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Investigation of the submarine active tectonism in the Gulf of Gökova, southwest Anatolia–southeast Aegean Sea, by multi-channel seismic reflection data

Hülya Kurt [a,*], Emin Demirbağ [a], İsmail Kuşçu [b]

[a] İstanbul Technical University (İTÜ), Department of Geophysics, 80626 Istanbul, Turkey
[b] Mineral Research and Exploration Directorate of Turkey (MTA), Jeoloji Dairesi, Eskisehir Yolu, 06520 Ankara, Turkey

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Abstract

Submarine active tectonism in the Gulf of Gökova located at the southwest Anatolia–southeast Aegean Sea region was investigated by means of multi-channel seismic reflection data. The Gökova basin is filled by the latest Miocene–Pliocene–Quaternary sediments with maximum thickness of about 2.5 km. The Lycian Nappes, which predominantly cover extreme southwestern Anatolia, constitutes the basement rocks for the Gökova province. The gulf was mainly opened by a buried major listric normal fault, so-called Datça Fault, which has not been previously discussed in the literature. The north-dipping, mainly E–W-trending Datça Fault is located at the southern part of the gulf, whereas its associated antithetic faults are located at the north. The onset time of the opening of the gulf is possibly in the latest Miocene–Pliocene. In terms of local rather than regional effects, the activity of the Datça Fault has decelerated, possibly since the Pleistocene. The Datça Fault might have gained its curved fault plane as it evolved, beginning as planar and/or using antecedent planes of the Lycian Nappes in the area. As the extension progressed, i.e., as the hanging wall block slipped further north, gravity may have impeded rather than helped the faulting. On the other hand, continuing extension in the area may have initiated a second phase of faulting, i.e., WNW–ESE-oriented subgrabens in the gulf and major E–W normal faulting in the northeast margin. A bathymetric low in the mid-gulf area and a horst–graben system in the eastern part of the gulf are observable from the bathymetric data and are well correlated to the seismic data. Although the main orientation of the gulf is E–W, more recent WNW–ESE structures are remarkable in the mid-gulf and in the eastern part of the gulf. The latest WNW–ESE structures are also in agreement with the results of GPS and SLR studies as well as plate motion modelling by total moment tensor of earthquakes in the western Anatolia–Aegean Sea region, particularly in southwestern Anatolia. The amount of total N–S extension within the gulf is estimated as at least 5.5 km since the latest Miocene–Pliocene with overall constant extension rate of at least 1.1 mm/y where the estimated extension factor is about $\beta = 1.3$.

Keywords: Gulf of Gökova; Aegean Sea; western Anatolia; extensional regime; active tectonism; seismic reflection

* Corresponding author. E-mail: kurt@itu.edu.tr

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1. Introduction

The purpose of this study is to investigate submarine active tectonism in the Gulf of Gökova by means of multi-channel seismic reflection data and furthermore to correlate the results with the previous onland tectonic frame, geophysical and geodetic studies. Paton (1992) studied the faulting and drainage patterns on the northern margin of the gulf. He also estimated the extension factor based on the initial and final dips of the faults which bound the tilted blocks by assuming a simple domino model ($\beta = 1.1$). Rift formation in the Gökova province is discussed extensively on the basis of land geology and bathymetry data in Görür et al. (1995). However, the submarine geology and geophysics of the area, the Gulf of Gökova, have not been studied in detail except for a shallow single-channel seismic reflection investigation by Uluğ et al. (1996).

The Gulf of Gökova is located in the southeast Aegean Sea along the coast of southwest Anatolia which is the region including the major rifts and grabens such as Gediz, Büyük Menderes, Gökova, Burdur, Acıgöl and Baklan. The gulf is surrounded by Bodrum Peninsula to the north, Datça Peninsula to the south and the island of Kos to the west. It has about 25 km maximum N–S width and 100 km E–W length (Fig. 1). The Gökova province is a part of the western Anatolia–Aegean Sea region, which is under a N–S regional extensional tectonic regime. The imprints of this extensional regime are clearly seen in the geology and geomorphology of western Anatolia as well as in the bathymetry of the Aegean Sea. Although there is no doubt about the present extensional regime, its causes and onset time have been debated. According to the most widely accepted model proposed by Dewey and Şengör (1979), the extensional tectonism is related to the westerly escape of the Anatolian plate in reaction to the collision of the Arab–African and Eurasian plates through the Bitlis continental collision zone. Other group of researchers suggest that back-arc spreading of the relatively thickened Aegean crust in the eastern Mediterranean subduction is another reason for the N–S extension (Le Pichon and Angelier, 1981). Gravitational spreading of the relatively thickened Aegean crust is also suggested by Le Pichon and Angelier (1979) and Seyitoğlu and Scott (1991). In addition to these different models on the origin of the extension, the onset time is also debated. Dewey and Şengör (1979) and later Şengör et al. (1985) put the onset time in the Late Miocene, whereas Seyitoğlu and Scott (1991) propose the Early Miocene.

In the center of this ongoing debate, the Gökova province is mainly characterized by two successive tectonic regimes. These overlapping rift and graben systems are seen in the land geology (Fig. 1). The first one is the N–S compressional paleotectonic regime, possessing the later counter-clockwise rotation, and resulted in a NW–SE rift and graben system. The NW–SE-oriented paleotectonic rifts and grabens, i.e., Milas–Ören and Yatağan Muğla Rifts, are filled by mainly Middle Miocene to Quaternary deposits of continental origin. The second one is the neotectonic regime, possessing the N–S extension that has resulted in mainly E–W-oriented rift and graben systems, i.e., Gökova Rift (Görür et al., 1995). The Lycian Nappes, which cover a large area in the extreme southwest of Anatolia, constitute the basement for both systems. The Lycian Nappes can be divided into two major units: the Intermediate Complex at the bottom and Peridotite Nappes at the top (Brunn et al., 1971; Bremer, 1971; Bernoulli et al., 1974; Brunn et al., 1976). The Köyceğiz slice of the Intermediate Complex, which is mainly Permian to Upper Cretaceous sedimentary rocks, outcrops in the Gökova area (Görür et al., 1995).

Global Positioning System (GPS) and Satellite Laser Ranging (SLR) studies in recent years indicate that the relative plate motions in the western Anatolia–Aegean Sea region have accelerated from north to south counter-clockwise, particularly in southwestern Anatolia (Oral et al., 1995; Le Pichon et al., 1995; Reilinger et al., 1997; Barka and Reilinger, 1997). The largest differential motions are obtained across the Büyük Menderes and Gediz Grabens in western Anatolia and possibly in the Gulf of Gökova. According to Reilinger et al. (1997), the extension rate is about 14 ± 5 mm/y at Marmaris station in Datça Peninsula (Fig. 2). Barka and Reilinger (1997) suggested that the present tectonic regime in western Anatolia–Aegean Sea causes E–W- and WNW–ESE-oriented graben and normal fault systems. On the other hand, the NE–SW-oriented Acıgöl, Baklan and Burdur basins are remarkable from geological and seismological studies (Taymaz and Price, 1992; Price and Scott, 1994).

