Natural Hazards **24:** 133–146, 2001.

The Tsunami of August 17, 1999 in Izmit Bay, Turkey

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(Received: 19 June 2000; in final form 20 September 2000

Abstract. The Kocaeli 1999 Earthquake with an Mw = 7.4 caused major hazards throughout the NW of Turkey from Tekirdag to Bolu. Historical data indicates that some of the earthquakes around Izmit Bay have caused tsunamis. In this study, tsunami research for the Kocaeli 1999 Earthquake has been made also taking into consideration historical data. In this research more than about 70 data at 35 localities have been used to determine the tsunami evidences in the bay. Coastal observations indicated runups which were ranging from 1 to 2.5 m along the shores. However, the wave runups are more complex along the south coast due to the presence of coastal landslides (Değirmendere, Halidere, Ulasli, Karamürsel) and subsided areas (Kavakli to Yeniköy) along the shore. West of Yalova, evidence of tsunami rapidly diminished. In addition, possible tectonic mechanism has been determined by using 33 single-channel high-resolution digital seismic reflection profiles which were acquired following the Kocaeli 1999 Earthquake. As a result it has been determined that the Kocaeli Earthquake has created tsunami in Izmit Bay.

Key words: Tsunami, Izmit Bay, Marmara Sea, Coastal Landslides, Slumps

1. Introduction

The North Anatolian Fault Zone (NAFZ) is a major dextral strike-slip fault zone placed along the boundary between the Anatolian micro plate and the larger Eurasian continental block (Figure 1a). Its northern strand passes through Izmit Bay and has been the source of numerous large earthquakes throughout history. In the 20th century, beginning with the 1939 Erzincan Earthquake (Figure 1b), a series of large earthquakes have broken segments of the NAFZ both eastwards and westwards. An earthquake (00:01:39.80 UTC, August 17th 1999) of magnitude Mw = 7.4 occurred on the northern strand of the NAFZ with a macroseismic epicentre near the town of Gölcük (Figure 1c). The earthquake originated at a depth of 17 km and caused right-lateral strike-slip movement on the fault. Hereafter, it will be named as the Kocaeli 1999 Earthquake.

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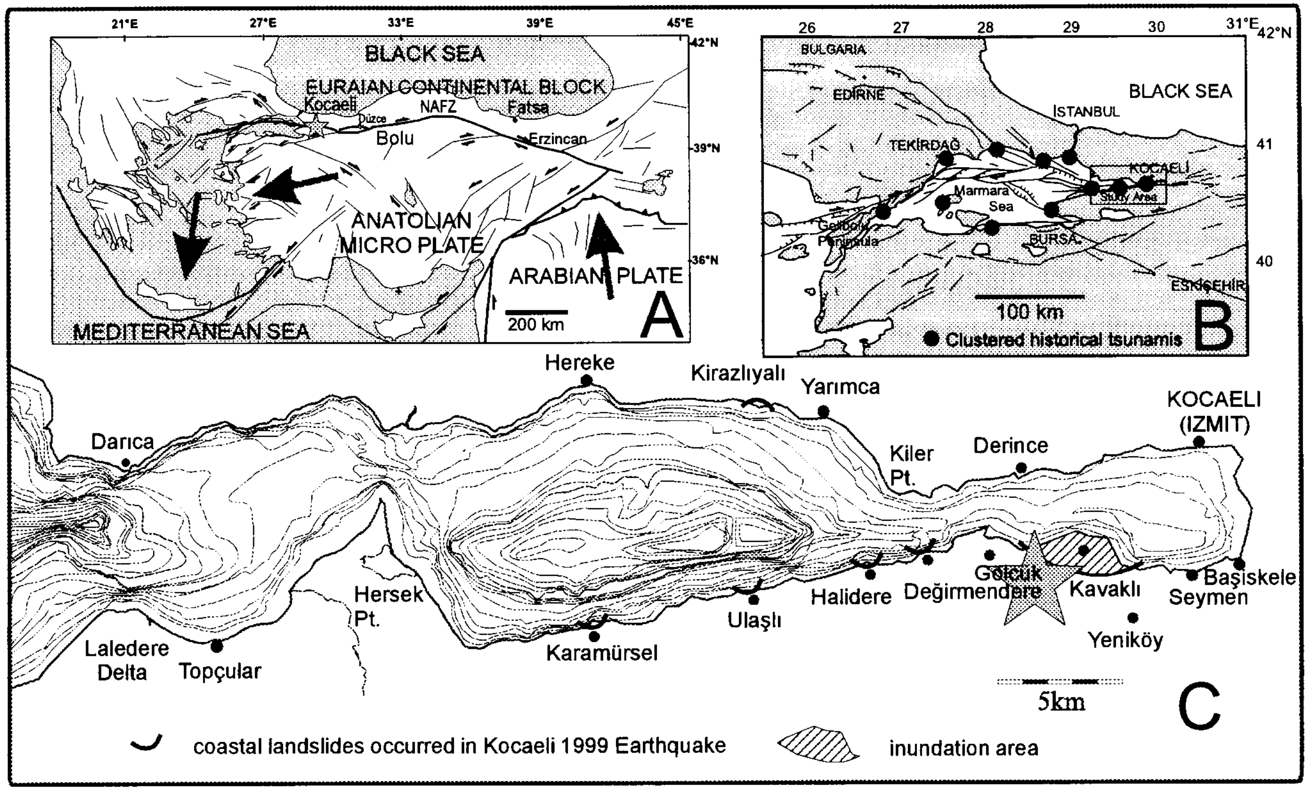

