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Late quaternary seismic stratigraphy and active faults of the Gulf of İzmit (NE Marmara Sea)

Mahmut Okyar · Ali Pinar · Devrim Tezcan · Züheyr Kamaci

Abstract The Upper Quaternary seismic stratigraphy and active faults of the Gulf of İzmit were investigated by means of high-resolution shallow seismic profiling data in the source region of 1999 İzmit earthquake. High-resolution seismic reflection data correlated with borehole data indicate that the stratigraphy of İzmit Bay consists of three distinct depositional sequences formed in response to middle Pleistocene-Holocene sea-level changes. Reflector R, separating the pre-Holocene sequences (1 and 2) from the Holocene sequence (3), represents an erosional unconformity produced by the subaerial fluvial erosion of the continental shelves at the time of the last glacial maximum. Occasional, anomalous reflections (acoustic turbidity) observed within the Holocene sequence are interpreted as gas accumulations. The maximum thickness of the Holocene sediments is found to be about 25 m. The isopach map of Holocene sediment implies that the thickness of the Holocene decreases from the east towards the central and western basins of İzmit Bay. Two distinct fault systems are interpreted in İzmit Bay. The main fault system extending roughly in an E-W direction along the Gulf of İzmit is an active right lateral strike slip fault with a normal component. The secondary faults are normal faults striking in different directions and these are identified as being both active and inactive. In addition, prominent compressive features are identified in the seismic cross-sections of some profiles acquired to the east of Hersek Peninsula where the focal mechanisms of the aftershocks of the 1999 İzmit earthquake also reveal predominantly reverse faulting mechanisms, as identified by a local dense seismic network.

Keywords Holocene · Late-quaternary · Shallow seismic · Tectonics · North Anatolian Fault · İzmit Bay

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Introduction

İzmit Bay is one of the most densely urbanized and industrialized coastal inlets of the Marmara Sea. It is 60 km long and 2–10 km wide, and has an area of approximately 310 km^2 (Tuğrul et al. 1989). Geologically, İzmit Bay is located on the northern branch of the North Anatolian Fault (NAF) (Fig. 1) which ruptured during the M_w 7.4 earthquake on 17 August 1999 (Barka 1999). Seismological studies indicate that the total length of the ruptures is about 180 km, some of which are submerged under the Gulf of İzmit and the Sea of Marmara, with maximum displacements of 5 m (Emre et al. 2000).
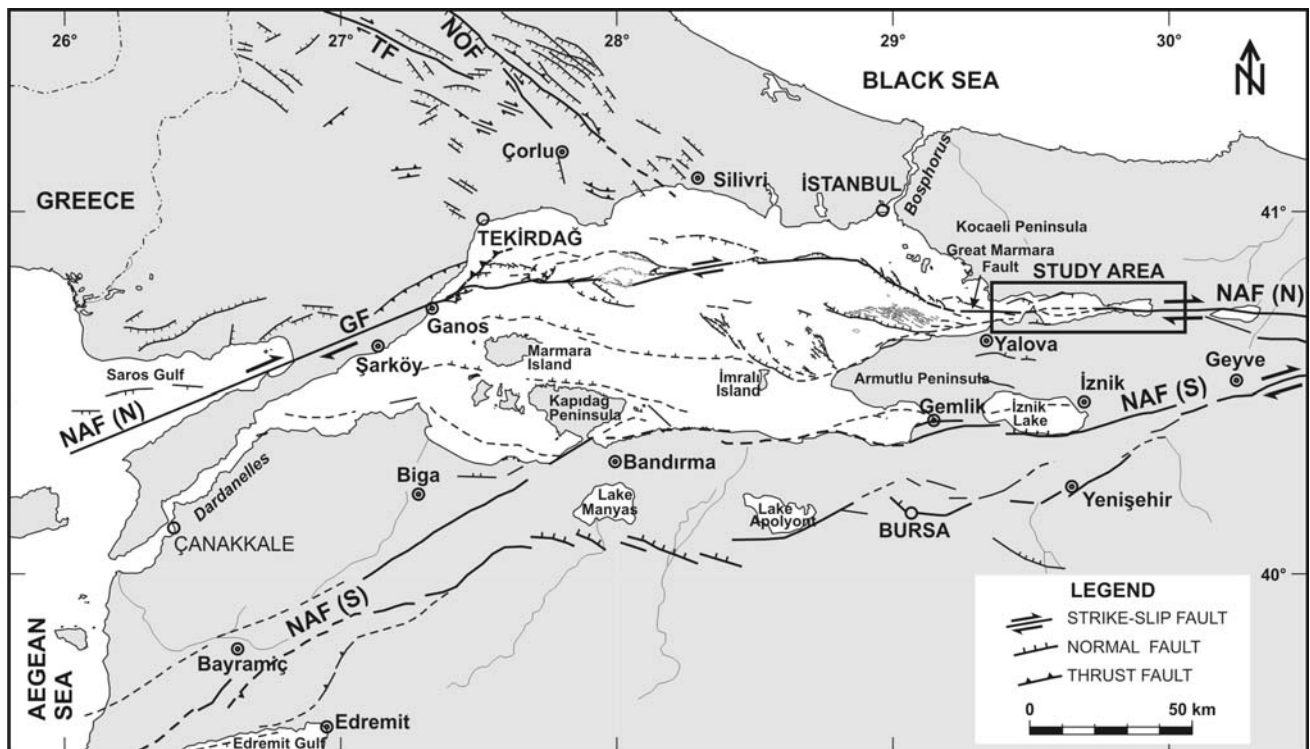
Large-scale marine seismic surveys in the bay, prior to the earthquake of 17 August, have been performed during cruises of the R/V Sismik-1 (General Directorate of Mineral Research and Exploration) in 1983 and the R/V Koca Piri Reis (Dokuz Eylül University) in 1994. Although the former data sets have been interpreted by different research groups (Özhan et al. 1985; Özhan 1986; Kavukçu 1990; Bargu and Yüksel 1993; Akgün and Ergün 1995; Koral and Öncel 1995; Barka and Kuşçu 1996; Barka 1997; Özhan and Bayrak 1998), there is limited information on the seismic data acquired by the R/V Koca Piri Reis (Şenöz 1998).

Fig. 1 Tectonic map of the Marmara region compiled from Armijo et al. (1999, 2002). According to these researchers, the right-lateral North Anatolian Fault (NAF) splays westward into two main segmented branches. The northern branch (N) passes beneath the Sea of Marmara, and it accommodates most of the lateral motion. The southern branch (S), remaining on land south of the Sea of Marmara, accommodates much less motion. GF = Ganos Fault. Note tectonic lines showing the North Osmancık Fault (NOF) and Terzili Fault (TF) compiled from Görür and Okay (1996)

Özhan et al (1985), Özhan (1986), Kavukçu (1990), Bargu and Yüksel (1993), Barka and Kuşçu (1996), Barka (1997) and Özhan and Bayrak (1998) mapped the faults in İzmit Bay (Fig. 2), and proposed different structural models for the evolution of the bay. Some workers (Özhan et al. 1985; Özhan 1986; Kavukçu 1990; Özhan and Bayrak 1998) suggested that İzmit Bay developed as an east-west trending graben under the control of the North Anatolian Fault Zone (NAFZ), while others (Barka and Gülen 1988; Bargu and Yüksel 1993; Barka and Kuşçu 1996; Barka 1997), accounted for the en echelon strike-slip character of the NAF, and suggested a pull-part model, which was also accepted by Akgün and Ergün (1995), Koral and Öncel (1995) and Şenöz (1998).

Özhan et al. (1985), Özhan (1986), and Özhan and Bayrak (1998) have reported that the infill of İzmit Bay, consisting of Plio-Quaternary deposits, was about 25–30 m thick. Bargu and Yüksel (1993) also mapped the spatial distribution of the Holocene sediments in the bay (Fig. 2).

Apart from these large-scale marine seismic surveys, Alpar and Güneysu (1999) carried out a small-scale survey in the vicinity of the Hersek Delta during the cruise of the R/V Arar of İstanbul University, prior to the 1999 earthquake. They interpreted four different seismic units above the acoustic basement.

After the 17 August 1999 İzmit (Kocaeli) Earthquake, marine seismic surveys were carried out by R/V Sismik-1 (Şengör et al. 1999), R/V Arar (Alpar 1999; Alpar and Yaltırak 2000; Gökaşan et al. 2001; Alpar and Yaltırak 2002; Cornier et al. 2006) and R/V Bilim of Middle East Technical University. Additionally, a special seismic research cruise was performed in March 2000, jointly by the General Directorate of Mineral Research and Exploration (MTA) of Turkey, Kochi University (Japan) and the Geological Survey of Japan (Kuşçu et al. 2002).

Şengör et al. (1999), Alpar (1999), Alpar and Yaltırak (2000, 2002) and Kuşçu et al. (2002) recognized two different groups of faults, classifying them as main nd secondary (Fig. 2). According to these workers, the main fault, trending in a roughly E-W direction, has a dextral strike-slip character and joins the Great Marmara Fault (Fig. 1). The secondary faults, which are mostly oblique to the main fault, are products of dextral shear. However, Gökaşan et al. (2001) proposed several active faults in the Bay (Fig. 2), one of which was interpreted as a buried main fault and was recognized as a new rupture of the NAF, probably active since the end of the last glacial maximum.