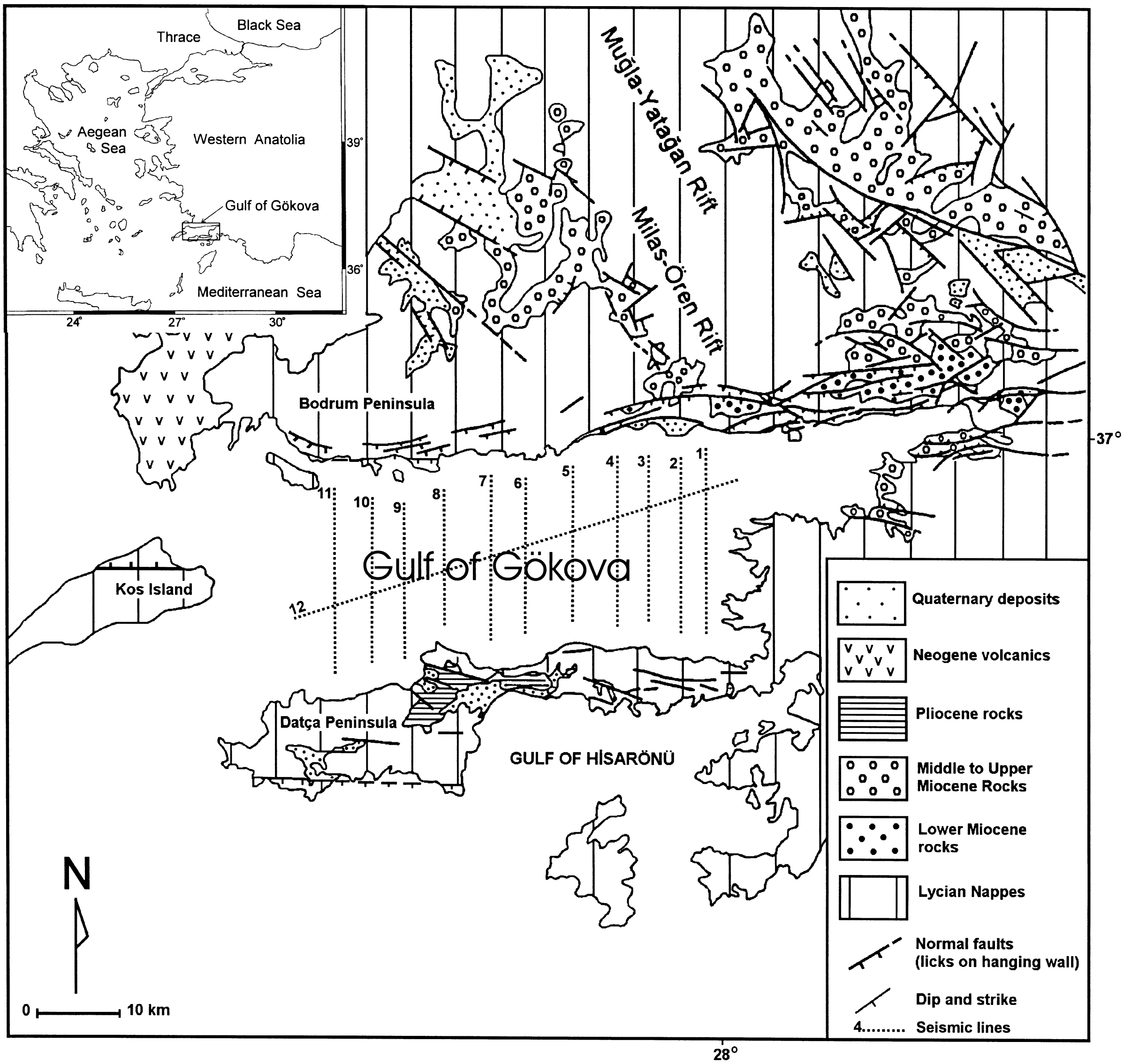

Fig. 1. Land geology map of the Gökova province (modified from Görür et al., 1995; the original map also includes inferred submarine faults). Notice the E–W-oriented new rift system (the Gulf of Gökova and its margins) and NW–SE-oriented older rift systems (Muğla–Yatağan Rift and Milas–Ören Rift).

Acceleration of the velocity field in southwestern Anatolia towards the eastern Mediterranean basin is noticeable in Le Pichon et al. (1995). In summary, according to the recent GPS and SLR studies, one can expect E–W- and WNW–ESE-oriented fault systems in the Gulf of Gökova.

Rates of extension in the western Anatolia–Aegean Sea region are also studied by moment tensors of earthquakes (Eyidoğan, 1988; Jackson et al., 1992). Eyidoğan (1988) states that N–S extension in western Anatolia increases from north to south, and the dominant extensions in southwestern Anatolia is N–S with a rate of 13.5 mm/y which is obtained from the total seismic moment release of 25 earthquakes. Jackson et al. (1992) calculated the velocity field in the Aegean region on the basis of moment

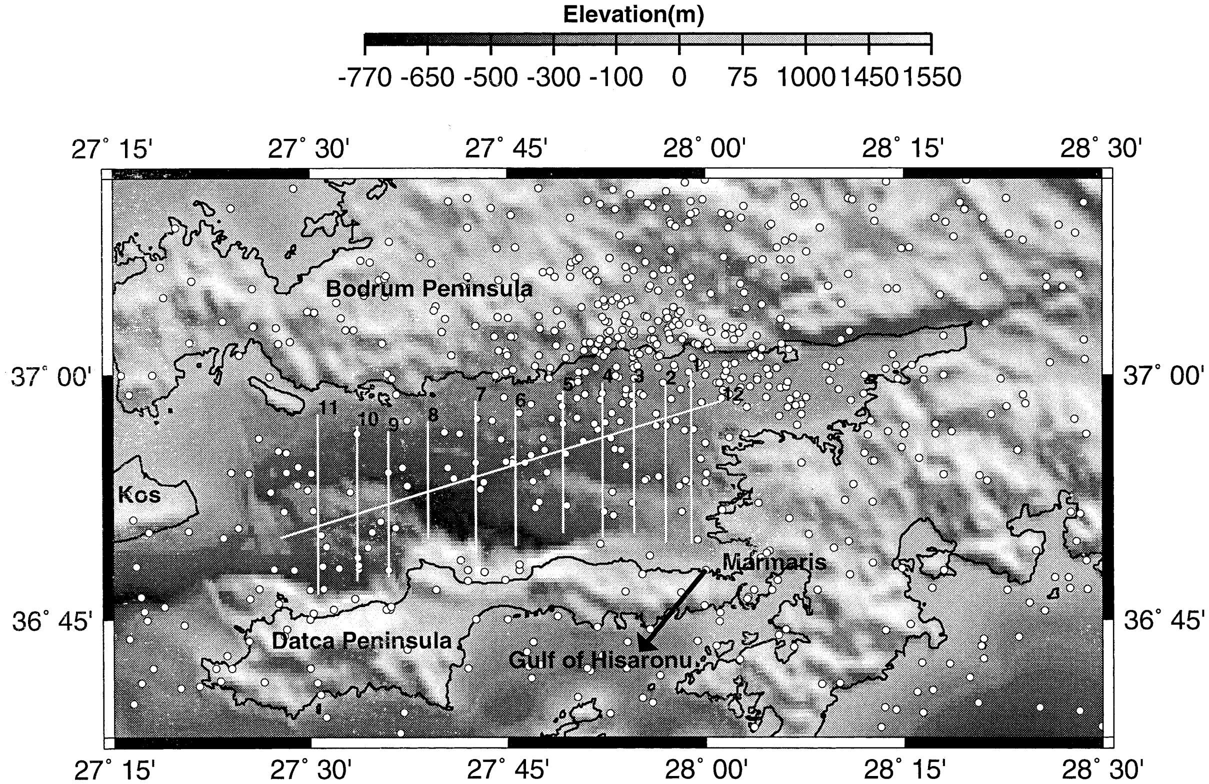

Fig. 2. Bathymetry, topography and marine seismic line map of the Gökova area. Dominant E–W trend of the gulf, WNW–ESE-oriented bathymetric lows and highs in the mid-gulf and in the eastern part of the gulf, and NW–SE-oriented topographic lows and highs of the older rifts are remarkable. White dots show the epicenter distribution of the earthquakes from ISC catalogues. The GPS velocity vector taken from Reilinger et al. (1997) shows the direction of plate motion at the Marmaris station.

tensors of earthquakes occurring between 1909 and 1983. Horizontal velocities obtained in that study clearly show an increase towards the southwest. In summary, the velocity field of crustal deformation calculated from the moment tensors of earthquakes in the western Anatolia–Aegean Sea region also shows similar results to GPS and SLR studies, a notable increase towards the south and southwest.

Studies dealing with estimating the rates and explaining the nature of deformation in the western Anatolia–Aegean Sea region are usually based on well known rifts and grabens in the region. In this study, it is shown that the Gulf of Gökova was mainly opened by an E–W-oriented, presently buried major normal listric fault, the so-called Datça Fault, which has never been discussed in the literature before. The estimated overall rate of extension in the gulf is at least 1.1 mm/y and the amount of total extension is at least 5.5 km. We estimated the extension factor (McKenzie, 1978a; Wernicke and Burchfiel, 1982; Jackson and McKenzie, 1983; Gibbs, 1983; White et al., 1986; Jackson and White, 1989) as at least $\beta = 1.3$ by taking the ratio of the length of seismic section-11 (extrapolating the Datça Fault to sea level) and the length of the rollover marked by reflections from the top of the basement.

2. Data acquisition and processing

Multi-channel seismic data were collected on one longitudinal and eleven transversal lines (total of 224 km) in order to investigate the expected E–W-oriented active tectonism in the Gulf of Gökova in August 1996 (Figs. 1 and 2). The energy source was a 10 gun source array with a volume of 1380 cubic inch, which is well enough to penetrate to a depth of a few kilometers. The number of channels is 48 for lines 10 and 11 and 96 for the rest of the lines. Receiver group interval, shot interval, and near offset are 12.5 m, 50 m and 237.5 m, respectively. These parameters provided six- or twelve-fold common-depth-point (CDP) data. Sampling interval and record length were selected as 2 ms and 5120 ms while real time 8–210 Hz band-pass filtering was applied to raw data before recording. Although a Differential Global Positioning System (DGPS) was operated during the recording, most of the lines were recorded by using only the GPS mode of the system because of bad differential signal reception from the base station.

The data were processed in the data processing laboratory of the Department of Geophysics, İstanbul Technical University (İTÜ). A conventional data processing stream was applied to the data as follows: data transcription, in-line geometry definition, editing, CDP sorting, gain correction, band-pass filtering, velocity analysis, normal-move-out correction, muting, stacking, signal shaping deconvolution, band-pass filtering, automatic gain control, and post-stack finite-difference time migration. Moreover, detailed velocity analysis and post-stack finite-difference depth migration were applied to the critical parts of the data from an interpretational point of view to better image the curved planes. Fortunately, the sea bottom multiples are not strongly represented in the data because of a possible low acoustic contrast between the high salinity of the Mediterranean waters and soft marine sediments in the sea floor. In addition, the sea bottom multiples were eliminated as much as possible by avoiding multiple reflection hyperbolas on CDP gathers during repeated velocity analyses.

3. Imprints of the active tectonism in the bathymetry and topography

The composite map of the topography and bathymetry of the Gökova area was prepared by using different data sets (Fig. 2). The detailed bathymetric data in the gulf were obtained from the Turkish Navy bathymetric charts and from single- and multi-channel seismic data. The rest of the bathymetry and topography data were obtained from a ‘Global Land One-km Base Elevation (GLOBE)’ model of the ‘National Geophysical Data Center (NGDC)’ and ‘International Bathymetric Chart of the Mediterranean’ prepared by the ‘Intergovernmental Oceanographic Commission, GEODAS’. The first data set (the one from Turkish Navy bathymetric charts and from the shallow and multi-channel seismic data) has more resolution than the other data sets. Therefore, there are some artificial disturbances where two data sets were adjoined. This is most noticeable to the east of Kos Island where two data sets join in a N–S direction. Nevertheless, the map in Fig. 2 is free of artificial disturbances for areas within the gulf and surrounding topography.