Figure 1. (A) Study area and simplified tectonic map of the Turkey. Solid lines are strike-slip faults with arrows on each side showing direction of motion, ticked lines are normal faults with ticks on the downthrown block and lines with solid triangles are thrust faults with triangles on the overriding block. The large solid arrows show directions of motion of Arabian and Anatolian plates with respect to the African plate. Three strands of the NAF zone are shown. Figure was drawn from Barka and Kadinsky-Cade (1988), Barka (1992). (B) Tectonic setting of the Marmara Sea region (Yaltırak *et al.*, 2000). The cluster of historical tsunamis were superimposed (data from Altınok and Ersoy, 2000). (C) Bathymetric map of Izmit Bay (Güneysu, 1999). The symbol of asterisk shows the epicentre of the Kocaeli 1999 Earthquake.

The field observations indicated that the Kocaeli 1999 Earthquake produced at least 120 km of surface rupture on land and right-lateral offsets as large as 4.2 m with an average of 2.7 m. Most of the damages (more than 17,000 casualties, 25,000 injuries and 75,000 collapsed or heavily damaged buildings) were concentrated within 20 km of Gölcük and ranging from small displacements to complete collapse of coastal structures such as ports, jetties, cranes and piping systems. Subsidence, masses of coastal landslides and the sea water inundation were occurred at Kavakli, Değirmendere, Halidere, Ulasli and Karamürsel (Figure 1c).

1.1. GEOLOGY OF IZMIT BAY

Izmit Bay is an elongated gulf, 53 km long and 2–10 km wide. The sea-floor relief and coastal zone physiography lie in E–W direction. It was formed by three small tectonically active sub-basins; the western, central and eastern basins (Figure 1c). The western sub-basin has a chaotic deep morphology. A ridge formed by the sedimentary deposits transported by the Yalakdere river (Figure 1c) and placed at the Hersek water passage (2.7 km wide with an average depth of 55 m) separates the western and central sub-basins and plays an important role in the oceanographic circulation. The maximum water depth in the central basin is 204 m and it is separated from the eastern sub-basin by another shallow and narrow ridge. The eastern basin is the shallowest and ends with a swampy area.

The basement lithologies in Izmit Bay unconformably overlain by 25–30 m thick Plio-Quaternary deposits mainly composed of fine-grained continental siliclastic material resulting from fluvial and littoral processes. The western basin is also subjected to accumulation of silt-sized sediments (Ergin and Yörük, 1990). The transpressional and transectensional regimes of the NAFZ, which is the best known right-lateral strike-slip transform fault (>1500 km) of the world, affected the region during the neotectonic period (Crampin and Evans, 1986). The sub-basins of Izmit Bay were created by the EW compressional and NS tensional forces due to a response to the kinematical block displacements at active zones (Barka and Kadinsky-Cade, 1988; Barka, 1992). The actual basin-fill deposits in these sub-basins are still under the influence of the northern strand of the NAFZ (Özhan *et al.*, 1985; Sakınç and Bargu, 1989; Seymen, 1995). Barka and Kuşçu (1996) argued that the best structural model for Izmit Bay is a pull-apart model in which strike-slip fault segments (laterally descending towards right) create the tectonic sub-basins of Izmit Bay (Figure 2a). On the contrary, some researchers (Şaroğlu *et al.*, 1992) believe that there is only one main fault which is right lateral along Izmit Bay (Figure 2b) and connected to the Gelibolu Peninsula (Figure 1b) continuously going through the Marmara Sea as proposed by Le Pichon *et al.* (2000).