The studies of Gökaşan et al. (2001), Alpar and Yaltırak, (2002) and Kuşçu et al. (2002) also provided information on the subbottom stratigraphy of the İzmit
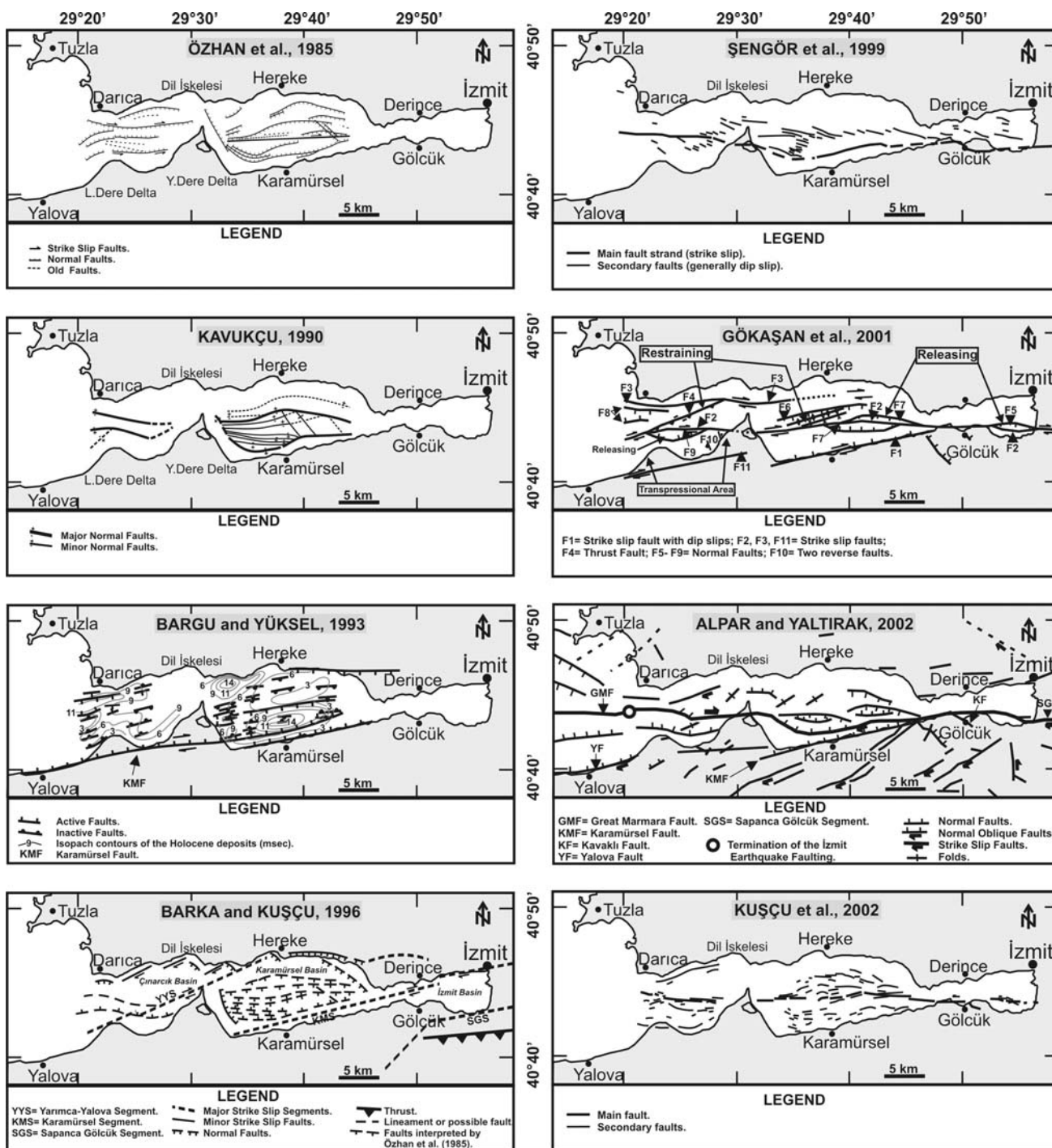
Fig. 2 Structural maps of the İzmit Bay and its surroundings prepared by Özhan et al. (1985), Kavukçu (1990), Bargu and Yüksel (1993), Barka and Kuşçu (1996), Şengör et al. (1999), Gökaşan et al. (2001), Alpar and Yaltırak (2002), Kuşçu et al. (2002). Of these researchers only Bargu and Yüksel (1993) mapped the thickness of Holocene sediments in the İzmit Bay. Note contradictory fault patterns proposed for the Bay by Özhan et al (1985), Kavukçu (1990), Bargu and Yüksel (1993) and Barka and Kuşçu (1996) who used same seismic data sets of the R/V Sismik 1 cruise in 1983, and by Gökaşan et al. (2001) and Alpar and Yaltırak (2002) who used same seismic data sets of the R/V Arar cruise in 1999

Bay. Gökaşan et al. (2001) identified two main sequences separated by an unconformity. These authors also contend that the upper sediments were deposited since the end of last glacial maximum, and the lower sediments (comprising several units) were deposited during the Plio-Quaternary. However, Alpar and Yaltırak (2002), using the same data, identified four seismic units: Unit 3 (Holocene), Units 2a–2b (middle to late Pleistocene) and Unit 1 (acoustic

basement). Kuşçu et al. (2002) identified two seismic sequences and interpreted them as Holocene marine sediments and pre-Holocene fluvio-lacustrine sediments. However, no attempts were made to map the spatial distribution of the late Quaternary sediments. Furthermore, both structural and stratigraphic interpretations of the bay by Gökaşan et al. (2001) and Alpar and Yaltırak (2002) contain several contradictions, despite using the same seismic data sets (see Okyar (2003) and reply by Alpar and Yaltırak (2003)).

The primary objective of the present study is to describe the upper Quaternary seismic stratigraphy and to map the thickness distribution of the Holocene in İzmit Bay, based on high-resolution seismic profiles (Fig. 3). This is important in understanding the depositional environments and sedimentary facies in the region. Seismostratigraphic interpretations were supported by borehole data.

A secondary objective of this study is to identify and map the active faults in İzmit Bay. This adds important information to our current knowledge and understanding of the tectonic setting of İzmit Bay. All available published structural maps were analysed for comparison purposes. In addition, some peculiar tectonic features observed in the cross-sections, such as transpressional features, are correlated with seismology data to ensure that these are not artefacts.

Material and methods

The data used in this study were collected in the source region of the earthquake of 17 August 1999 by R/V Bilim using a JMC 50 kHz echo-sounder, and an EG&G Uniboom 400 Hz–14 kHz subbottom profiler. A Differential Global Positioning System (DGPS) was used for navigation throughout the cruise.

Interpretation of seismic sequences and reflection characters followed standard methods discussed by Mitchum et al. (1977), Sangree and Widmier (1977, 1979), Vail et al. (1977), Brown and Fisher (1977, 1979), Badley (1985) and Boggs (1987). Depth conversions from time sections were made using a sound velocity of 1500 m/s for water and 1700 m/s for sediments.

Morphology

İzmit Bay, may be divided into eastern, central and western basins in terms of the morphological characteristics. The bathymetry is shown in Fig. 4.

The eastern basin is about 16 km long with width varying between 2 and 5 km (Tuğrul et al. 1989), and corresponds to the inner part of the bay. It is connected to the central basin by a 2-km-wide opening just to the west of Gölcük (Fig. 4). The basin is characterized by an east-west trending submarine depression, defined by the 30 m isobaths (Fig. 4). The origin of this depression has been ascribed to tectonic movements (Güneysu 1999). According to Algan et al. (1999), the eastern basin is mainly filled by sediments eroded from the surrounding land.

The central basin is about 20 km in length and 3–10 km in width (Tuğrul et al. 1989). It is connected to the western basin by a narrow opening, about 3 km wide and 60 m deep, (Fig. 4). The seafloor off the southern coast is steep, with an average gradient of 7°, whereas off the northern coast, it flattens to approximately 2°. The isobath lines enclosing the deeper (>70 m) areas of the central basin resemble an elliptical depression whose longer axis trends in an E-W direction. The central part of the depression is as
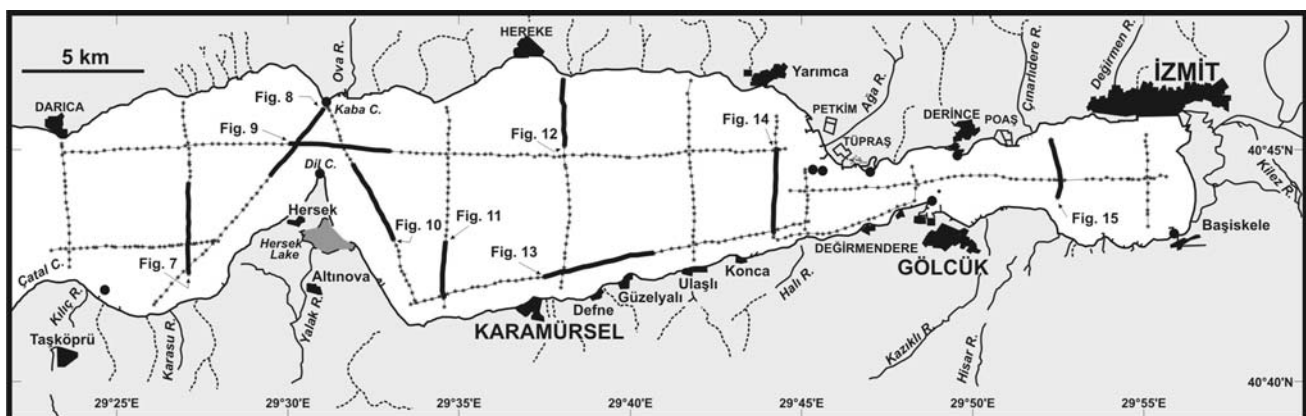
Fig. 3 Location of profiles obtained on board the R/V Bilim during the İzmit Bay cruise of September 1999. Seismic reflection profiles presented in this paper are marked by thick lines and by the corresponding Fig. numbers
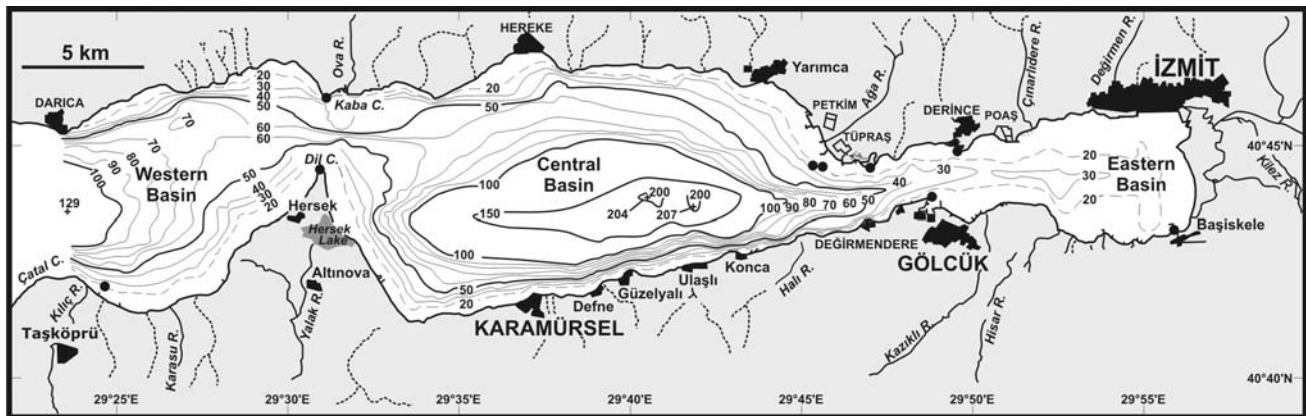
Fig. 4 Bathymetry of İzmit Bay (water depth contours are in meters)

deep as 207 m. As for the eastern basin, its origin is assumed to be tectonic (Güneysu 1999). The central basin receives sediments from the northern coast, Hersek Delta and from the western basin (Algan et al. 1999).