Bathymetry of the gulf demonstrates that the main structural trends are E–W oriented; however, WNW–ESE-oriented slopes in the mid-gulf and in the eastern part of the gulf are also remarkable (Fig. 2). The northern shelf of the gulf is sharply cut by E–W- and WNW–ESE-oriented scarps and slopes, which are observed on the seismic sections 6 through 11 (Figs. 3–5). Most of these scarps and slopes are related to the faults extending to the seabed. In contrast to the north, no shelf area is present at the southern part of the gulf. Bathymetry abruptly drops by hundreds of meters near the coast. This sudden gradient in the bathymetry extends E–W and it is well observed in the shallow seismic reflection data (Uluğ et al., 1996). The deepest locality in the bathymetry is about 770 m in the middle of the gulf. This bathymetric low is bounded by WNW–ESE- and E–W-trending slopes along the gulf. Bathymetry of the eastern part is characterized by WNW–ESE-extending lows and highs, which are associated with a small-scale horst–graben system, observed in the seismic sections 1 through 5 (Fig. 6). The seabed in the easternmost part (inner gulf) is relatively shallow and smooth because of the prograding delta deposits of the streams in the northeast of the gulf (Paton, 1992; Uluğ et al., 1996).

To the north of the gulf, the topographic imprints of the NW–SE-oriented paleotectonic rift and graben systems are observed (Fig. 2). Topography of the north and south margins of the gulf display mainly E–W-oriented slopes. This is most evident on the northeast margin where the strong topographical gradients (Fig. 2) correspond to mainly E–W-oriented active normal faults (Paton, 1992; Görür et al., 1995) (Fig. 1).

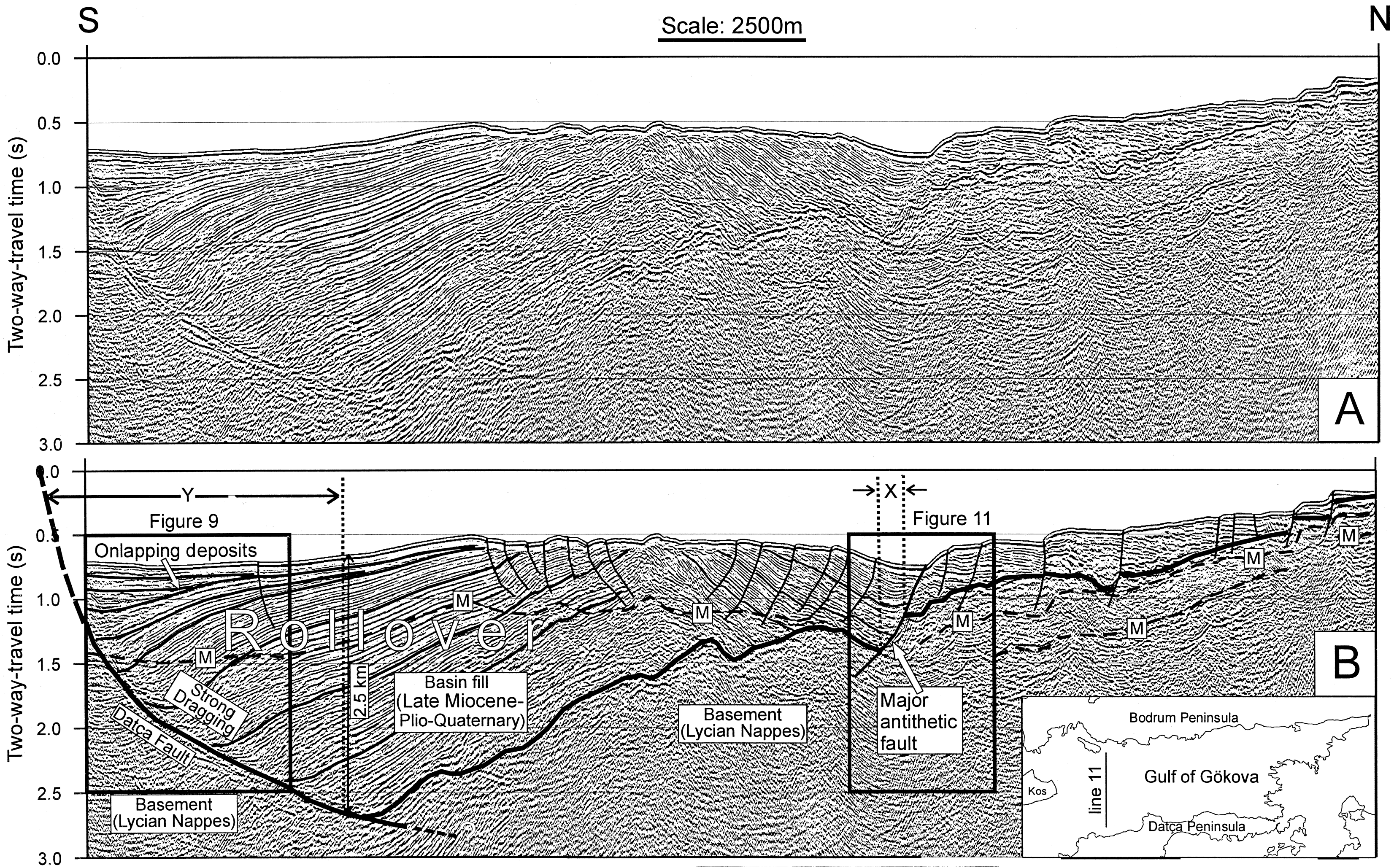

Fig. 3. (A) Time-migrated seismic section 11. (B) Interpreted section. The curved discontinuity on the left is the major listric normal fault, the so-called Datça Fault, between the Datça Peninsula and Gökova basin. The synthetic and antithetic faults of the Datça Fault are observed at the north. The bold line defines the rugged surface of the basement and the thin lines define the remarkable faults and bedding. Rectangular areas are zoomed in Figs. 9 and 11. *X* and *Y* are the horizontal separations used in the estimation of the rate of extension within the gulf. Label *M* shows first-order sea bottom and basement multiples.

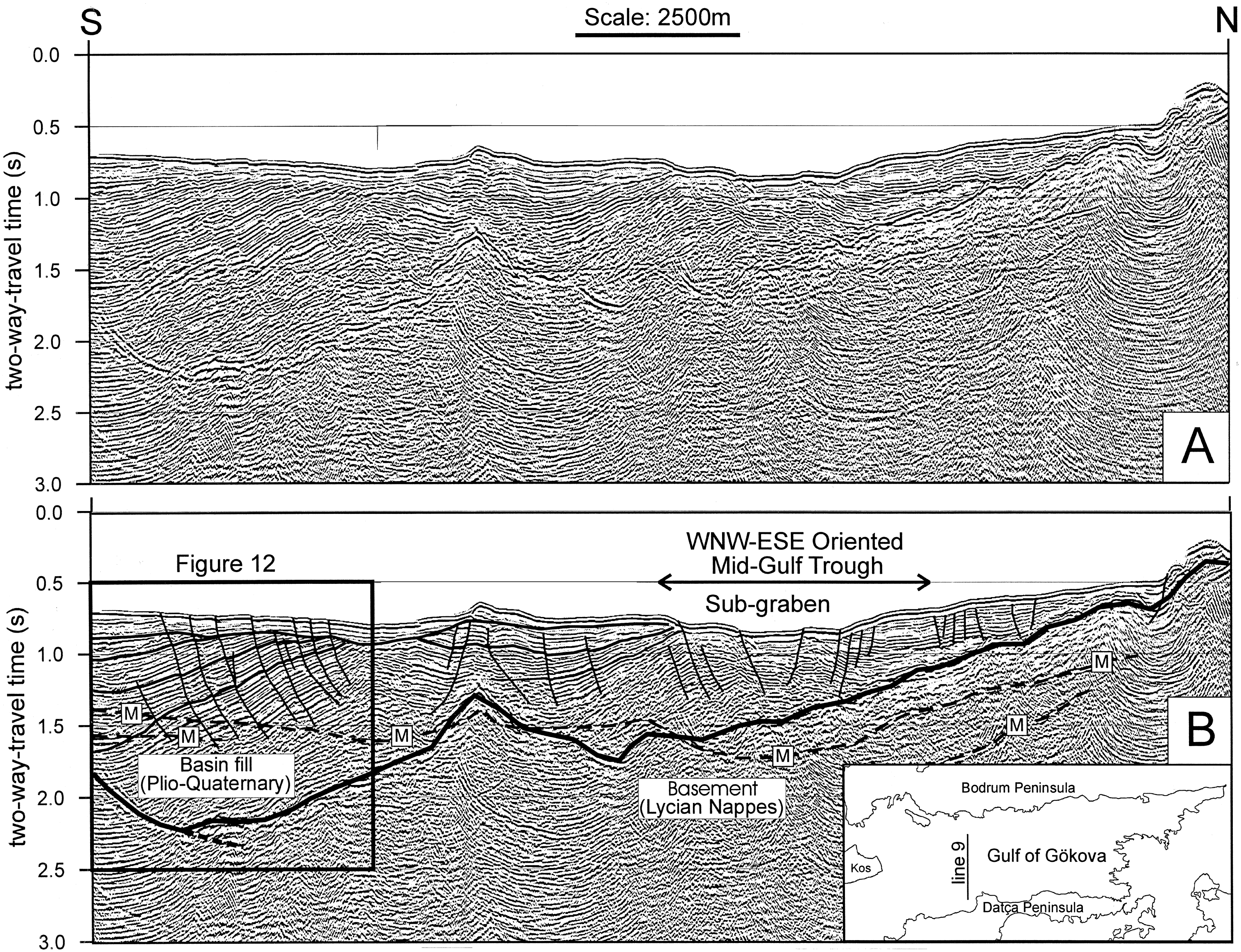

Fig. 4. (A) Time migrated seismic section 9. (B) Interpreted section. The curved discontinuity on the leftmost at around 2 s twt time is the Datça Fault. A developing subgraben system (WNW–ESE-oriented mid-gulf trough) to the north and synthetic fault system in the southern part of the section are remarkable. Rectangular area is zoomed in Fig. 12. Label *M* shows first-order sea bottom and basement multiples.

