, which started operating actively in the late Miocene and since then has played an important role in the evolution of the Gulf of Saros (Şengör et al. 1985).

Geological evolution

On the basis of its tectonic setting, structural geology, and the stratigraphy, the geological history of the Gulf of Saros may be summarized as follows:

The Gulf of Saros formed disrupting the heterogeneous Eocene to Oligocene rocks of the fore-arc Thrace basin (Turgut et al. 1991; Görür and Okay 1997). The site of the future Gulf of Saros stayed as an erosional area until the late Miocene, when the westward escape tectonics of Anatolia affected the Marmara region (Dewey and Şengör 1979; Şengör et al. 1985; Dewey et al. 1986). As a consequence of this tectonic escape, Anatolia has been driven westward along two major strike–slip faults on the dextral North Anatolian and the sinistral East Anatolian transform faults to override the oceanic lithosphere of the Mediterranean along the Hellenic and the Cyprus subduction zones (Şengör et al. 1985; Barka 1985; Dewey et al. 1986; Taymaz et al. 1991) (Fig. 1). This escape system caused a N–S extension in the Marmara region with a cumulative amount increasing towards the Aegean (Le Pichon and Angelier 1981; Şengör et al. 1985). The interaction between the extension and the North Anatolian Fault resulted in the development of the Gulf of Saros, starting from the late Miocene. As noted before, the western end of the North Anatolian Fault was originally curved southward (Fig. 10). This curvature is accentuated along with the extension through the time. As the strike-slip continued on the westernmost part of the concave segment, its eastern part acquired the character of a transtensional fault zone and thus generated the wedge like Saros graben (Fig. 10). When the extension bended the fault segment sufficiently to preclude further strike–slip, a new strand formed to the south (Şengör et al. 1985).

During the early stage of its development in the late Miocene, the Gulf of Saros was shallow and filled mostly with deltaic and neritic clastic sediments (the Sultaniçe and the Göztepe formations). In the Pliocene–late Pleistocene, there was a break in sedimentation on the shelf areas, as indicated by the unconformity below unit 3.

Probably during this time, both shoulders of the gulf were uplifted and emerged, while the trough area deepened along faults. This must have been due to the increased tectonic activity of the North Anatolian Fault, because in the Pliocene a widespread transgression was taking place throughout the Mediterranean and the Aegean Sea (Hsü and Bernoulli 1978; Steininger and Rögl 1984). Onset of the increased activity of the North Anatolian Fault is indicated by the folding of the Upper Miocene fill in transpressional zones and by the development of a thick Pliocene alluvial fan (the Conkbayırı formation) in the central part of the Gallipoli Peninsula. The fan formed as the southern shoulder was rapidly uplifted and tilted southward (Yaltırak 1995).

A significant change in the tectonic style of the Gulf of Saros took place about 0.2 Ma ago, permitting sedimentation to resume on the shelf areas after a long hiatus. Similar changes have been reported elsewhere in the region for the past 0.5 Ma (Ferentinos et al. 1981; Chronis et al. 1991). The new phase of sedimentation started with a transgression probably during the Riss-Würm interglacial stage (130–25 Ka BP) and deposited unit 3. Between the Würm glacial stage and the following early phase of deglaciation (25–13 Ka BP), the sea level dropped as much as 120 m below the present sea level (this study, van Andel and Lianos 1984; Aksu et al. 1987) and thus caused the exposure of the shelf areas once again. During this regression, the prograding deltaic sequence of unit 2 was deposited. With the beginning of the Holocene, these areas were inundated for the last time and became the site of deposition for unit 1.

Summary and conclusion

The Gulf of Saros is an Upper Miocene transtensional basin formed from the interaction of the N–S extensional tectonic regime of the Aegean with the North Anatolian Fault. In the late Miocene, it was a shallow-marine Aegean graben with a large amount of sediment influx from the north. With the onset of increased tectonic activity in the Pliocene, its shelf areas were uplifted and eroded until late Pleistocene. Mainly during this time, it gained its present asymmetric morphology with an ~10-km-wide shelf in the north and an ~700-m-deep trough in the south. An important change in tectonics of the gulf at about 0.2 Ma caused marine sedimentation to resume on the shelf areas during the Riss/Würm interglacial stage. During the Würm glaciation, the global sea level was lowered and consequently the Aegean Sea regressed from the same areas along with the accumulation of extensive deltaic deposits. Following the deglaciation, the gulf was submerged in the Holocene as a whole and gained its present configuration.

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