The western basin corresponds to the outer part of the İzmit Bay and it has a direct communication with the deep eastern Marmara Sea. It is about 27 km in length and 3.0–5.5 km in width (Tuğrul et al. 1989). The maximum depth is 129 m between Darıca and Çatal Cape (Fig. 4). From the northern and southern coasts towards a depth of 50 m, the isobath lines seem to lie parallel to the general trend of the respective coastlines. The average gradients of the seafloor off the northern and southern coasts are 2.9° and 1.5°, respectively. The western basin receives sediments from the Sea of Marmara, Hersek Delta and partly from the Central Basin (Algan et al. 1999).

Apart from this, the seaward extension of the Hersek Delta can be traced up to the 50 m isobath on the bathymetric map (Fig. 4). This is evidenced by the end of the parallel isobaths beyond 50 m depth.

Stratigraphic setting

The whole succession of pre-Neogene deposits in the vicinity of İzmit Bay, known as basement rocks (e.g., Emre et al. 1998), is characterised by two distinct stratigraphic units in the Armutlu Peninsula to the south and the Kocaeli Peninsula to the north. Pre-Neogene rocks of the Armutlu Peninsula comprise pre-Upper Cretaceous metamorphic rocks, and a non-metamorphic discontinuous sedimentary cover of Upper Cretaceous-Eocene age (Göncüoğlu et al. 1987). However, pre-Neogene units of the Kocaeli Peninsula are non-metamorphic, mostly sedimentary, successions which comprise Palaeozoic (Ordovician-Lower Carboniferous and Upper Permian), Mesozoic (Triassic and Upper Cretaceous) and Paleogene (Paleocene-Eocene) rocks (Seymen 1995).

Onshore stratigraphy

Neogene-Recent stratigraphy of the Gulf of İzmit is represented by the Karasu, Kılınç, Yalakdere, Samanlıdağ, Altınova Formations and associated alluvial deposits (Fig. 5). Brief descriptions of these formations and deposits are given below:

The Karasu Formation consists of red, yellow and brown sandstones, conglomerates, siltstones and mudstones (Emre et al. 1998). In the type area at Karasu (eastern Black Sea, outside the area mapped in Fig. 5), the formation starts with a red, brown and yellow-variegated coloured paleosol horizon, which is up to 10 m thick. Towards the top, it is followed by sandstone, conglomerate, siltstone and mudstone alternations. The sandstones consist mainly of quartz grains, and gravel fragments in the conglomerates are strongly disintegrated. The type section of the formation is about 40 m thick and lies unconformable on the basement rocks. On the Kocaeli Peninsula, the Karasu Formation outcrops in the vicinity of Tuzla and Gebze (Fig. 5). In addition, disintegrated gravel particles of the Karasu Formation are observed within Upper Miocene formations at some localities of the Armutlu Peninsula. The Karasu Formation is interpreted to be deposited during peneplanation, developing under the intense weathering effects of a warm-humid climate. An Early-Middle Miocene age is attributed to this formation (Emre et al. 1998).

The 300-m-thick *Kılınç Formation* unconformably overlies the pre-Neogene basement rocks (Bargu and Sakınç 1990). From the bottom up it comprises reddish-brownish conglomerate, gravelly sandstone, reddish sandstone, siltstone, yellowish white silty claystone and gravelly sandstone, yellowish-white siltstone and claystone, coal-banded siltstone, bluish-white claystone and marl, and whitish marl containing clayey limestone (Bargu and Sakınç 1990). Ostracods, such as *Ilyocypris gibba* (Ramdohr) and *Candona Compressa* (Koch), found within the samples taken from the Kılınç locality, indicate an age
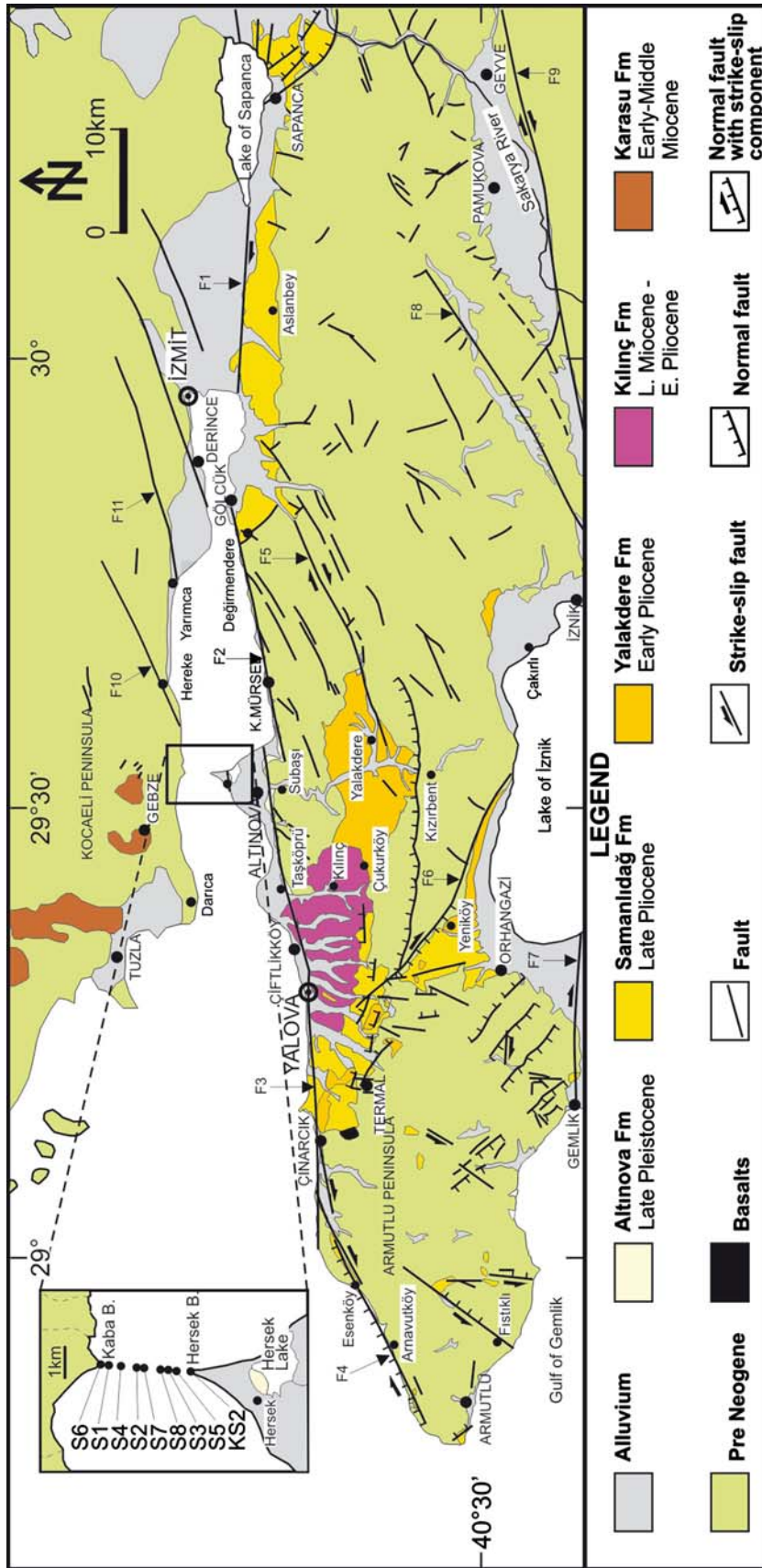
Fig. 5 Geological map of İzmit Bay and its surroundings (compiled from Göncüoğlu et al. 1987; Sakınç and Bargu 1989; Bargu and Sakınç 1990; Göncüoğlu and Erendil 1990; Erendil et al. 1991; Eisenlohr 1997; Emre et al. 1997, 1998). Note the İzmit Adapazarı Segment (F1), Gölcük Fault (F2), Yalova Fault (F3), Armutlu Fault (F4), Yalakdere Fault (F5), Orhangazi Fault, (F6), Gemlik Fault (F7), Adliye Fault (F8), İznik-Geyve Segment (F9) and the İzmit Fault Zone (F10–F11), discussed in the text. The inset shows the location of the boreholes illustrated in Fig. 6

of late Miocene-early Pliocene (Sarmatian-Pontian) for this formation (Akartuna 1968; Seymen 1995; Bargu and Sakınç 1990; Erendil et al. 1991). A lacustrine depositional environment is interpreted for the Kılınç Formation (Göncüoğlu et al. 1992).

The Yalakdere Formation lies unconformably on the pre-Neogene basement rocks, but rests conformably on the Kılınç Formation (Bargu and Sakınç 1990). It is comprised of yellowish-grey, grey, white, greyish-white coloured loosely cemented gravelly, sandy and silty beds occasionally alternating with claystone beds. The Yalakdere Formation, which is about 500 m thick, can be distinguished from the Kılınç Formation by its high content of gravel and sand-sized materials. An early Pliocene age is assigned to the Yalakdere Formation based on occurrences of molluscs such as *Dreissena* sp. and *Pontalmyra* sp. (Emre et al. 1998). The Yalakdere Formation is interpreted to be deposited in a lacustrine environment (Bargu and Sakınç 1990).

The Samanlıdağ Formation (Emre et al. 1998) unconformably overlies the Kılınç and Yalakdere Formations. It is composed of less gravelly mudstone, silt and sand materials. The Samanlıdağ Formation, is about 30–40 m thick, and is particularly observed in the vicinity of Termal, Orhangazi, Değirmendere, Aslanbey and Sapanca (Fig. 5). Although no fossils have been found in the deposits of Samanlıdağ Formation, a late Pliocene age is assigned to the formation based on correlation with similar formations in the eastern Marmara region (Emre et al. 1998).

The Altınova Formation (Sakınç and Bargu 1989; Marmara Formation of Sakınç and Yaltırak 1997) overlies the Samanlıdağ Formation. The formation is composed of loosely cemented sand, silty sand, clayey sand, marl, sandy marl deposits. These deposits contain fragments of bivalves, gastropods, foraminifers and coralline algae. On the basis of characteristic fossils within the Altınova Formation, the depositional environments have been interpreted as lacustrine to marine. For example, benthic foraminifers, such as *Ammonia beccarii* Linne and *Elphidium crispum* Linne indicate lacustrine conditions, while coralline algae *Lithothamnium* sp. implies marine conditions. According to Sakınç and Bargu (1989), the Altınova Formation was mainly deposited during the Tyrrhenian transgression (129 ka BP) and later subjected to regression due to uplift driven by motion on the NAF.