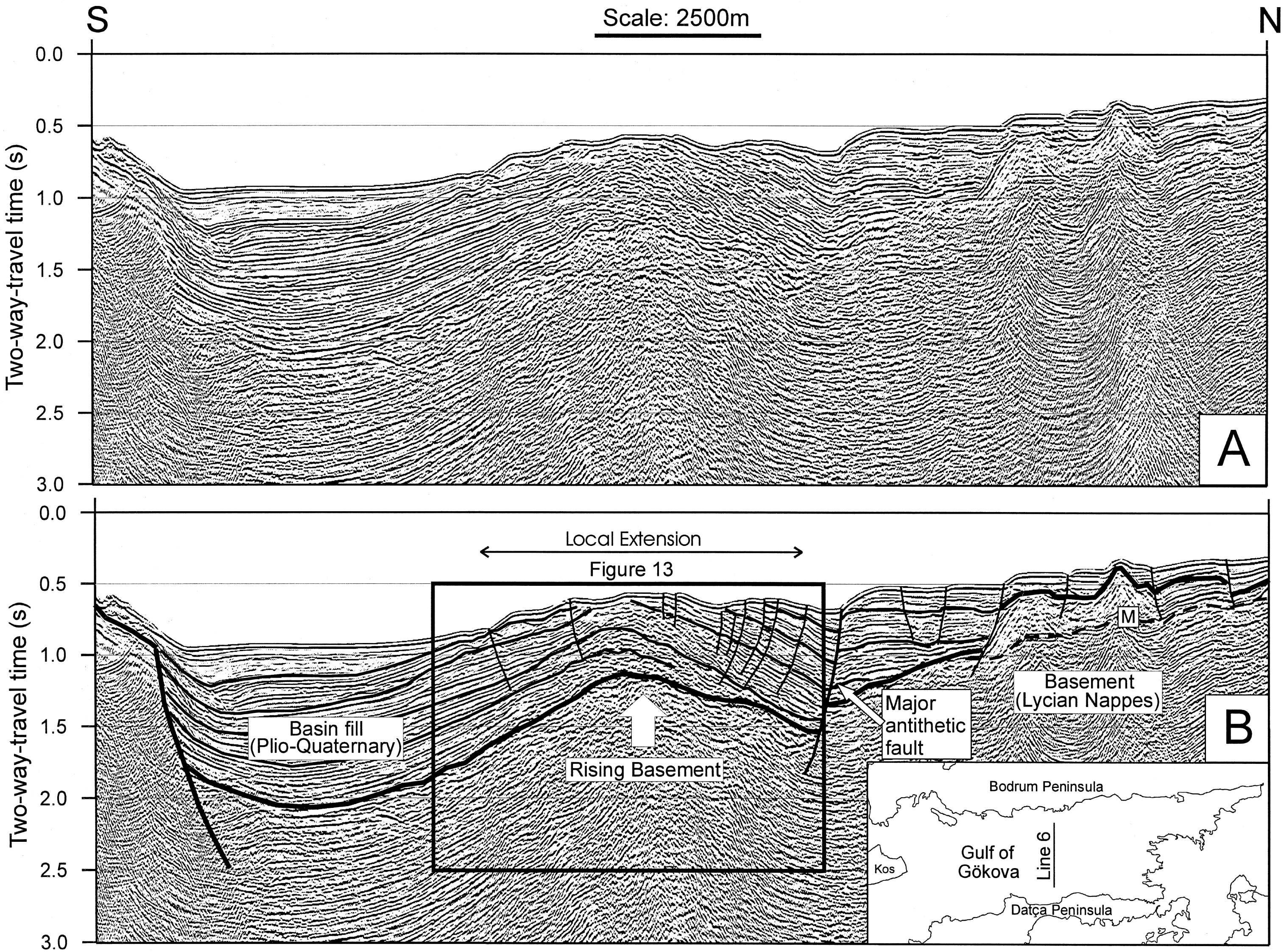

Fig. 5. (A) Time migrated seismic section 6. (B) Interpreted section. Continuation of the Datça Fault further to the east is observed. The rising basement in the middle causes a local fault system in the upper sediments. The bathymetric low in the southern part of the section corresponds to a WNW–ESE-oriented bathymetric low in Fig. 2. Rectangular area is zoomed in Fig. 13.

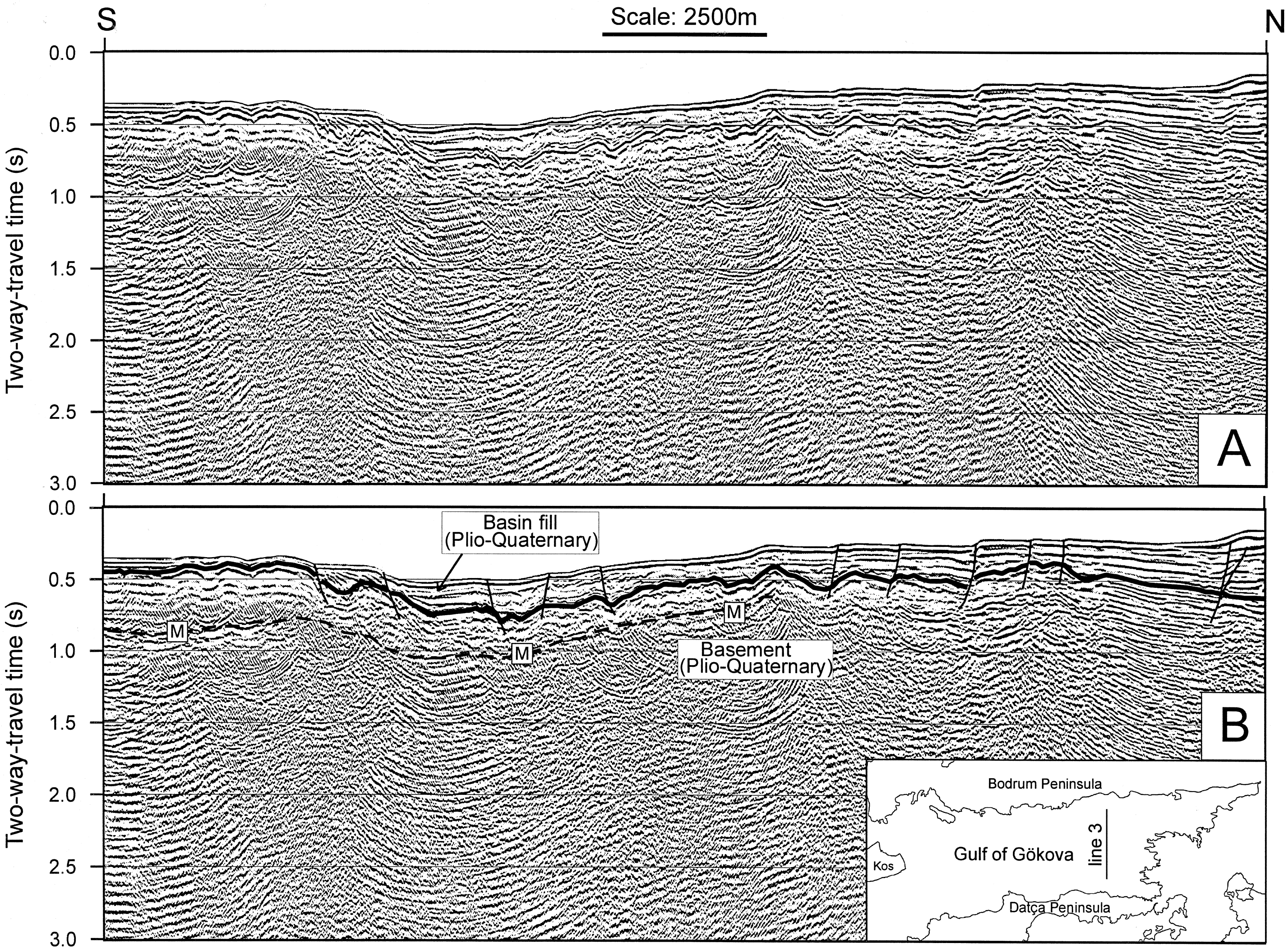

Fig. 6. (A) Time migrated seismic section 3. (B) Interpreted section. A typical section displaying the WNW–ESE-oriented horst–graben system in the eastern part of the gulf. Label *M* shows first-order sea bottom multiples.

4. Structural implications of the seismic data

Seismic data show that the Gulf of Gökova is bounded by a major discontinuity in the south and numerous normal faults in the north. The general orientations of the normal faults are E–W and WNW–ESE. Most of these faults cut the basin fill and the seabed while a few cause throws in the basement rocks which are mainly formed from the Lycian Nappes occupying a wide area in the extreme southwest of Anatolia. Inward of the gulf, the major fault and its associated antithetic and synthetic faults become less evident and further to the east they are replaced by a small-scale horst–graben system mainly oriented WNW–ESE (Figs. 7 and 8).