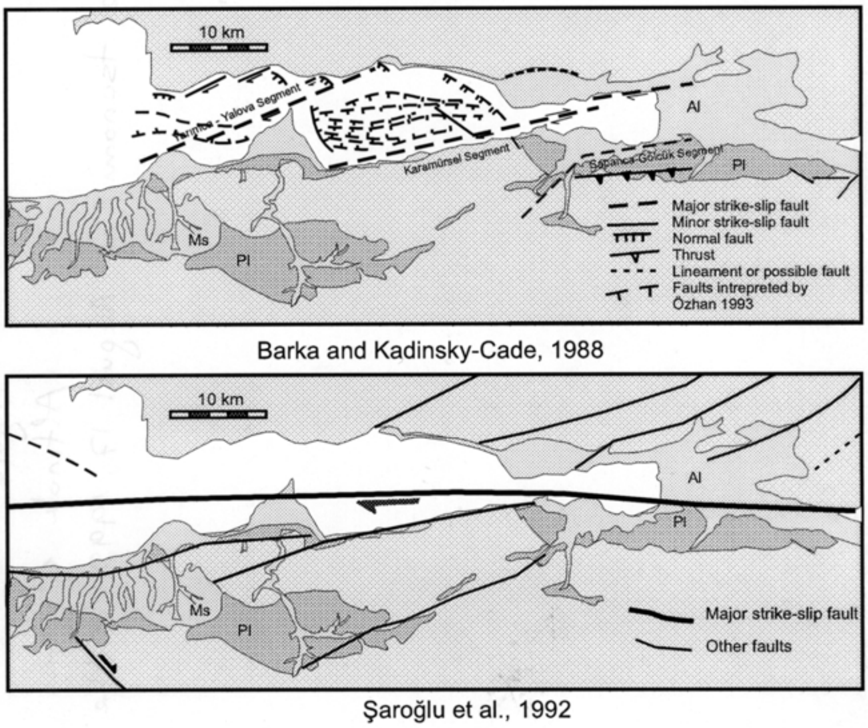

Figure 2. Tectonic models for Izmit Bay (Barka–Kadinsky-Cade, 1988; Şaroğlu *et al.*, 1992).

1.2. HISTORICAL TSUNAMIS

The NAFZ primarily involves horizontal ground displacements, and such tectonic movements do not usually generate tsunamis, in exception of the 1598 Amasya Earthquake-Black Sea tsunami and the 1939 Erzincan Earthquake-Fatsa (Figure 1a) tsunami (Altınok, 1999). However, some of the earthquakes along the western segment of the fault have had vertical ground movements and caused tsunamis. At least 9 major tsunamis have been reported to have occurred in the Marmara Sea in the past (Kuran and Yalçıner, 1993). Many of them were clustered around Izmit Bay, the best known being 325, 24/08/358, 08/11/447, 26/09/488, 15/05/553, 15–16/08/555, 14/12/557, 715, 740, 19/04/1878, 10/05/1878 and 18/09/1963 (Soysal, 1985; Altınok and Ersoy, 2000). The recent tunami occurred following the Kocaeli 1999 Earthquake and caused great waves which have been particularly damaging in Izmit Bay.

2. Tsunami Investigations

Almost all the industrial facilities are located along the coastal area of Izmit Bay which is open to earthquake and tsunami threats. Therefore, the aim of this paper is to describe the Izmit Bay tsunami generated by the Kocaeli 1999 Earthquake

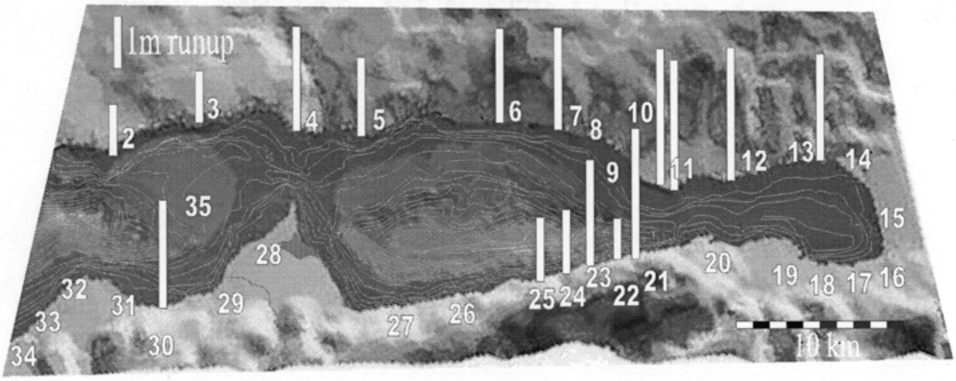

Figure 3. The tsunami runups superimposed on the topography and bathymetry maps of Izmit Bay.