Thermoluminiscence (TL) and radiometric (U^{234}/Th^{230}) dating of the marine terraces, situated at 90, 60 and 20 m elevations on the south coast of the Gulf of İzmit (i.e. on the southern block of the northern segment of the NAF), give ages of 260, 130 and 40 ka, respectively (Paluska et al. 1989). During the Tyrrhenian (129–80 ka BP), sea level was never higher than 30 meters in the Mediterranean and Black Sea, suggesting that the marine terraces located

at 90 and 60 m heights must have been tectonically uplifted (Sakınç and Bargu 1989). The rates of uplift on the southern block of the northern segment of the NAF were assumed to be 0.5 mm/yr (Sakınç and Bargu 1989).

In addition, Electron Spin Resonance (ESR) dating (Çetin et al. 1995) of material from boreholes along a S-N transect between Hersek Burnu and Kaba Burnu (Figs. 5, 6), indicated that the maximum age of the Altınova Formation was 817 ± 105 ka (Sakınç and Yaltırak 1997). However, the youngest ages of the Altınova Formation are correlated with the marine terraces on land (Sakınç and Yaltırak 1997), ranging in ages of 260–40 ka (Paluska et al. 1989).

Alluvial Deposits are present in the coastal and hinterland areas of İzmit Bay (Fig. 5). Coastal areas are mostly characterised by deltaic, beach and marsh deposits (Emre et al. 1998). Deltaic deposits occur mainly along the southern coast of İzmit Bay, while marsh deposits dominate in the eastern coast of the İzmit Bay. Hinterland areas of the bay are characterised by alluvial fan, flood plain and channel-fill deposits (Emre et al. 1998), which occur mainly in and around the Sakarya and Yalakdere River channels. Alluvial fan formations are also found along the southern and northern coasts of the Sapanca and İznik Lakes, respectively (Emre et al. 1998).

Sedimentological and chronological characteristics of the sediments recovered from boreholes

The most direct subsurface information on the region comes from the nine wells drilled in 1989–1990 for the İzmit Bay crossing project (Meriç 1995a). One of these boreholes was drilled on the land, and the others in the sea (Figs. 5, 6). Drilling depths of the wells range from 26.75 m in borehole S6 to 120.45 m in borehole KS2 (Fig. 6). ESR dating in the sub-samples (Çetin et al. 1995), obtained from boreholes, yields the ages ranging from 0.5 ± 0.2 to 817 ± 105 ka (Fig. 6). Chronologically, the oldest age of 817 ± 105 ka was dated as late Pliocene-early Pleistocene; ages ranging from 693 ± 126 ka to 186 ± 20 ka were dated as early-middle Pleistocene; and ages ranging from 35 ± 8.1 ka to 0.5 ± 0.2 ka were dated as late Pleistocene-Holocene (Meriç, et al. 1995).

According to sedimentological analysis (grain size, composition) the cored sediments mainly consist of gravel, sand, silt, and mud-sized particles (Ediger and Ergin 1995). Angular rock fragments (blocks), beach-rocks and limestone are also found in some of the boreholes (e.g. boreholes S1 and S6; Fig. 6).

The uppermost sections of the sedimentary columns comprise gravel-sized particles in boreholes KS2, S5, S8, S7, S4, and S6; sand sized particles in boreholes S3, and S2; and mud sized particles in borehole S1 (Fig. 6). These
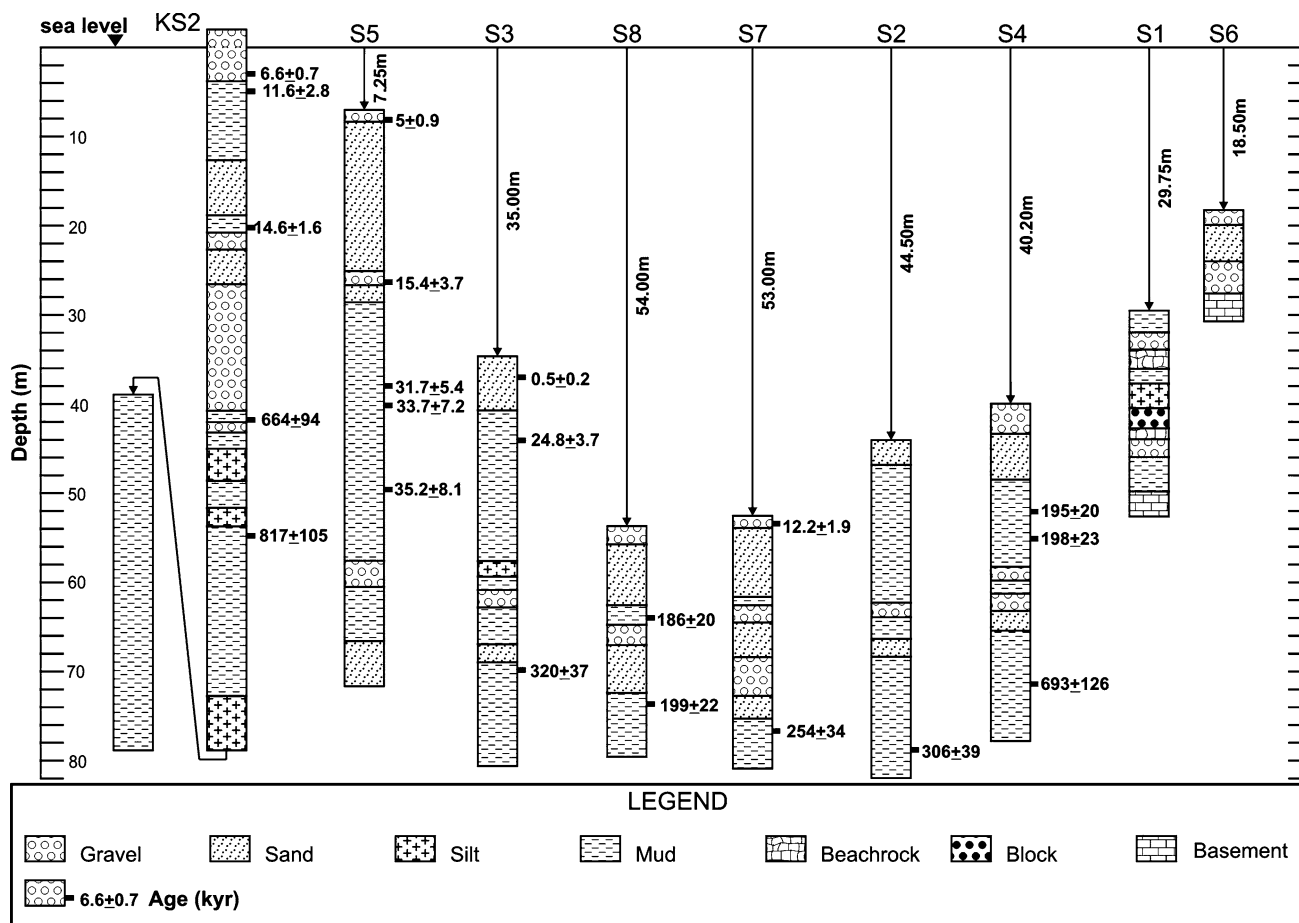
Fig. 6 Lithostratigraphic logs of the boreholes (KS2, S5, S3, S8, S7, S2, S4, S1 and S6) drilled in between the Hersek Burnu and Kaba Burnu (compiled from Ediger and Ergin 1995). Electron Spin

Resonance (ESR) datings of the borehole data are from Çetin et al. (1995). For location of the boreholes see Fig. 5

changes in the sediment grain size distribution are interpreted as the result of different environmental conditions. The computed total carbonate ($CaCO_3$) contents range from 17% to 86% in gravel-sized particles, from 14% to 20% in sand-sized particles, and 15% in mud-sized particles. High carbonate contents in gravel-sized particles are attributed to biogenic materials consisting of a large variety of calcareous remains of benthic organisms (Ediger and Ergin 1995).

In contrast, the gravel layers encountered at depths of 58.3, 62.1, 66, 63.3–71.6, 63, and 59.2–62 m, in boreholes S5, S3, S8, S7, S2, and S4 (Fig. 6), respectively, are interpreted as having been deposited under relatively high energy conditions. Moreover, the presence of fine-grained layers (mud and sand) above and below these gravel layers are regarded as indicative of transition from low to high energy conditions. The occurrence of these gravel layers at different depths has been explained as the result of tectonic movements along the NAFZ. Furthermore, Ediger and Ergin (1995) measured the differences of levels between upper and lower boundaries of the gravel layers, and

calculated that the total amount of basin subsidence attributable to tectonic movements was 16 m.

In borehole S1, the occurrence of beach rocks at depths of 34–36 m and 43–44 m is interpreted as indicative of sea level still stand during the transgression. At that time, a high terrigenous input came from the southern coast of the İzmit Bay, as shown by the occurrence of gravel beds at depths of 26.5 and 41 m in borehole KS2 (Fig. 6). The maximum carbonate content within these beds is 1% (Ediger and Ergin 1995).

The limestone layers, which are only observed in two boreholes, S1 and S6 (Fig. 6), are inferred to be of (?) Tertiary basement rock. These layers were observed at depths of 28 and 50 m in boreholes S6 and S1, respectively. Differences in the depths of limestone layers are interpreted to reflect normal faulting of up to 22 m in displacement.

Ediger and Ergin (1995) attributed the absence of basement limestone layers in other boreholes to either normal faulting movements or the high sedimentation rate. In particular, the muddy layers observed in boreholes KS2

and S5 exhibit significant age differences. In borehole KS2 muddy layers yield an age of 664 ± 94 ka at the depth of 41 m, whereas in borehole S5 the muddy layers gave an age of 33.7 ± 7.2 ka at about 40 m depth. This was interpreted to be due to normal fault movements with vertical throw of 40 m (Ediger and Ergin, 1995).
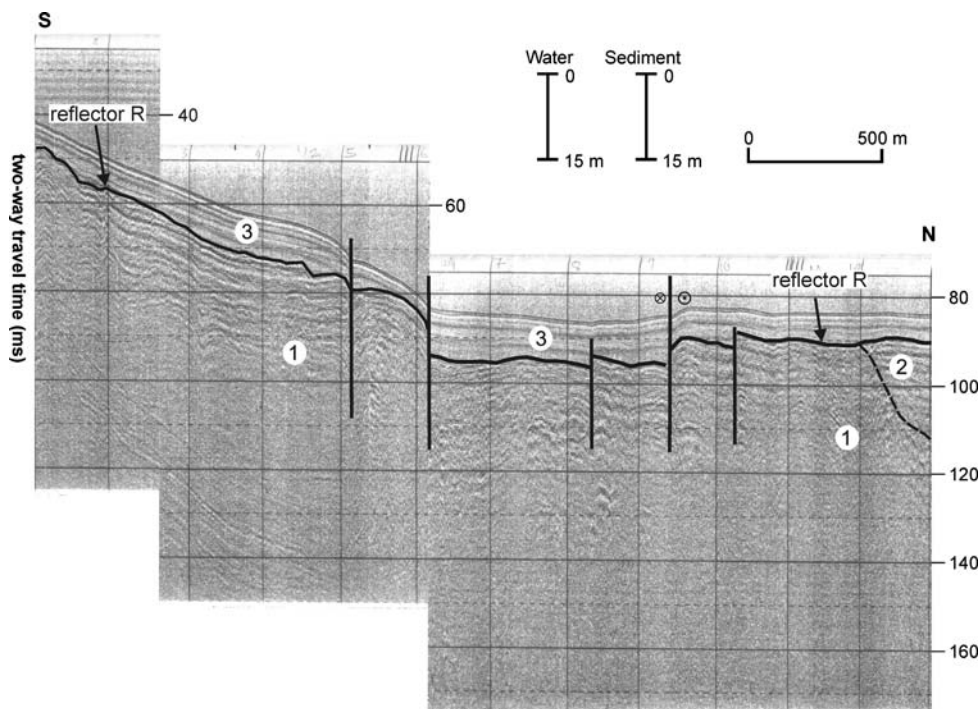
The fossil assemblages, particularly foraminifers, nannoplankton, ostracods, and molluscs, in the subsamples reflect the existence of different environmental conditions that developed under the effects of strong tectonism and regional climatic conditions including anoxic marine during the late Pliocene; marine-brackish during the early-middle Pleistocene; brackish-deltaic and continental at the beginning of the late Pleistocene; and marine from the end of the Pleistocene to the Holocene (Meriç 1995b).