The most important structure in section 11 is the major curved discontinuity in the southernmost part of the profile (Fig. 3). The reflections from this dis-

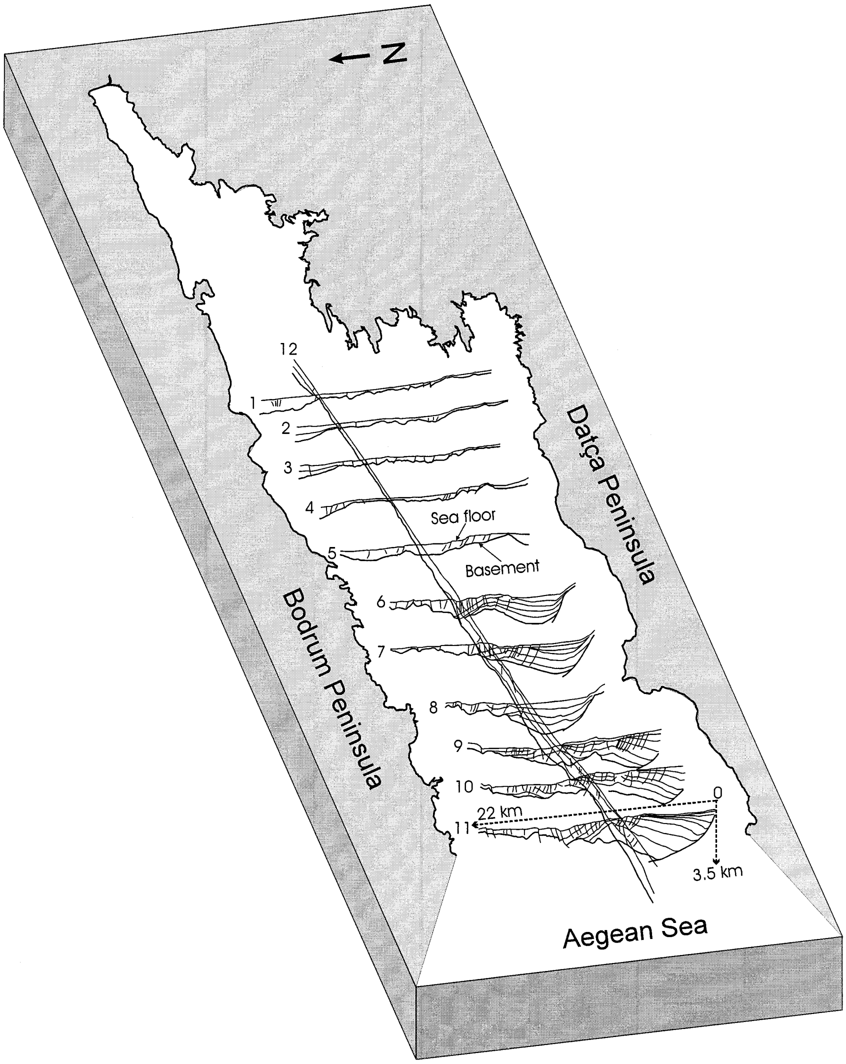

Fig. 7. Three dimensional structural view of the Gulf of Gökova constructed from the digitized interpreted seismic sections. Bold lines indicate the top of the basement and thin lines indicate the faults, bedding and seabed. The basin fill is thickest in the mouth and middle of the gulf, and thinnest in the inner parts. Notice the overstep of the Datça Fault to the north between the seismic lines 8 and 9. Approximate vertical and horizontal scales are shown by dashed lines on line 11. Horizontal scale line also represents the sea surface.

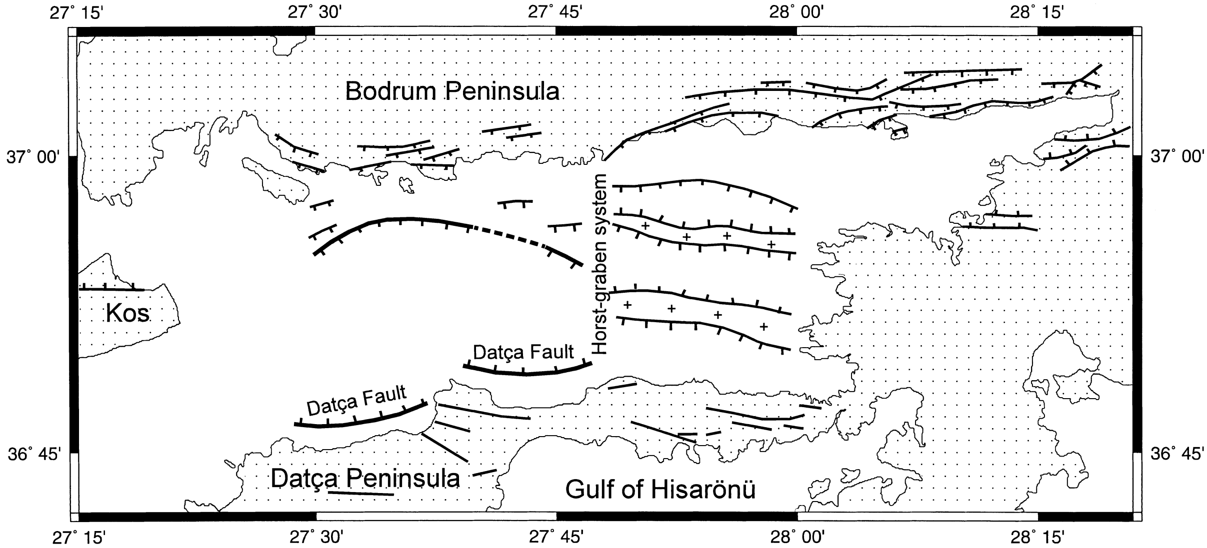

Fig. 8. Fault line sketch map constructed from the interpreted seismic sections. Major faults are shown in bold lines. The faults on land were adopted from Görür et al. (1995). Ticks are on hanging blocks.

continuity begin with a dip angle of about 40º. They are clearly observed down to 2.7 s two-way-travel (twt) time, where they decrease to dip angles of about 20º and disappear for possible reasons proposed in Section 5. Although a near coastline image of this feature cannot be seen in the seismic section, shallow seismic data from Uluğ et al. (1996) show that this discontinuity is the continuation of the steep slopes of the northern shores of Datça Peninsula. In spite of its major horizontal separation (Y in Fig. 3), this fault has not been reported and discussed in the literature dealing with the extension of the western Anatolia–Aegean Sea region. Nevertheless, it is inferred from the outcropping marine Pliocene sediments on Datça Peninsula that Datça Peninsula is a rising horst between the Gulfs of Gökova and Hisarönü (Görür et al., 1995). Therefore, this major discontinuity must be a major fault plane between the rising horst, Datça Peninsula, and the deepened gulf. We interpreted that the footwall of this major normal fault, the Datça Fault, consists of the formations of the Lycian Nappes because they predominantly outcrop on Datça Peninsula (Fig. 1) (Görür et al., 1995). This major fault shows a curved trace in plan-view constructed from seismic sections 9 through 11 and extends to the east with an overstep as observed on seismic sections 6 through 8 (Fig. 8).

The hanging wall of the Datça Fault consists of the formations of the Lycian Nappes at the bottom and thick syn-tectonically deposited beds at the top. The estimated maximum thickness of the basin fill is about 2.5 km in section 11 (Fig. 3). The age of these deposits is possibly Plio–Quaternary according to Görür et al. (1995). The rollover structure of the basin fill is clear in seismic section 11 (Figs. 3 and 9). Notice the divergent bedding and bending of the layers towards the fault plane. The layers of the basin fill are also strongly dragged against the fault plane especially in the interval between 1.2 and 2.2 s in the section (Fig. 3 and Fig. 9). All of these evidences show that the deposition and faulting occur simultaneously. In addition, the syn-tectonic sedimentation indicating the rate of faulting should have been so intense (possibly in the Pliocene along the western Anatolia coast according to Westaway, 1994) that strong dragging of the layers to the fault plane resulted. Following this argument and considering the occurrence of layers beneath the strongly dragged layers of possibly Pliocene age, we infer that the onset time of the Datça Fault may be as early as the latest Miocene. At the southern end of section 11, the uppermost reflections between 1.2 s twt time and the sea bottom display horizontal bedding and onlapping to the rollover structure (Fig. 9). The