based on onland observations, bathymetry and offshore shallow seismic data. There were regrettably no permanent or temporary tide gauges operated in Izmit Bay. Immediately after the Kocaeli 1999 Earthquake, more than 15 field expeditions have been arranged along the coastal area of Izmit Bay. The surface ruptures were investigated onshore around the bay. Tsunami events have been investigated at 35 localities along the coasts of Izmit Bay and more than 70 eyewitnesses have been interviewed. Some tsunami findings and onland geological observations have been tried to relate with the interpretation of the single-channel high-resolution digital (sampling rate 0.25 ms) sparker (1.25 kJ) seismic reflection profiles with which the sedimentary deposits were cleared up to 150 m below the seabed. Available literature on the bathymetry and neotectonic studies have also been re- evaluated. It has been examined some available tectonic models with which the Izmit Bay tsunami can be explained.

2.1. TSUNAMI OBSERVATIONS

All of the coastal line of Izmit Bay has been investigated for tsunami. The findings that help to detect the tsunami can be generally defined as retreat and inundation of the sea, maximum and minimum sea level elevations and runup heights (Table 1). Some of the important and reliable data observed at sea or from land are given below. See Figure 3 and Table 1 for localities written in parenthesis.

Dilovası Port (4): At the onset of the earthquake, 1998 gross ton tanker '*Nazan*' with a draft of 4.5 m, along with the other ships (Greek *Empros* and Turkish *Bora Mete*) first fell down and then uplifted (within the range of ∼3 m).

Table I. Some samples from tsunami observations in Izmit Bay. The asterisk stands for the locations where tsunami occurred but not described sufficiently

No.	Locality	Receding distance (m)	Inundation distance (m)	Minimum elevation (m)	Maximum elevation (m)	Runup (m)
2	Darıca		4			>1
3	Eskihisar		15			>1
4	Dilovasi			3	2–2.5	2
5	Tavşancıl	*	25–30			1.5
6	Hereke		30			1.80
7	Şirinyali		15			>2
8	Kirazliyali		*			2.5
9	Yarımca	15–20	>60			2.5
10	Körfez		100			
11	Kiler Point		20			2.5
12	Derince Port			*	*?	2–2.5
13	Çene Suyu	80	60			2?
14	Izmit, Marina	40	25			
17	Seymen	2?	50			
19	Kavakli		300?			
21	Değirmendere	150?	35?		>10	2.5
22	Halidere	15	60	1.5		0.8
23	Ulasli		>5			2
24	Güzelyali	10–15	4			1.25
25	Defne Mahallesi	*	4			1.5
26	Karamürsel	*	*			
27	Kaytazdere		15?			
28	Hersek		>30			
29	Havuzdere	*?	*			
30	Topçular	*	*?			2?
35	Offshore Topçular			30 ?	30 ?	

Tavşancıl (5): Water in the local port withdrew during the earthquake. In a very short period of time, the sea came back and flooded up to 25 m inland inundating the first floor of the houses.

Şirinyah (7): The first floors within 5 m to the sea were flooded. The wave carried the seabed material such as live mussels into the houses damaging their doors and windows.

Yarımca Yachting Club (9): The sea first receded 15–20 m and when it came back, uplifted the motor yacht 25 m and moved it 50 m. The second wave inundated 30 m of the shore, ripped off the iron entrance door of of the yachting club, sweeping it along the coastal line for about 70 m.

Derince Port (12): The main cranes went off their rails due to horizontal and vertical movement of a caisson up to 40 cm. Two tugboats (1501 and 1503), boarding alongside a ship which was moored to the port, first dived on their bows as result of the withdrawal and then were uplifted 2–2.5 m. While the boat '*Körfez-1*' was mooring a fishing wharf at Körfez (locality 10 in Figure 3) at around 03:00 a.m. that night, the captain experienced that the boat bottom touched the sea floor and boat drifted back to the sea. In less than half a minute, the boat rose with the rising water and drifted towards the fishing wharf. The captain rescued the boat by reversing his engine on maximum revolutions.