Offshore stratigraphy

High-resolution seismic reflection profiles obtained from İzmit Bay indicate the presence of three distinct depositional sequences (Figs. 7–15). The pre-Holocene sequences (1 and 2) are separated from the Holocene sequence (3) by an irregular reflector (R).

A seismic sequence is defined as a seismic stratigraphic unit consisting of genetically related, conformable reflectors on seismic profiles; the unit is bounded at its top and base by unconformities (Mitchum et al. 1977). Seismic sequences are regarded as equivalents of depositional sequences.

Sequence 1

This is the oldest sequence in the surveyed area and is commonly characterized by discontinuous subparallel (Figs. 7, 9, 14 and 15) and chaotic (Figs., 10 and 13) reflectors. The former imply lateral variations in lithologic composition (Sangree and Widmier 1979). The chaotic configurations are interpreted as strata deposited in a variable, relatively high-energy setting (Mitchum et al. 1977). Additionally, chaotic to wavy (Figs. 8, 11 and 12) reflectors within Sequence 1 suggest folding (Mitchum et al. 1977).

Lithologically, the upper parts of Sequence 1 correspond to muddy, sandy and gravely layers in boreholes S4 (Fig. 8) and S7 (Fig. 9). ESR dating of the muddy layers in boreholes S4 and S7 yields ages of 693 ± 126 ka and 254 ± 34 ka, respectively (Çetin et al. 1995), interpreted as early-middle Pleistocene (Meriç et al. 1995). During the early-middle Pleistocene, marine brackish conditions were interpreted in the İzmit Bay (Meriç 1995b).

The top of Sequence 1 forms an unconformable contact with the overlying sequences 2 and 3 (Figs. 7–15). Unfortunately, the lower boundary of this sequence could not be identified on the seismic data due to limited subbottom penetration ($\sim$70 m) of the seismic system used in this study.
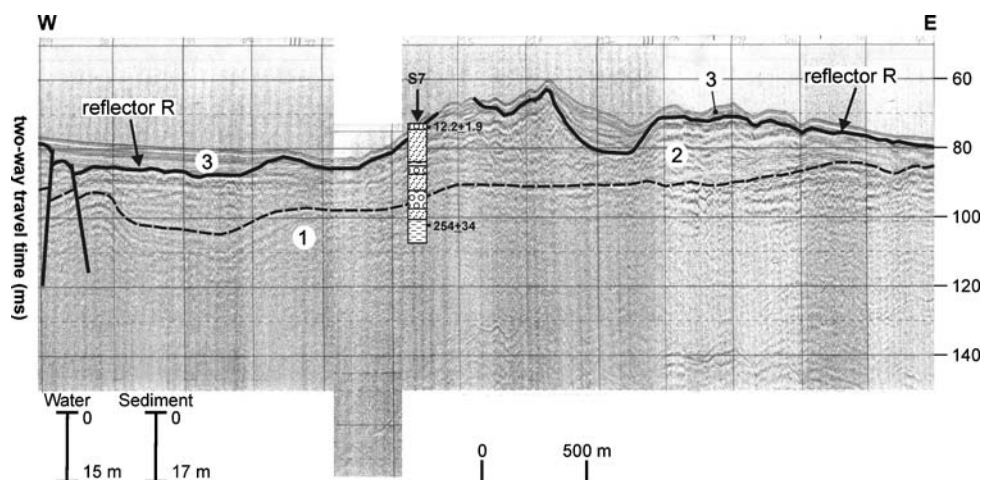
Sequence 2

Sequence 2, which overlies Sequence 1, exhibits discontinuous subparallel to chaotic (Figs. 7–10, 13), chaotic (Fig. 11), and chaotic to wavy (Fig. 12) reflectors.


Fig. 7 High-resolution seismic reflection profile (for location see Fig. 3) showing sedimentary sequences (1, 2 and 3) and active faults discussed in the text. Dot indicates the displacement toward viewer. Cross indicates the displacement away from viewer

Fig. 8 High-resolution seismic reflection profile (for location see Fig. 3) showing sedimentary sequences (1, 2 and 3) and active faults. Note the graben structure resulted from the normal faults in the central part of the profile. Borehole S4 that was crossed by the seismic profile is also included
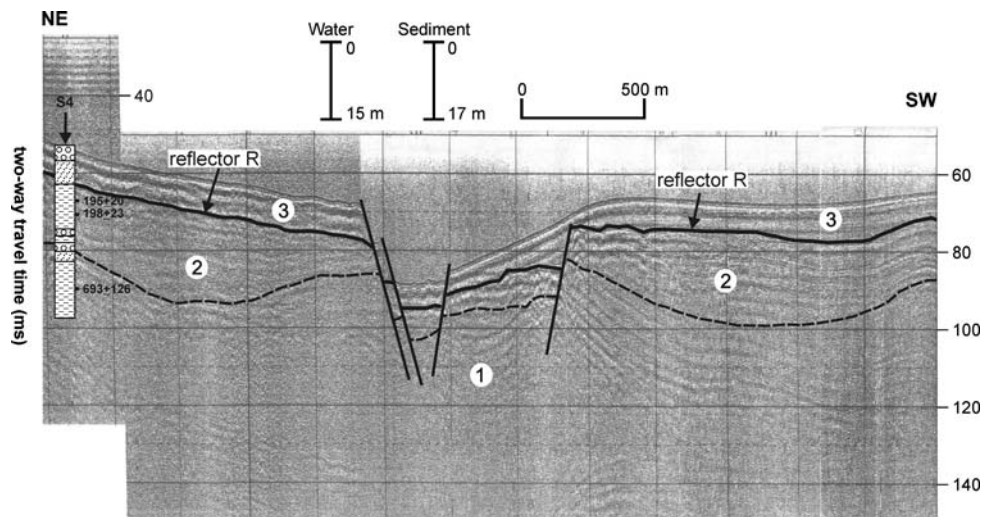
Fig. 9 High-resolution seismic reflection profile (for location see Fig. 3) showing sedimentary sequences (1, 2 and 3) and active faults. Note sequence 2 is locally outcropping at the sea floor in water depths of 53 m. Borehole S7 that was crossed by the seismic profile is also included
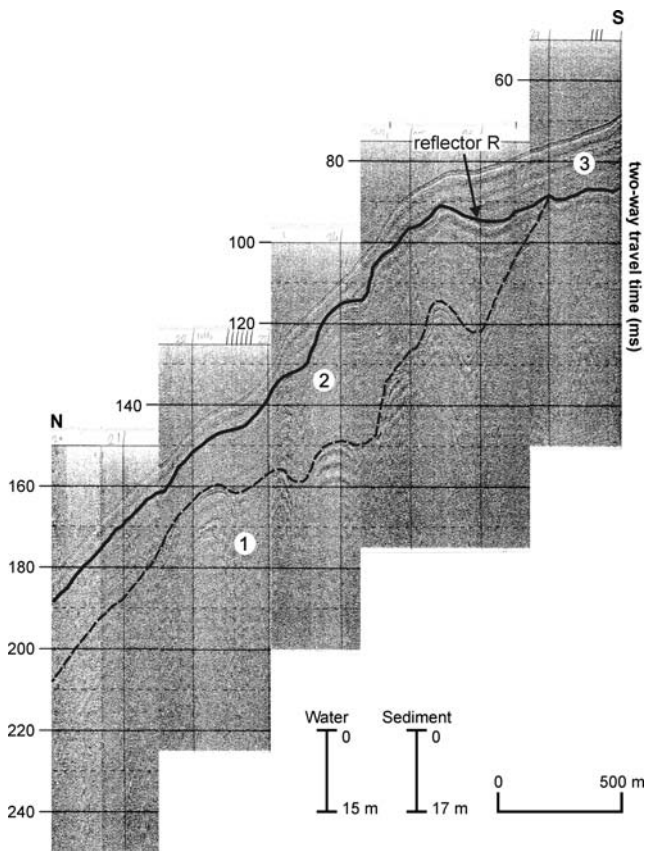
Fig. 10 High-resolution seismic reflection profile (for location see Fig. 3) showing sedimentary sequences (1, 2 and 3) and the active fault. Note the sea floor deepening and the sediment thickening of the downthrown side of the fault. Dot indicates the displacement toward viewer. Cross indicates the displacement away from viewer
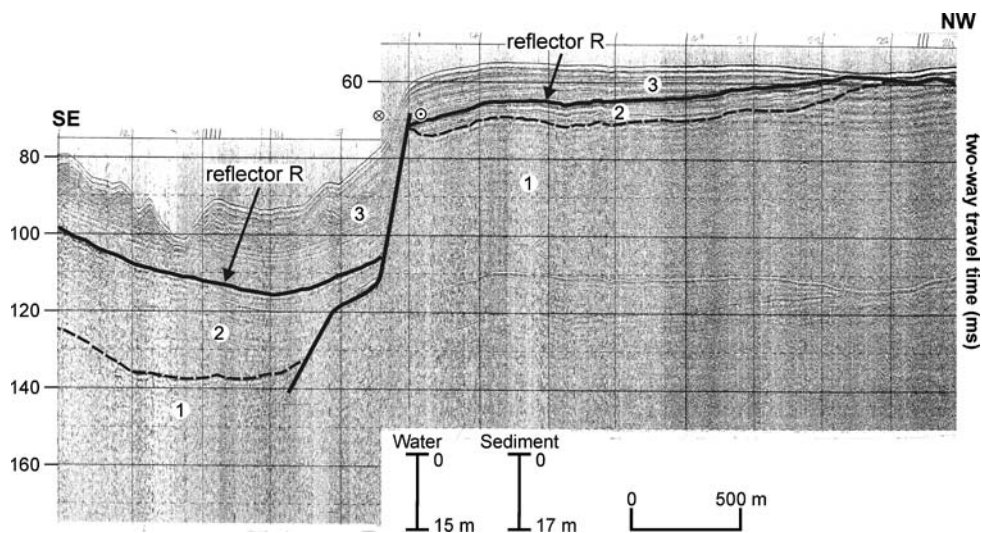
Sequence 2 comprises muddy, sandy and gravely layers in boreholes S4 (Fig. 8) and S7 (Fig. 9). The ages of the muddy layers in borehole S4, were calculated as 195 ± 20 and 198 ± 23 ka (Çetin et al. 1995), and

dated as middle Pleistocene (Meriç et al. 1995). As explained above, marine brackish conditions was defined for İzmit Ba, during the early-middle Pleistocene (Meriç 1995b).