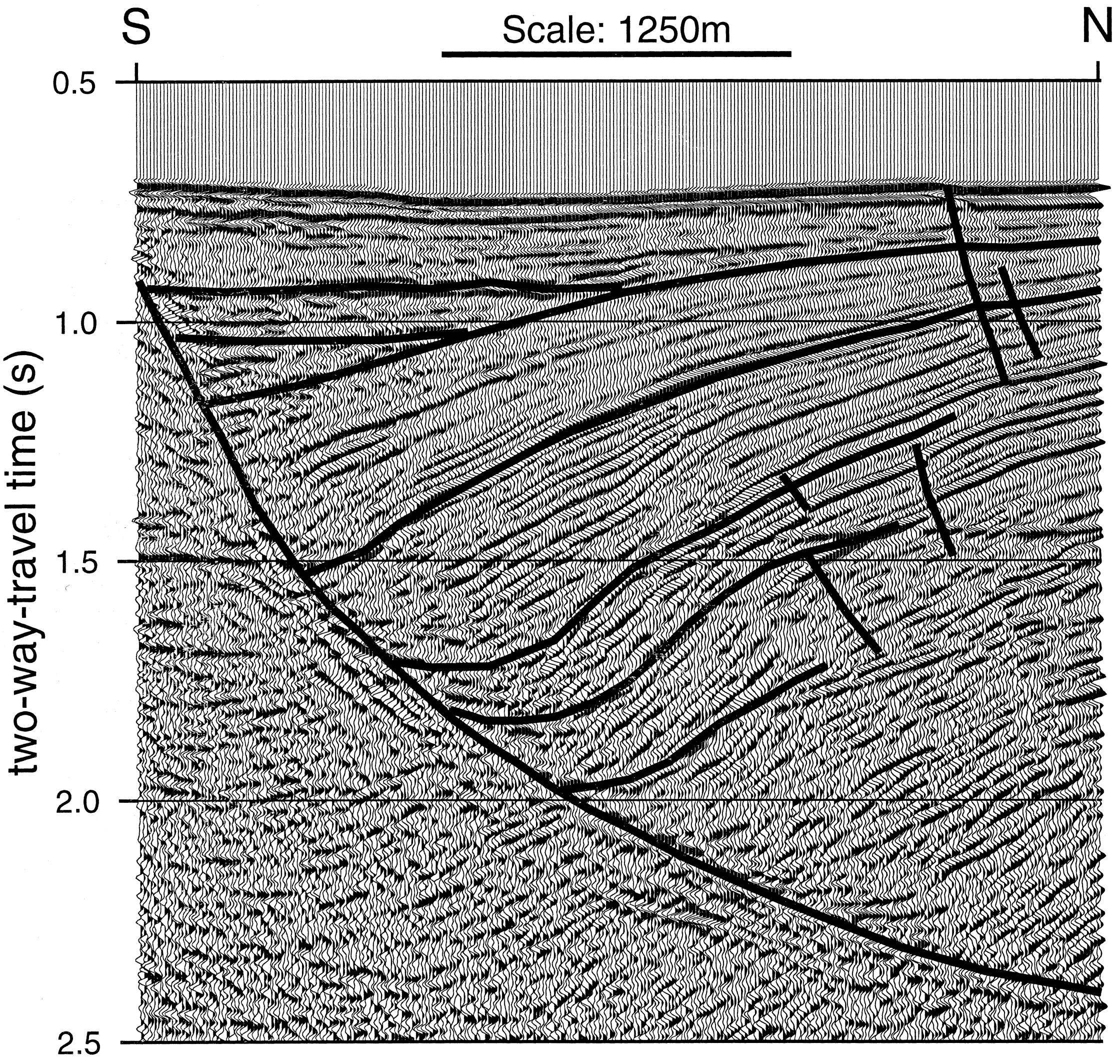

Fig. 9. Zoomed area in Fig. 3. The major discontinuity is the so-called Datça Fault. Notice the bending, divergent bedding and dragging against the fault plane. The horizontal bedding above 1.2 s twt time marks possible deceleration of the faulting.

implications of this change in bedding are given in Section 5.

It is highly possible that the degree of curvature of the Datça Fault is exaggerated in the time seismic sections due to velocity increase with depth. A detailed velocity analysis for depth migration was carried out for the southern half of the seismic data in Fig. 3 to test if the fault plane is planar or curved. A post-stack finite-difference depth migration by using the detailed velocity function was applied to the data (Fig. 10). Note that curvature of the plane is still observed. The velocity values in depth migration must be at least 25% or more in order to make this fault planar. Such amount of error is unlikely to happen in the velocity analysis; therefore, we concluded that the major discontinuity is a curved normal fault plane. Similar structures are noted in some studies (i.e., Wernicke and Burchfiel, 1982; Badley, 1985; Smith et al., 1989). The approximate dip angle of the fault plane at various locations is also shown in Fig. 10. Jackson and McKenzie (1983) argue that in many cases listric normal faults are produced by the

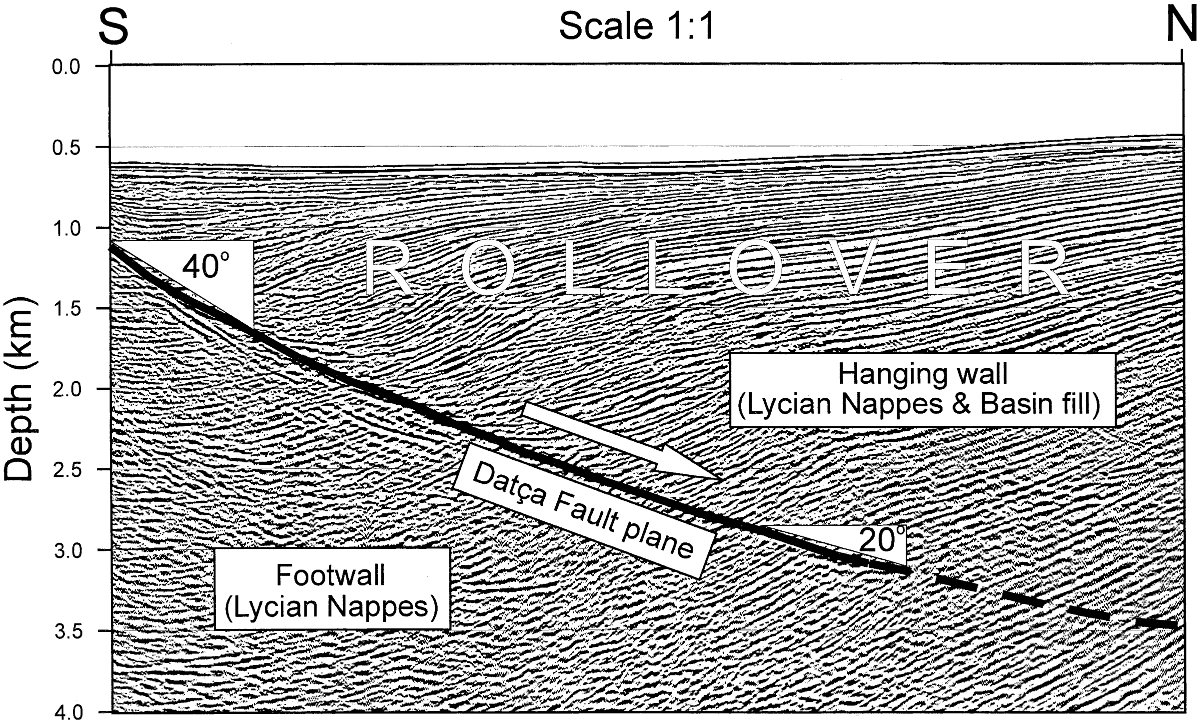

Fig. 10. Post-stack finite-difference depth migration of the southern half of section 11. The vertical and horizontal scales are about the same. The curvature of the Datça Fault is still observable. Note that the dip angle is gradually decreasing in the slip direction.

reactivation of thrusts as normal faults. Following this argument, the neotectonic regime might have reactivated some ancient thrust planes in the Gökova area. Indeed, the Lycian Nappes outcropping widely in the extreme southwest of Anatolia and forming the basement of the Gökova area had been thrust over the autochthonous Mesozoic and Tertiary sequences during the paleotectonic regime (Brunn et al., 1971, 1976; Bremer, 1971; Bernoulli et al., 1974).

Northern parts of sections 6, 9 and 11 display the synthetic and antithetic faults of the Datça Fault. These planar and rotational normal faults make sharp scarps at the sea bottom, they cut the basement, and are well correlated with the bathymetry (Figs. 2, 11 and 12). Another set of faults that are mainly planar are also observed in the middle part of the seismic sections (Figs. 5 and 13). They are possibly developed as a reaction to a local extension resulting from uprising basement. Therefore, these faults are mainly located on either sides of the rising crest of the basement. Alternative causes of this rising basement can be discussed in terms of Gibbs (1984): ramp–flat–ramp fault plane geometry may cause an uprising in the hanging wall where the shape of the fault plane shows flat-to-ramp transition and if the hanging wall was trapped by an antithetic fault. The ramp–flat portion of the ramp–flat–ramp geometry and antithetic fault are observed in our data (Fig. 5). However, we cannot observe the final flat-to-ramp transition because of a low or no acoustic impedance contrast between the hanging wall and the footwall for possible reasons given in Section 5. Another possible explanation is to consider the rising basement as a horst block between two subgrabens. However, this would require oppositely dipping faults on either side of the rising basement which are not observed in the seismic data.

A WNW–ESE-oriented horst–graben system is the noticeable feature in the eastern part of the gulf. This system is observed in seismic lines 1 through 5 and partially in the bathymetry data (Figs. 2 and 6). Moreover, the fault line map constructed from the seismic sections displays the main structural components of this system (Figs. 7 and 8). Notice that the