The fisherman's cottage at Çene Suyu, Izmit (13): A fisherman sitting by the coast claimed that the sea receded by about 30 m following the earthquake and then a giant wave rushed in, and after totally destroying the jetty pulled him into the sea. Finally, he climbed on board a boat floating nearly and observed that the sea receding again for about 20 to 30 m was thrown back to its original position by a second wave.

Izmit Marina (14): The sea receded about 40 m and passing down the seaport, thoroughly wetted the coast. The moored boats fell down for 2 m.

Seymen (17): Between the eastern part of the bay, where the fault rupture enters into the sea, and Seymen at the southern part, small disturbances, coming from northwest (Yalçiner *et al.*, 1999), were observed.

Yeniköy (18): A platform floating 150 m off the coast was found to be thrown on the coastal band following the earthquake.

Kavakli (19): There was no any apparent proof about the tsunami evidence at Kavakli, because a devastating subsidence caused sea water inundation.

Değirmendere (21): The passenger ship '*Atatürk*' (375 gross tons and 50 m in length) had been moored to the Değirmendere wharf and the fishing boat '*Kırcıllıoğlu-4*' (300 gross tons and 36 m length) was boarding alongside '*Atatürk*'. The captain of the '*Atatürk*' stated that he was woken up by a knocking sound coming under the ship a few minutes before the earthquake. This is highly possibly a small earthquake (highly possibly a foreshock) just occurred a few minutes before the main shock at the same location (Figure 4). Then sea receded, the wharf collapsed, both vessels were drifted with the receding sea thrown back about 150 m and lifted up with a proceeding great wave. The captain of the fishing boat '*Abonoz*'

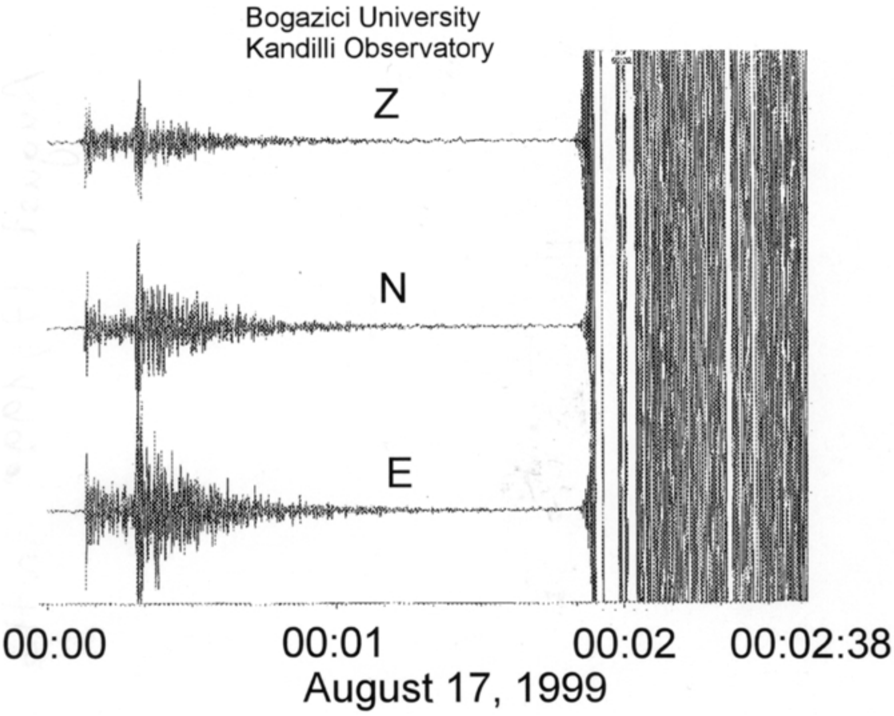

Figure 4. A foreshock awakened the captain two minutes before the main shock. Courtesy Kandilli Observatory and Earthquake Research Institute of Turkey.

which was near '*Atatürk*' and '*Kırcıllıoğlu-4*' reported that '*Kırcıllıoğlu-4*' was uplifted as high as a plane tree (more than 10 m) with the sea rise. The fishing boat '*Kırcıllıoğlu- 4*' uplifted two times above the '*Atatürk*' ship and then sank. A man who was awake at that moment and was watching the sea while sitting in his 5th floor balcony in Değirmendere felt a slight tremor for a very short period of time before the great earthquake. Later, he observed that the sea receded for about 150 m before the main shock and noted the advent of a great wave with the occurrence of the earthquake. He claimed that the wave was equal to the height of an plane tree about 12 m. Observations indicated that the sea, when it came back, flooded up to 35 m inland since some mussel and dead fish were seen in this inundation area. There was a subsidence along the coastline 250 m along the shore and 70 m wide. Two piers, a hotel, a restaurant, a cafe and 14 trees at Çınarlık Park were swept away to the sea. Bubbles were seen over the sea just after the earthquake.