Fig. 11 High-resolution seismic reflection profile (for location see Fig. 3) showing depositional sequences (1, 2 and 3)
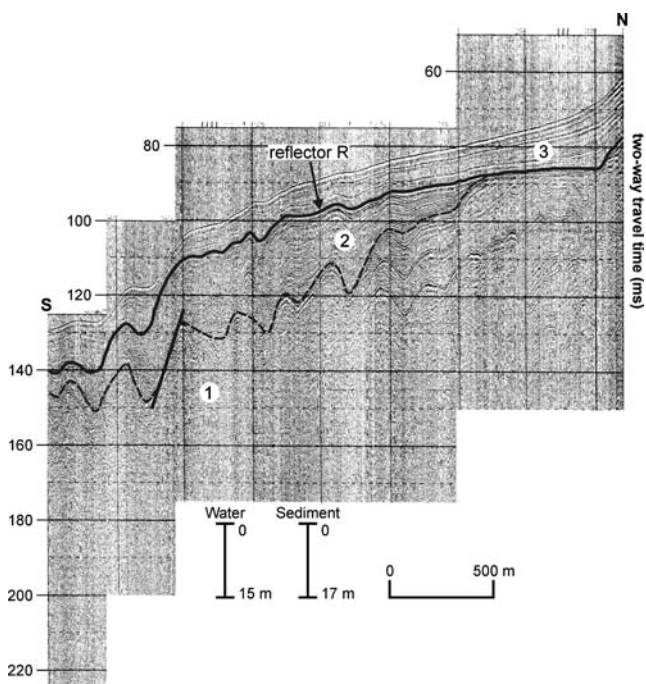
Fig. 12 High-resolution seismic reflection profile (for location see Fig. 3) showing depositional sequences (1, 2 and 3) and inactive fault

The base of Sequence 2 is characterised by onlap and downlap reflection terminations (Figs. 7–13). Of these, onlap reflection terminations were interpreted to be indicative of transgression (Vail et al. 1977) that most probably occurred in the post-glacial period. The upper boundary of Sequence 2 (reflector R), is an erosional unconformity (Figs. 7–13) that can be attributed to the pre-Holocene surface produced by the subaerial erosion of the continental shelves at the time of the last glacial maximum (e.g. Park and Yoo 1988; Tesson et al. 1990; Ergin et al. 1992; Okyar et al. 1994).

The maximum thickness of Sequence 2, which was calculated to be 45 m, is found in the central basin. This sequence is missing in some parts of the western and central basin, and it is almost completely absent in the eastern basin, probably due either to erosion or non-deposition.

Sequence 3

Depositional Sequence 3 is bounded at its top by the present sea floor, and its bottom is delimited by reflector R. This sequence is characterized by continuous parallel and occasionally chaotic reflectors (Figs. 8–15).

Sequence 3 comprises sandy and gravely layers in boreholes S4 (Fig. 8) and S7 (Fig. 9). The gravely layers in borehole S7, which yielded an age of 12.2 ± 1.9 ka (Çetin et al. 1995), were deposited under marine conditions (Meriç 1995b).

On some seismic profiles Sequence 3 contains anomalous zones or sections (Fig. 15). These are very similar to features, described in other regions, that have been interpreted as indicating the presence of gas in sediments (Schubel 1974; Carlston et al. 1985; Korsakov et al. 1989; Judd and Hovland 1992; Taylor 1992; Long 1992; Hovland 1992; Okyar and Ediger 1999). In this area, the observed anomalous zones have also been interpreted as representing gas accumulation in Sequence 3 and are referred to as zones of "acoustic turbidity (AT)". The term "acoustic turbidity" refers to those parts of the seismic section where subbottom detail is lost probably due to the effects of gas bubbles within the sediment pore space (Davis 1992). Alpar and Yaltırak (2002) and Kuşcu et al. (2002) also reported gassy sediments and gas seeps on some seismic data recorded in the Gulf of İzmit.

The thickness of Holocene sediments (Sequence 3) is shown in Fig. 16, as an isopach map. In general, the thickness of Holocene sediments decreases from the eastern towards the central and the western basins (Fig. 16). This implies a westward decrease in the sediment supply.

The maximum sediment accumulations occur in three locations, two of which are located in the central basin and one in the eastern basin, where Holocene sequences reach a

Fig. 13 High-resolution seismic reflection profile (for location see Fig. 3) showing depositional sequences (1, 2 and 3) and active faults. Note the graben structure caused by the normal faults at both ends of the profile
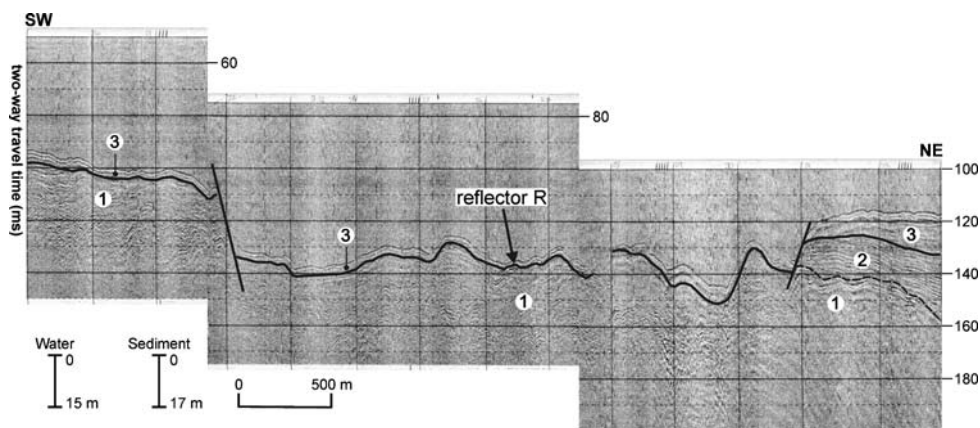
Fig. 14 High-resolution seismic reflection profile (for location see Fig. 3) showing depositional sequences (1, 2 and 3) and active faults. Note sea floor deepening and sediment thickening on the downthrown side of the main active fault. Dot indicates the displacement toward viewer. Cross indicates the displacement away from viewer
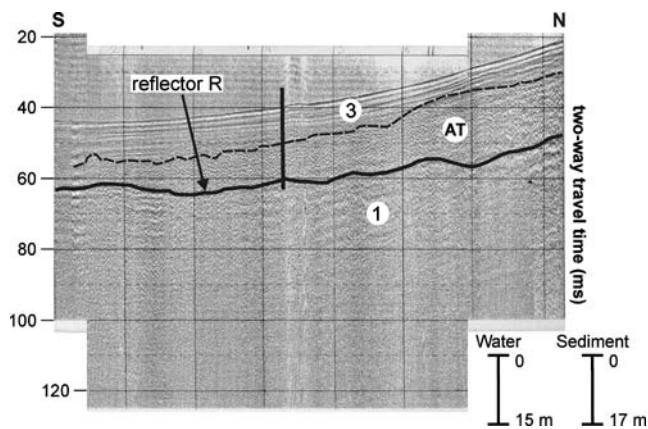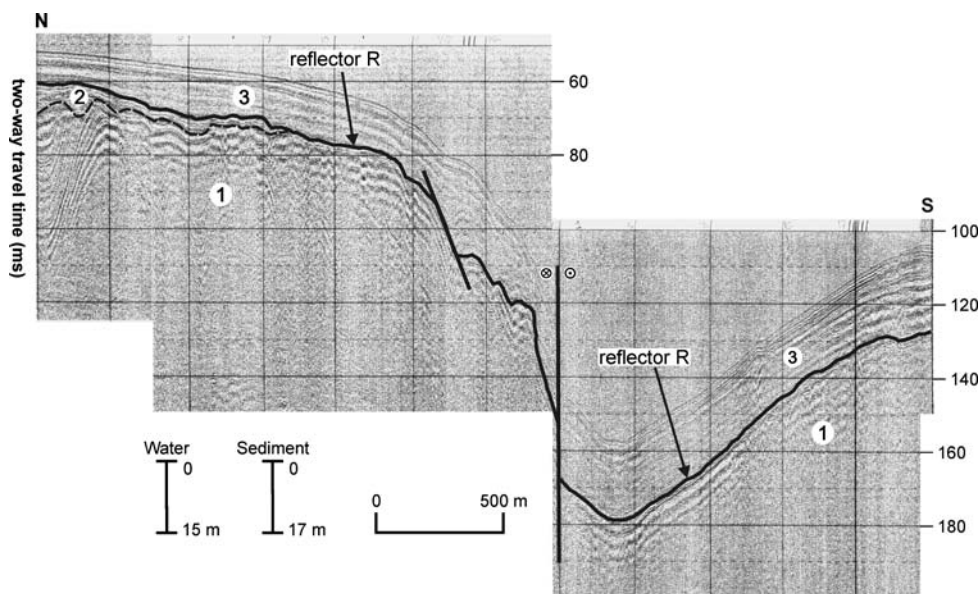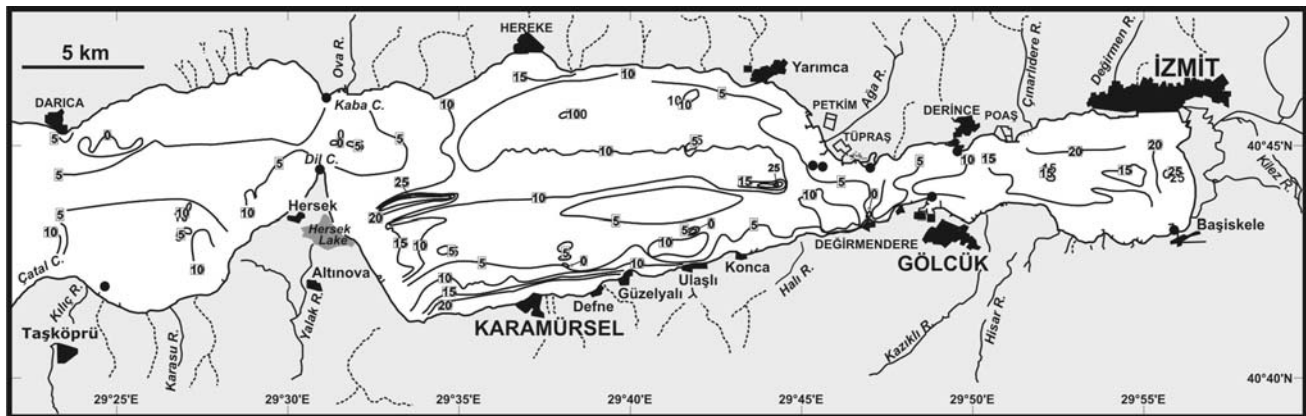
Fig. 15 High-resolution seismic reflection profile (for location see Fig. 3) showing depositional sequences (1 and 3) and fault. Note acoustic turbidity (AT) within the depositional sequence 3

Holocene deposits are missing at some localities in the western and central basins in the İzmit Bay (Fig. 16), due to erosion and or non-deposition. The absence of the Holocene can also be attributed to the presence of steep-dipping fault planes. In these places Sequences 1 or 2 crop out at the sea floor.