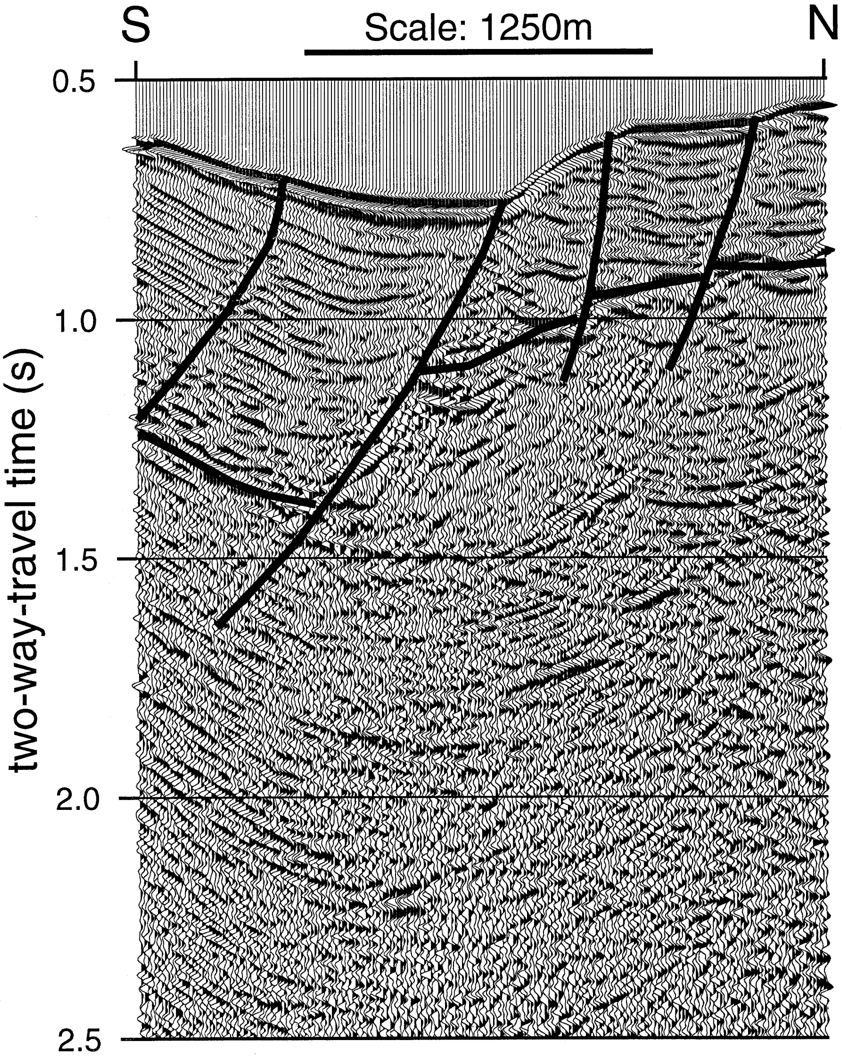

Fig. 11. Zoomed area in Fig. 3. Close view of one of the major antithetic faults of the Datça Fault in section 11. This fault cuts the basement as well as the basin fill and the sea bottom.

horst–graben system in this part of the gulf extends mainly WNW–ESE and it is well correlated with the shape of the eastern shoreline. This correlation suggests that the fault system may extend towards the land although no remarkable faults are mapped in Fig. 1. Notice from Fig. 7 that the basement topography observed in seismic lines 1 through 4 becomes deeper to the north. This is possibly due to tilting of the basement towards the major faults observed at the northeast margin. Therefore, the horst–graben features in the eastern part of the gulf should have been formed by the synthetic and antithetic faults of the major normal faults located at the northeastern margin of the gulf. This horst–graben system is also partly covered in the northeast by seaward-prograding deposits of the streams developed at the northeast of the gulf. Because the horst–graben system is partly buried, erosional factors should be dominant at the northeast margin of the Gulf of Gökova. Indeed, recent studies on land show the liveliness of the erosion (Paton, 1992; Görür et al., 1995; Uluğ et al., 1996). Sediments filling the grabens in this

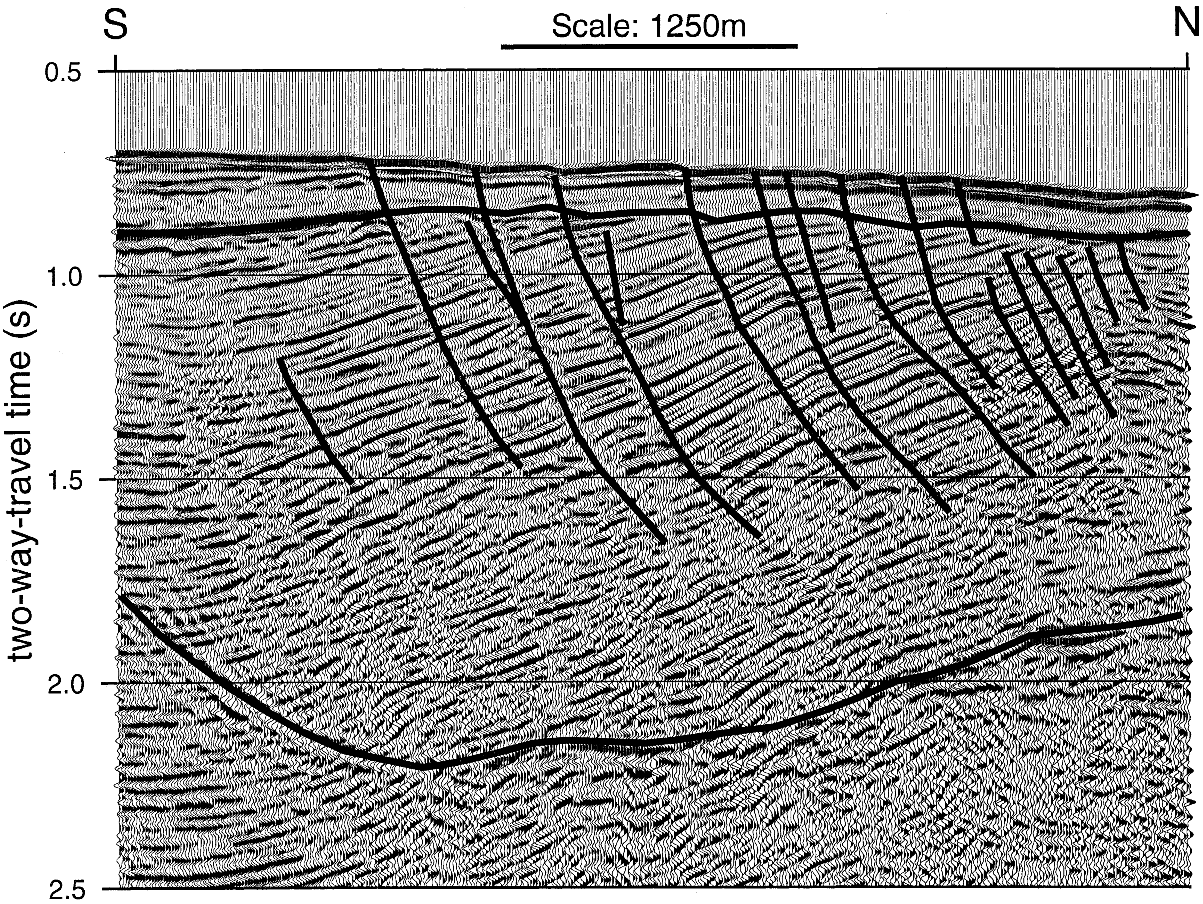

Fig. 12. Zoomed area in Fig. 4. Close view of the synthetic faults of the Datça Fault in section 9.

part of the gulf are possibly Pliocene–Quaternary in age and the maximum estimated thickness is about 500 m.

The gulf-mouth trough in the west and the horst–graben system in the east are gradually separated by a bathymetric low in the middle part of the gulf. The maximum depth of this bathymetric low is about 770 m and is crossed by seismic lines 6 through 9 (Fig. 2). It is mainly extended WNW–ESE and bounded by the eastward continuation of the Datça Fault at the south and the shelf break at the north. Normal faults opening a new basin at the north within the gulf can be observed in Fig. 4. Notice that these faults are forming a new subgraben and this is possibly related to the differential motions in southwest Anatolia observed from recent GPS studies (Oral et al., 1995; Le Pichon et al., 1995; Reilinger et al., 1997; Barka and Reilinger, 1997). Indeed, Reilinger et al. (1997) suggests that the largest differential motions occur within the Gediz, Büyük Menderes grabens and possibly in the Gulf of Gökova due to the counter-clockwise rotation of the Anatolian Block.

5. Discussion

The Gulf of Gökova is mainly oriented E–W. In spite of this orientation, the submarine tectonism in the gulf differs from west to east. In the gulf-mouth area to the west, the major structural feature is the E–W-oriented Datça Fault, which has not been previously noted in the literature. Besides this feature, the WNW–ESE-oriented mid-gulf trough in the mid-