Halidere Pier (22): The sea receded 10–15 m and then flooded up to 50 m inland where moss and jelly fish have been observed. '*Tatlısu*' ship (349 gross tons and with a drift of 4 m) fell down more than 1 m below the pier, hit the bottom, her shaft and propeller were damaged and ropes were broken off.

Ulasli (23): The sea first receded and inundated more than 5 m. The wave dragged 7 people near the seaside and only 2 of them have survived. The Ulasli Municipality building and the restaurants along the coast sank into the sea together with cars, construction equipment and boats taken away by the sea. At the Ulasli local port, the ship '*Kırat*' broke her ropes off and fell down below the pier and uplifted above its previous level.

Güzelyali (24): At the onset of the earthquake, the sea outside the breakwater, rose up and then withdrew and boats were stranded. When the sea came back, the inundation distance was about 5 m.

Karamürsel (26): The sea receded first and then inundated the shore. There was a coastal subsidence (20 m) along the 800 m coastline.

Topçular (30): The sea first receded a very short period of time before the main shock. A sailor in a boat tied to the jetty observed that the wave lifted the ship and heard the 'mayday' signals of the '*Okmeydanı*' ferryboat on his wireless.

Aksa Factory (31): Moss and dead fish were found along the 70–100 m coastal band of the Laledere (or Kilic) Delta (Figure 1c), showing inundation. A 60 square meter platform 750 m away from the coast completely vanished. It was later found in a depth of 25 m in the seabed. Tsunami findings became gradually weaker towards Yalova (locality 33).

Offshore experiences (35): Meanwhile the ferryboat '*Okmeydanı*' was sailing with a 10-knot speed from Topçular to Eskihisar (localities 30 and 3 in Figure 3), 2.6 miles away from Topçular, at the locality 35 (Figure 3) where the water depth was 90 m. The ferry fell down with the sea and the captain suddenly observed with a wave having a 30 to 40 m height about 100 m away from bow. He then saw that the wave wall progressed towards Eskihisar (offshore Topçular in Table 1).

According to the eyewitness reports, the runup and inundation measurements, the period of the tsunami was less than one minute. The arrival time was a few minutes on the northern coasts and one minute or so on the southern coasts (see also Yalçiner *et al.*, 1999).

2.2. UNDERWATER EVIDENCES (SEISMIC DATA)

The northern margins of Izmit Bay are steep and the basins are asymmetric in geometry (Güneysu, 1999). Surface-breaking faults caused some bathymetric changes. Interviewed divers reported that sea deepened from 3 m to about 17 m in front of the building of the Ulasli Municipality. On the other hand, masses of coastal landslides at Değirmendere caused about 20 m deepening.

Seismic data present two main stratigraphic sequences (Figure 5). The upper stratigraphic units are less deformed while the basement units are deformed by faulting and folding. The upper units are generally unconformable on the lower ones or the basement. They are thickest in the deepest part of the graben and gradually thinning southward. This reveals intervening hydrodynamic and tectonic conditions during late Quaternary.

Comparing to the well-known slumps placed on the continental slope of the eastern Marmara basin where the average slopes are 10.8 ± 2.6° and 9.7 ± 1.9° for northern and southern margins, respectively (Alpar and Yaltırak, 2000), there are very rare slumps in the western and central basins of Izmit Bay. The silt/clay ratio is lowest in the eastern Marmara basin showing low-energy conditions and the sedimentation (^{210}Pb) rate is about 1 mm/a (Evans *et al.*, 1989; Ergin and Bodur, 1999). However, the deposition rate in Izmit Bay is much lower than that in the Marmara Sea; in the order of 0.25 mm/a (Ergin and Yörük, 1990). This may indicate, in Izmit Bay, underwater slumping may not be easily developed, but sediment progression is more important, as indicated by the deltaic successions along the southern coast.

The main offshore fault activated by the Kocaeli 1999 Earthquake is a west trending single dextral strike-slip fault at the westward prolongation of the Sapanca-Gölcük segment observed on land (Figure 5). It parallels the coasts of Seymen, Kavaklı, Gölcük and Değirmendere, where large areas subsided and extensive parts of Gölcük and Değirmendere were permanently inundated. The maximum displacement on the master fault is 4.1 m in Gölcük (Emre *et al.*, 2000). The master fault passed under the Hersek Delta (with 0.6–1 m lateral displacement) without giving any surface rupture on the delta (Alpar *et al.*, 1999). It lost its activity somewhere in the western basin. Due to the releasing mechanism caused by the bending of the master fault northward, small scale en echelon fracture zones were observed along the southern margins of the central and western basins. Such a fault geometry indicates that Izmit Bay constitutes a negative flower structure controlled by a west trending dextral master fault. The small basins of Izmit Bay were opened above the master fault.