Structural setting

The structural setting of the Marmara Sea region is mainly controlled by the right-lateral strike-slip NAF, which was initiated in eastern Turkey between 10 and 13 Ma (Şengör et al. 1985; Hubert-Ferrari et al. 2002) and extended by propagation to the west (Armijo et al. 2002). The fault reached the site of the present Marmara Sea at 5 Ma (Armijo et al. 1999). To the west of 30.5° E, the NAF splays into two main branches that are 100 km apart (Armijo et al. 1999, 2002). The northern branch bounds the southern side of the Gulf of İzmit, outlines the Marmara

thickness of up to 25 m (Fig. 16). Seismic profiles indicate that the thickest sections in the central basin are associated with the downthrown side of the faults (Figs. 10 and 14).

Fig. 16 Isopach map showing the thickness of Holocene sediments (Sequence 3). Contours in meters

pull apart basin, cuts the Dardanelles structure, and marks the southern side of the Saros Gulf (Fig. 1). The İzmit earthquake occurred on that branch, east of the Marmara Sea.

Onshore structural setting

Numerous faults of different types, sizes and ages exist onshore in the vicinity of the Gulf of İzmit (Fig. 5). They are concentrated on the Armutlu rather than the Kocaeli Peninsula. This feature must have been originated from the branching of the NAF in the north and south of the Armutlu Peninsula (Fig. 1).

Of the faults studied, the İzmit-Adapazarı Segment, Gölcük Fault, Yalova Fault, Armutlu Fault, Gemlik Fault and İznik-Geyve Segment were identified as being active, while the Yalakdere Fault, Orhangazi Fault, Adliye Fault and İzmit Fault Zone were interpreted as being inactive (Emre et al. 1997, 1998) (Fig. 5). No active faults have been observed on the northern part of the İzmit Bay.

During the 17 August 1999 İzmit earthquake, the İzmit-Adapazarı Fault segment was completely ruptured, whereas the Gölcük Fault was broken from its eastern end near the Gölcük (Lettis et al. 2002, Barka et al. 2002).

Previously, the Gölcük Fault (Fig. 5) was interpreted as being a normal fault by Bargu and Yüksel (1993) (Fig. 2). However, recently, right-lateral oblique motion was reported by Gökaşan et al. (2001) and Alpar and Yaltırak (2002), who named the Gölcük Fault as "Fault 1 (F1)", and the "Karamürsel Fault", respectively (Fig. 2). Gökaşan et al. (2001) recognised Fault 1 (F1) as a boundary fault that probably developed in the gulf since the basin's initial opening as a pull-apart basin. However, Alpar and Yaltırak (2002) concluded that the Karamürsel Fault was not an extension of the NAF, but was short, dextral synthetic 'P'–shear.

The Yalova Fault (Fig. 5) (the 'Karamürsel Fault' of Bargu and Yüksel (1993), 'Fault 11 (F11)' of Gökaşan

et al. (2001) 'Yalova Fault' of Alpar and Yaltırak (2002)), is interpreted as a right-lateral oblique fault (Fig. 2). According to Bargu and Yüksel (1993), the fault enters the sea from the east of the Yalakdere Delta and extends towards the centre of İzmit Bay (Fig. 2). Gökaşan et al. (2001) also explained a left step-over between the dextral strike slip Fault 11 (F11) and Fault 2 (F2), which may produce a transpressional area, where the Yalakdere and Laledere deltas are present (Fig. 2). Alpar and Yaltırak (2002) interpreted the Yalova Fault in the same way as described above for the Karamürsel Fault and concluded that the Yalova Fault offsets the valleys between the Yalakdere and Laledere deltas in a right-lateral sense (Fig. 2). Eastward, the Yalova Fault can be traced a very short distance into the Marmara Sea (Emre et al. 1997, 1998).

The Armutlu Fault (Fig. 5) is a NE-SW trending right lateral oblique fault (Eisenlohr 1997; Emre et al. 1997, 1998). The South Boundary Fault (SBF of Okay et al. 2000) delineates the southern margin of the North Marmara Fault System (NMFS of Armijo et al. 2002). The South Boundary Fault emerges in the vicinity of Esenköy and joins the Armutlu Fault. Therefore, it can be concluded that the Armutlu Fault may be the onshore continuation of the South Boundary Fault. However, this requires that the Armutlu Fault bifurcates.

The Gemlik Fault and the İznik-Geyve Segment of the NAFZ (Fig. 5) have been transtensionally combined with each other by an en echelon arrangement in the vicinity of the İznik Lake (Emre et al. 1997, 1998). Neotectonic evaluation of the İznik Lake basin as a pull-apart structure has been attributed to this feature (Emre et al. 1997, 1998).

In contrast, the inactive faults mapped in Fig. 5 developed during the late Miocene-Pliocene (Emre et al. 1997). Of these faults, the NW-SE trending Orhangazi Fault has been interpreted as a right lateral oblique fault (Erendil et al. 1991; Barka 1997; Eisenlohr 1997) while the NE-SW
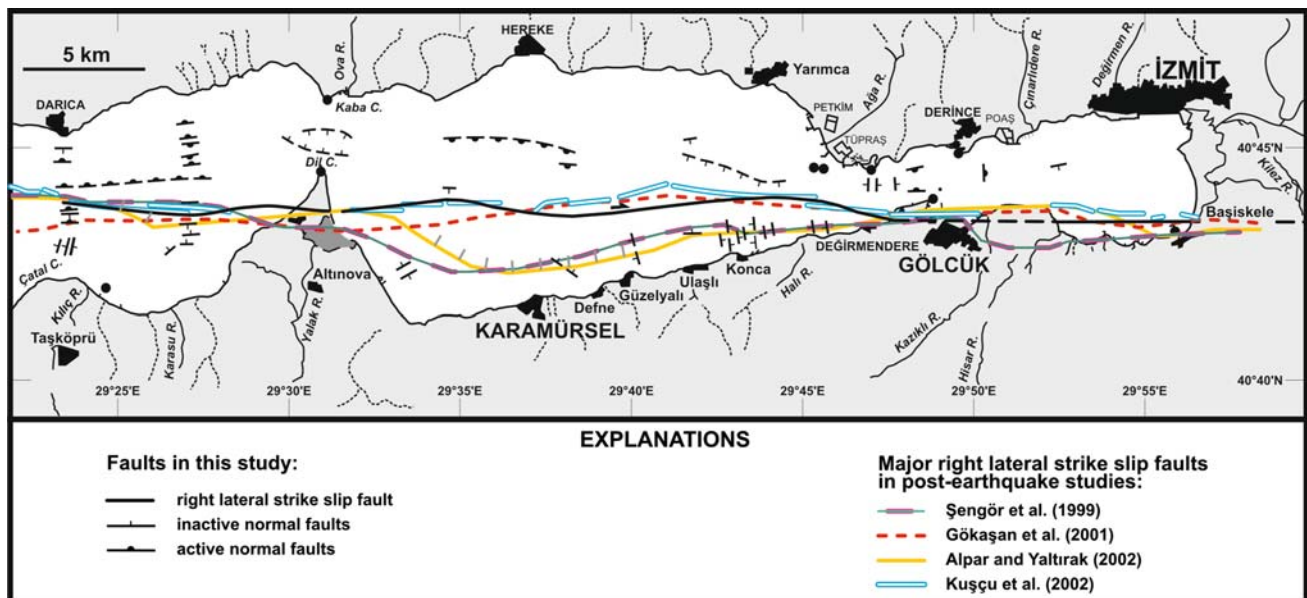
Fig. 17 Map showing the locations of the main right lateral strike slip and normal faults (shown in black) interpreted in this study, and the position of the main right lateral strike slip fault (shown in grey) reported in the literature after the 17 August 1999 İzmit (Kocaeli) Earthquake

trending Yalakdere Fault has been regarded as a sinistral strike-slip fault (Bargu and Sakınç 1990).

Apart from these structures, some small-scale normal faults, striking mostly in a NW-SE direction, were also identified on the western area of the Armutlu Peninsula (Fig. 5). Eisenlohr (1997) stated that these normal faults are younger than the strike-slip faults in the area.

Offshore structural setting

Analysis of high-resolution seismic data (Figs. 7–10 and 12–15) and a review of published data (cf. Özhan et al. 1985; Kavukçu 1990; Bargu and Yüksel 1993; Barka and Kuşçu 1996; Şengör et al. 1999; Gökaşan et al. 2001; Alpar and Yaltırak 2002; Kuşçu et al. 2002) suggest the presence of two distinct faults systems in the İzmit Bay area.

The main fault system extending roughly in an E-W direction along the Gulf of İzmit is a right-lateral strike slip fault with a normal component (Figs. 7, 10 and 14). This fault, deforming the internal structures of the Holocene sequence and/or exposed on the sea floor, is an active fault. The normal component on the main fault is pronounced on the seismic profiles to the east of Hersek Peninsula and the south of Yarımca in the central basin (Figs. 10, 14). On these seismic profiles, the downthrown side is marked by sea floor deepening and/or sediment thickening. The maximum vertical displacement of this fault was calculated to be 28 m on the SE-NW trending seismic lines located to the east of the Hersek Peninsula (Fig. 10).