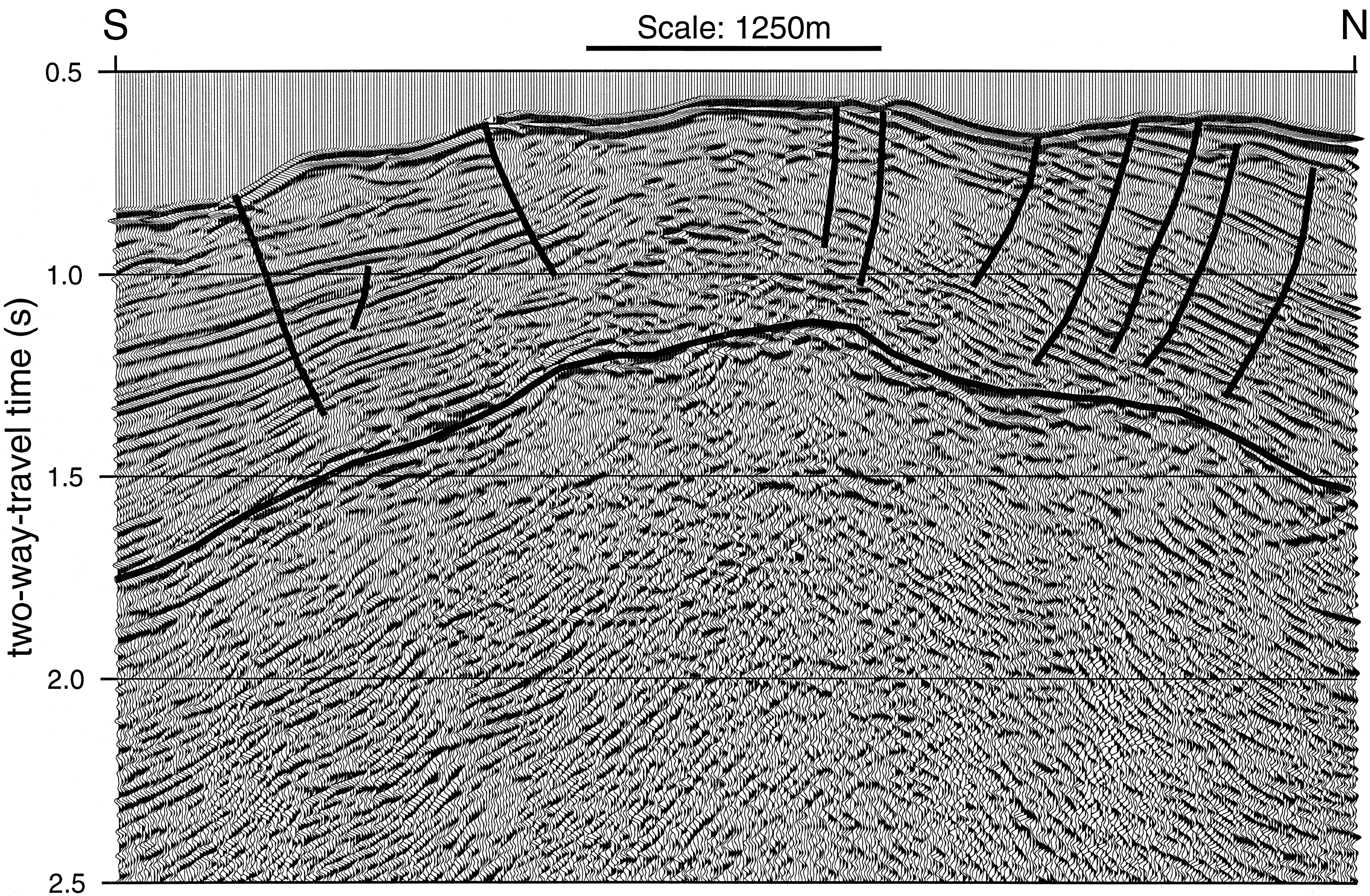

Fig. 13. Zoomed area in Fig. 5. Faulting in the basin fill associated with the local extension due to rising basement is remarkable in section 6.

dle of the gulf and the WNW–ESE-oriented horst–graben system in the east as well as E–W-oriented major normal faults in the northeast margin are the other important features.

The opening of the Gulf of Gökova must have been essentially initiated by the Datça Fault located at the south and its associated antithetic faults at the north. The onset time of this faulting is possibly in the latest Miocene–Pliocene because of the following arguments. There are estimates about the age of extension in the Gökova area. Böger (1978) reported normal faulting commencing in the Latest Miocene on Kos Island which might be an indication for the opening of the gulf. Görür et al. (1995) suggested a Pliocene age on the basis of the age of accessible sedimentary infill and the discordant relation of the Gökova rift with the paleotectonic rifts. According to Westaway (1994), the rate of extension in western Anatolia accelerated in Pliocene times. This argument is consistent with our data in Figs. 3 and 9. Note that strong dragging of layers against the fault plane, especially in the interval between 1.2 and 2.2 s (possibly spanning the Pliocene times), shows that the rate of faulting might have been high during the deposition of these layers. It is inferred from the existence of basin fill beneath the strongly dragged layers of possibly Pliocene age that the onset time of the Datça Fault may be as early as the latest Miocene.

The continuation of the Datça Fault plane to the north is not seen in section 11. We interpreted that the hanging wall consists of Lycian Nappes at the bottom and basin fill at the top. Therefore, where the fault plane is in contact with the basin fill, strong reflections are observed due to the high acoustic impedance contrast; however, where the fault plane is through the Lycian Nappes, the fault plane could not be observed due to a low or no acoustic impedance contrast. For this reason, we cannot follow the fault plane of the Datça Fault to the deeper parts of the seismic section.

Horizontal bedding and onlapping above 1.2 s in Figs. 3 and 9 imply that faulting decelerated, possibly in the Pleistocene. We refer to this age based on a sediment deposition rate on the coast of the Aegean Sea estimated by Westaway (1994). The amount of sedimentation near the Turkish coast of the Aegean Sea is about 1.1 mm/y. The total time to accumulate the 500 m thick uppermost horizontal bedding in section 11 takes about 500,000 years by assuming a constant deposition rate. Therefore the activity of the Datça Fault has been possibly decelerated since the Pleistocene. Faults in extensional regions become curved at depth as the deformation evolves, even if the faults were planar to start with. It is also argued that in many cases listric normal faults are produced by the reactivation of thrusts as normal faults (Jackson and McKenzie, 1983). The deceleration of the activity of the Datça Fault may be explained by low dip angle of the fault plane as the deformation progresses. This low dip angle may cause the gravity force to impede as described in (Jackson, 1987) so that the gravity force is no longer helping the hanging block slip on the fault plane. When the deceleration was initiated possibly in the Early Pleistocene, the continuing extension in the region was taken up by some other faults at some other places, i.e. by the faults at the northeast margin of the gulf (Figs. 1 and 8). In addition, Uluğ et al. (1996) proposed a transfer fault (Gibbs, 1984) between these two different styles of extensional areas of the Gulf of Gökova; however, we were unable to test this proposal because of the inadequate number of deep seismic E–W profiles.

McKenzie (1972, 1978b) gives the focal mechanism solution of a major earthquake (1968.12.5 with magnitude 5.5) by the gulf located at the south of Kos Island. The focal mechanism solution of this earthquake shows two alternative fault planes. We propose that the southeast-dipping plane (46° dip and 57° strike) is the fault plane because the north-dipping Datça Fault has not been possibly active since the Pleistocene. Therefore, this earthquake may be related to one of the faults which is a member of the same extensional style observed on the northeastern margin of the gulf at present. Epicentral distribution of the earthquakes (from the International Seismological Center (ISC) catalogue between 1964 and 1993) in the Gökova area shows a relatively high activity in the northern part of the gulf (Fig. 2). The activity observed in the northeastern margin of the gulf is possibly related to the normal fault system observed on land (Fig. 1). An earthquake-monitoring network was operated in the Gökova area by ITU in August 1995. The earthquake activity in the southern part of the Gulf of Gökova where the Datça Fault is located is relatively small compared to activity in the northeast (Eyidoğan et al., 1996). In summary, the Datça Fault is less active relative to the structures at the northern parts of the gulf at present. We infer from this and previous discussions that the style of extension in the gulf has possibly changed since the Pleistocene.

The recent studies using GPS and SLR measurements and modeling of earthquakes (Eyidoğan, 1988; Jackson et al., 1992; Le Pichon et al., 1995; Reilinger et al., 1997; Barka and Reilinger, 1997) indicate that plate motion is accelerated to the south in southwestern Anatolia. Residual velocities concentrated in southwestern Anatolia (Reilinger et al., 1997) and the horizontal velocity modelling in the western Anatolia–Aegean Sea region (Jackson et al., 1992) imply that southwestern Anatolia is under a NE–SW to NNE–SSW tension. The latest WNW–ESE structures observed in the Gulf of Gökova must have developed under this tension. Indeed, it is stated in Jackson et al. (1992) and Barka and Reilinger (1997) that the expected direction of the normal faults are WNW–ESE, being consistent with our observation in the Gulf of Gökova.

The Datça Fault is the most significant feature in the opening of the Gulf of Gökova. In addition, it may be significant in the calculation of the overall extension in the western Anatolia–Aegean Sea region. However, in various researches, the overall extension in the western Anatolia–Aegean Sea region has been estimated by considering only well-known main structures. It is important to keep in mind that the Datça Fault and similar buried structures may affect the explanation of the estimated extension rates in this region. The overall rate of extension in the gulf was estimated as at least 1.1 mm/y from seismic section 11. In estimating this rough value, we assumed that the gulf began to open in the latest Miocene–Pliocene (5.2 m.y.). We considered the total horizontal separation of the Datça Fault and its major antithetic fault ($X + Y = 5.5$ km in Fig. 3). The actual rate must be larger than 1.1 mm/y when the minor antithetic faults are considered and/or if the onset of the opening of the gulf is younger than latest Miocene–Pliocene. We estimated the extension factor as at least $\beta = 1.3$ by taking the ratio of the total length of the seismic section (extrapolating the Datça Fault to the sea level) and the length of the rollover structure of the basement in the hanging wall block. Paton (1992) gave the extension factor $\beta = 1.1$ by assuming a simple domino model and using the initial and final dips of the faults at the northeast margin of the gulf. This value may be somewhat of an underestimation for the whole gulf because the main extension was taking place in the further west.

6. Conclusions

Multi-channel seismic reflection data from the Gulf of Gökova, southwest Anatolia–southeast Aegean Sea, were processed and interpreted in this study. Principal results are as follows.

The most prominent result is that the Gulf of Gökova is mainly opened by the E–W-oriented, buried Datça Fault located at the south and its antithetic faults located at the north. This fault has never been reported and discussed in the literature before.

The Datça Fault might have begun to work in the Latest Miocene–Pliocene. In terms of local rather than regional effects, its activity has been decelerated, possibly since the Pleistocene. The Datça Fault has gained its curved fault plane as it evolved, beginning as planar and/or using antecedent thrust planes of the Lycian Nappes. As the extension progress, i.e., the hanging wall block slipped further north, the gravity force may have impeded rather than helped the faulting. On the other hand, continuing extension in the area may have initiated a second phase of faulting, i.e., WNW–ESE-oriented subgrabens in the gulf and major E–W normal faulting at the northeast margin. This is consistent with the NE–SW to NNE–SSW tension of southwestern Anatolia obtained from the GPS and SLR studies as well as from the moment tensor solutions of earthquakes.

Although it is a rough estimate, the overall rate of extension within the gulf is at least 1.1 mm/yr. The overall extension within the gulf since the latest Miocene–Pliocene is at least 5.5 km where the extension factor (β) is about 1.3. In previous studies, the results of modeling to estimate the rate of extension of the western Anatolia–Aegean Sea region are usually explained by well-known structures in the region. However, the existence of buried structures, such as the Datça Fault, may be significant when estimating and explaining the overall extension of the western Anatolia–Aegean Sea region.

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