2.3. RUPTURES ALONG THE COASTAL AREA

Beyond subsidence, coastal landslides and the sea water inundation, some surface-breaking ruptures, two of them most important, were observed on land (Figure 5). The first and most important rupture is placed at Kavakli (Gölcük). It is 3.2 km long and strikes N60W. It is an oblique normal fault. The north block of the faulting blocks has been downthrown 2 m on average, submerging into the sea. Its secondary component is strike-slip and about 0.5 m with maximum of 1 m (Altınok *et al.*, 1999).

The second one is a normal fault striking N80W at Kiler Point near the shore (locality 11, Figure 1c, Figure 5). It has also a strike-slip component of about 10

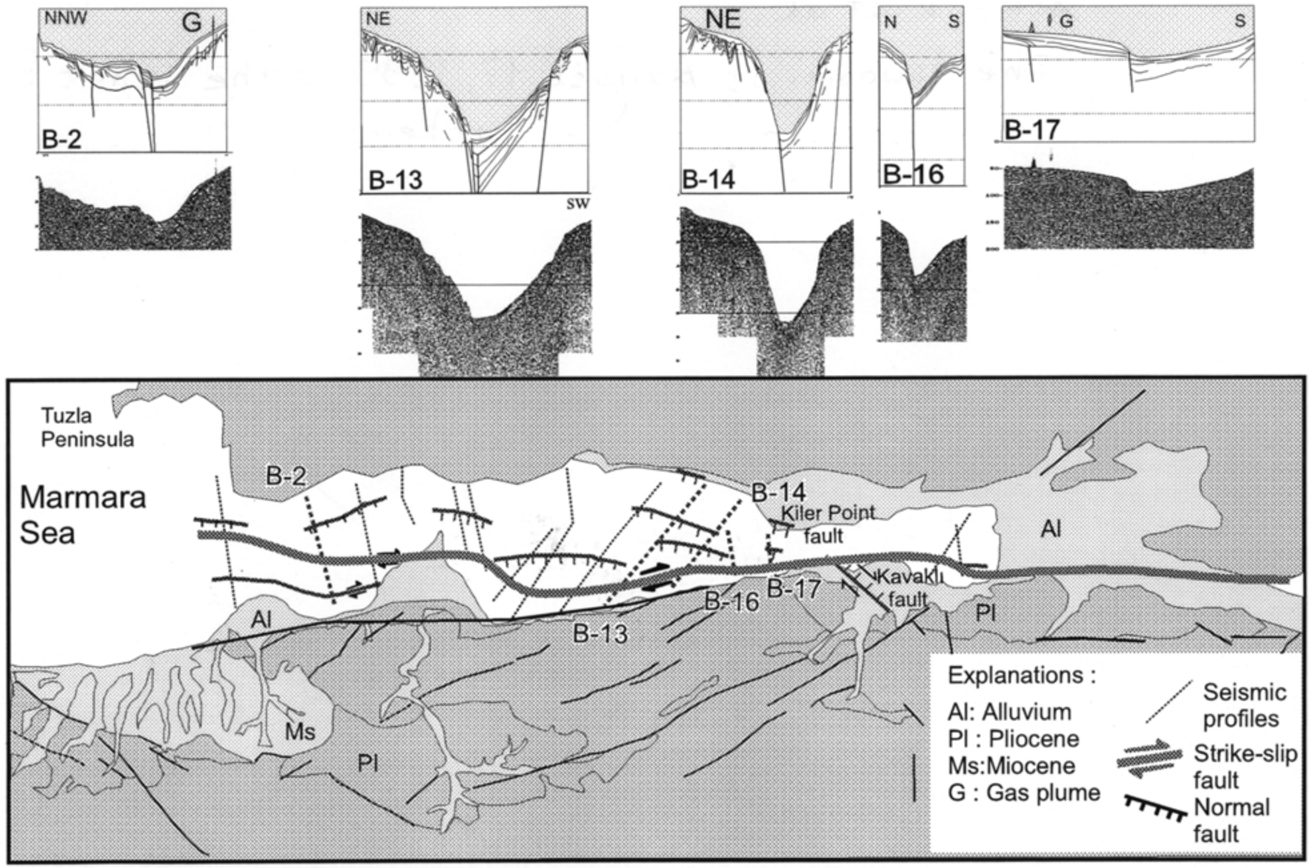

Figure 5. Some seismic sections and their interpreted line drawings. The EW trending continuous thick line, which underlies the Hersek Delta and continues westward, presents the right-lateral main surface rupture of the Kocaeli 1999 Earthquake.