The secondary faults are normal faults striking in different directions, and their throws are measured to be less than 20 m. Of these, faults affecting the Holocene sequence and/or cropping out on the sea floor were interpreted as active (Figs. 7–9, 13–15), while the others were interpreted as inactive (Fig. 12).

Active normal faulting results in the development of horst and graben structures in the Gulf of İzmit (Fig. 17). In particular, NNW-SSE and NW-SE trending faults concentrated off the coast of Karamürsel and Değirmendere were first identified in this study. For example, a graben structure can be clearly distinguished in seismic profiles (Fig. 13), running parallel to the southern coast. Altınok et al. (1999) stated that coastal slumping at Değirmendere caused about 20 m deepening in the 17 August 1999 İzmit (Kocaeli) Earthquake. Depth changes from 3 m to about 17 m have also been reported. Inactive faults may have formed before the NAF reached the Sea of Marmara (e.g. Emre et al. 1998).

Discussion and conclusions

Stratigraphic interpretations

High-resolution seismic reflection profiles obtained from İzmit Bay reveal the presence of three distinct depositional sequences (1, 2 and 3). These sequences are also encountered in the boreholes.

Sequence 1, the lowermost sequence penetrated by drilling yields early-middle Pleistocene sediments, dated between 693 ± 126 ka and 254 ± 34 ka. These sediments were deposited in marine brackish environmental conditions. Sequence 1 is unconformably overlain by Sequences 2 and 3, and is present throughout the study area.

Sequence 2 includes middle Pleistocene sediments dated between 195 ± 20 and 198 ± 23 ka. Onlap reflection terminations at its base indicate a transgressive depositional evolution. The upper boundary of Sequence 2 (reflector R), is an erosional unconformity, produced by the subaerial erosion of the continental shelves at the last glacial maximum. The maximum thickness of Sequence 2 was 45 m in the basin centre. Although this sequence is missing in some parts of the western and central basin, it is almost completely absent in the eastern basin, probably due either to erosion or non-deposition.

Sequence 3 is the uppermost unit and its sediments were dated as younger than 12.2 ± 1.9 ka. The whole sequence, which is underlain by the pre-Holocene erosional unconformity (reflector R), is inferred to be Holocene in age. On some seismic profiles Sequence 3 contains anomalous reflections (acoustic turbidity, AT) that have been interpreted as representing gas accumulation in the sediments. The maximum thickness of the Holocene (Sequence 3) is found to be about 25 m. In general, the tendency of decreasing thickness of the Holocene toward the western basin is attributed to the decreasing sediment supply from the east to west.

Previous stratigraphic interpretations made by Özhan et al. (1985), Özhan (1986), Bargu and Yüksel (1993), Özhan and Bayrak (1998), and Gökaşan et al. (2001) were mainly based on the analysis of seismic data but were not supported by borehole data. In contrast, the main result of this study is based on the synthesis of the full set of borehole data and the seismic data.

The stratigraphic interpretations of the present study are not consistent with the previous study of Alpar and Yaltırak (2002). In contrast, the stratigraphic interpretations of Kuşçu et al. (2002) are partly compatible with the results of the present study. In their interpretation, Kuşçu et al. (2002) assigned a Holocene age for the upper layers by correlating a single seismic line with boreholes S3 and S7. However, due to the limited penetration on seismic data, the different seismic units below the Holocene were not discriminated and therefore pre-Holocene age proposed for the entire lower sedimentary pile.

The isochron map of Holocene sediments prepared by Bargu and Yüksel (1993) is incomplete (Fig. 2) due to limited seismic data availability. For example, the thickness distribution of the Holocene in the inner (eastern) basin was not mapped in that study. However, in the present study, the whole Gulf of İzmit has been mapped. In addition, a 14 m sec maximum thicknesses of the Holocene calculated by Bargu and Yüksel (1993) (Fig. 2) appears to be rather low compared with the seismic data interpreted for this present study. In particular, higher thickness values than those calculated by Bargu and Yüksel (1993), can be clearly seen on the downthrown sides of the faults in Figs. 10 and 14. Here, the Holocene is up to 30 ms thick. Therefore, the isochron map presented in this study is believed to provide a more accurate representation of the thickness distribution of the Holocene.

Structural Interpretations

Two distinct fault systems are recognized from the seismic data presented in this study. The main fault system extending roughly in an E-W direction along the Gulf of İzmit is interpreted as an active right-lateral strike slip fault with a normal component. Comparisons made between the positions of the main fault, which were mapped in the previous post-earthquake marine seismic studies (e.g. Şengör et al. 1999; Gökaşan et al. 2001; Alpar and Yaltırak 2002; Kuşçu et al. 2002), reveal that the locations defined by Şengör et al. (1999) and Alpar and Yaltırak (2002) are somewhat different than the positions indicated by Gökaşan et al. (2001) and Kuşçu et al. (2002) (Fig. 17). This feature is clearly evident in the mapped positions of the main fault relative to the E-W axis of the central basin of İzmit Bay. In the studies of Gökaşan et al. (2001) and Kuşçu et al (2002), the position of the main fault appears to be aligned approximately east-west, whereas in the studies of Şengör et al. (1999) and Alpar and Yaltırak (2002), the fault bends southward down towards the coast. The main fault position mapped in the present study largely corresponds to the location defined by Gökaşan et al. (2001) and Kuşçu et al. (2002) (Fig. 17).

Transpressive features

It is obvious that the upper Sequence 3 provides evidence concerning the deformations associated with the 1999 İzmit earthquake (Fig. 7–15). While the smooth portions of the unit indicates no recent movements, the highly distorted portions are attributed to nearby recent faulting. Moreover, we notice that the disturbed portions of the cross-sections, where we suggested strike-slip and dip-slip faulting, are mostly limited to a narrow band around the proposed faults (e.g., Fig. 7). However, some cross-sections or parts of cross-sections do not follow this rule (e.g., Fig. 13).

The most striking feature that places the cross-section illustrated in Fig. 13 apart from the others is that Sequence 3 leaves its general smooth undisturbed character and continuous deformational features emerge along the

Fig. 18 The solid lines are the observed and inferred fault ruptures as determined by Cormier et al. (2006). The solid circles are the locations of the aftershocks of the 1999 İzmit earthquake for which focal mechanism are estimated by Nakamura et al. (2002) and Pinar et al. (2008)
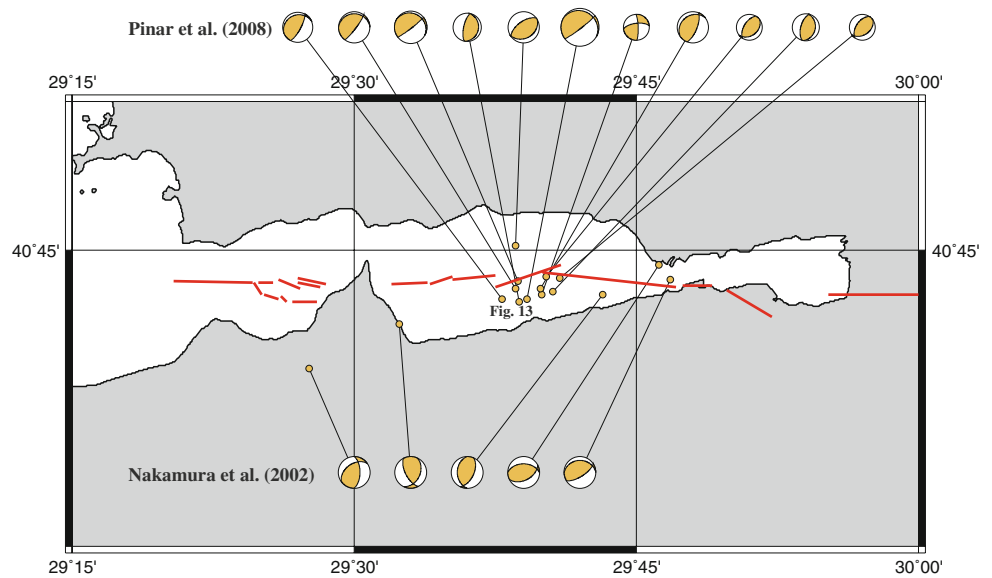
profile. Taking into account the WSW-ENE direction of the profile (Fig. 3) and the compressional deformation pattern within Sequence 3 (Fig. 13) one may claim that the region is experiencing E-W compression. The causes of such compression are a matter of debate.

In addition to the shallow seismic and bathymetry data we investigate the faults surrounding the region where the seismic data of Fig. 13 were collected incorporating seismotectonic data. The faults beneath İzmit Gulf were investigated following the 1999 İzmit earthquake in order to determine the western termination of the ruptures (Şengör et al. 1999; Gökaşan et al. 2001; Alpar and Yaltırak 2002; Kuşçu et al. 2002; Cormier et al. 2006). Figure 17 shows the results of these studies, illustrating the general extension of the North Anatolian fault across the İzmit Gulf. The results of Cormier et al. (2006) are given in Fig. 18. The largest discrepancy in the course of the major fault trace coincides roughly with the site illustrated in Fig. 13 (i.e., in the vicinity of the compressive region). While Şengör et al. (1999) and Alpar and Yaltırak (2002) draw the major fault line parallel to the southern shoreline, Gökaşan et al. (2001), Kuşçu et al. (2002) and Cormier et al. (2006) interpret the fault to run midway between the southern and northern shorelines of the Gulf.

Figure 18 illustrates the major fault trace as deduced by Cormier et al. (2006), the aftershocks located by Ito et al. (2002), the fault plane solutions of the aftershocks determined by Pinar et al. (2008), and the reverse focal mechanisms of the aftershocks derived by Nakamura et al. (2002) in the proximity of the focused area.

We show just a portion of profile in Fig. 13, but the profile extends from the east of Hersek Peninsula to the west of Gölcük (Fig. 3) and we observe the compressional features, similar to those illustrated in Fig. 13 along the entire profile, suggesting that this is not a local feature as suggested by Dolu et al. (2007) and Cormier et al. (2006) but is evident along a segment 20–25 km in length. The focal mechanisms of the aftershocks of the 1999 İzmit earthquake that took place in the proximity of this segment generally show predominantly reverse faulting mechanisms (Nakamura et al. 2002; Pinar et al. 2008) which is additional strong evidence for compression.

However, the major moment release associated with the 1999 İzmit earthquake, as modelled using teleseismic data (Gülen et al. 2002), occurred on fault segments that show predominantly strike-slip faulting. By virtue of the fact that these major segments are onshore it is obvious that the focal mechanism of the 1999 mainshock event may not reflect the pattern of deformation beneath the Gulf of İzmit. This could be simply because the contribution of the seismic moment released on the offshore faults to the total seismic moment should be much lower compared to the onshore fault segments.

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