cm. This fault plunges into the sea at both ends. The distance between two ends is about 200 m. The width of the fractures ranges between 0.1–1 m (Altınok *et al.*, 1999). The gas plumes coming from the recent sediments as recorded on the northern end of Line B17 (Figure 5) indicate compressional forces in front of the Kiler Point fault. Beyond the normal faults observed on seabed, both these faults on land imply that vertical movements occurred during the Kocaeli 1999 Earthquake.

3. Conclusion

Izmit Bay is a tectonically active depositional area. Seismic reflection profiles indicate that the sub-basins in the bay are asymmetric, northern margins being steeper. This asymmetric geometry is a result of half graben formation. The less deformed upper seismic units, which are unconformable on the deformed basement, bear occasional slumps. However, there are not direct evidence if they were triggered by the recent earthquake.

The main offshore fault activated by the Kocaeli 1999 Earthquake is an EW-trending single fault lying as a westward extension of the Sapanca-Gölcük segment. This major fault crossed Seymen, Kavakli, Gölcük and Değirmendere shores, causing coastal landslides. It sneaked under the Hersek Delta and lost its activity somewhere in the Çınarcık Basin (Figure 2). In addition to the right lateral main fault, some small-scale normal faults, having strike-slip components, were also ruptured mostly under the control of the main fault. Some of these normal faults are placed in the middle of the central basin (Figure 5). They caused the Izmit Bay tsunami together with the main fault. Meanwhile, the others are placed at some localities along the northeastern and southeastern coasts (between Yarimca and Derince, Kiler Point in front of an oil refinery and Kavakli in front of the Ford car factory) and possibly made tsunami waves more complicated. The dip-slip characteristic of the Kavakli and Kiler Point faults indicate a NNE-SSW trending extension (Figure 5).

Accompanying to the faulting events observed on land and recorded at sea, a few coastal subsidence and landslide events (Kavakli, Gölcük naval base and some urban centres such as Değirmendere, Ulasli and Karamürsel) occurred. These events are not due to the Izmit tsunami but the result of the tectonic deformation (flower structure) of the NAFZ. However, these events possibly made tsunami waves more destructive and related wave motions caused deaths along the southern coasts.

Even it was the small hours (03:02 a.m.), dragged people and objects, sunk or wrecked boats readily showed that the Kocaeli 1999 Earthquake generated tsunami. The most prominent evidence of the tsunami is the sea receding during the earthquake at both sides of the bay. Field observations indicated a maximum runup of 2.5 m.

Since the period of the tsunami is less than one minute and the tsunami reached the northern coasts a few minutes later than the southern coasts, the centre line of the tsunami source is lying along the central basin of Izmit Bay closer to the southern coast (Figure 5). It is highly possible that this line follows the deepest parts of the sub-basins.

This tsunami possibly may not be a well developed one. This is due to the surface-breaking faults of this earthquake was within the semi-enclosed Izmit Bay basin forming a limited marine area. Furthermore, as secondary effects, coastal subsidence, landslides and ground liquefaction, even they are not the main triggering factors of this tsunami, possibly made tsunami waves more complicated and destructive.

As a consequence, the cause of the Izmit tsunami was tectonic. Its origin was on the E–W trending tectonic deformation along the basin closer to the southern coast. The tsunami waves possibly became more complicated by sudden local subsidences along the coastal areas.

Acknowledgements

This study was partly supported by the University of Istanbul, Research Funds (1268/050599 and B-369/21032000). The authors wish to thank to Dr. C. Synolakis from the University of South California, USA and Dr. F. Imamura from Tohoku University, Japan. The authors wish also to express their sincere thanks to Dr. E. Doğan for his financial support, and also to the officers and crew of the research vessel *R/V Arar* for their care and effort during seismic data acquisition. We thank Cem Gazioglu for generously supporting us on computational matters during topographic data mapping. We also thank the B.Ü. Kandilli Observatory and Dr. Ali Pinar for earthquake data and Dr. Timur Ustaömer and Mr. Erdal Herece for their kind help in the field.

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