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ORIGINAL

Evidence for active faults in Küçükçekmece Lagoon (Marmara Sea, Turkey), inferred from high-resolution seismic data

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Abstract A total of 42 km of high-resolution seismic reflection and bathymetric data were collected for the first time to document stratigraphic and structural features of the uppermost 5 m of the Holocene sedimentary infill of Küçükçekmece Lagoon along the Marmara Sea coast of Turkey. The lagoon gradually deepens from 1 m off the northern coast to a maximum of 20 m in the southern basin. Stratigraphically, the uppermost seismic unit is characterized by a generally parallel reflection configuration, indicating deposition under low-energy conditions. In the southern basin of the lagoon, the sub-bottom is locally characterized by frequency attenuated and chaotic reflections interpreted as gas-charged sediments. Structurally, the soft sediment of the first 5 m below the lagoon floor is locally deformed by active strike-slip fault zones, here named FZ1, FZ2, and FZ3. These fault zones are NW–SE oriented and follow the long axis of the lagoon, compatible with the geographic alignment of the lagoon, the onland drainage pattern, and the scarps of the surrounding terrain. Moreover, the fault zones in Küçükçekmece Lagoon are well correlated with active offshore faults mapped during previous studies. This suggests that the FZ1, FZ2, and FZ3 fault zones are not merely local fault systems deforming the Küçükçekmece Lagoon bottom, but that they may be part of a regional fault zone extending both north and southward to merge with the northern branch of the North Anatolian Fault Zone (NAFZ) in the Çınarcık Basin. This, however, needs to be confirmed by further structural and seismological studies around Küçükçekmece Lagoon in order to more firmly establish its link with the NAFZ in the Marmara Sea, and to highlight potential seismic risks for the densely populated Istanbul metropolitan area.

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Introduction

Küçükçekmece Lagoon is located along the northern Marmara Sea coast of Turkey about 10 km north of the North Anatolian Fault Zone (NAFZ), which extends from the Karlıova region (east Anatolia) to İzmit Bay (west Anatolia), and from the Çınarcık Basin to the Gulf of Saros in the Marmara Sea (Fig. 1). The lagoon is connected to the Marmara Sea by a narrow channel, as a result of which the water body is slightly brackish. It covers an area of 16 km^2 and is fed by the Sazlidere, Eşkinoz and Nakkaşdere streams (Figs. 1, 2). The study area plays an important role in understanding the hazard risk of the Istanbul metropolitan area and the densely populated Avcılar district, which was badly damaged and suffered numerous casualties during the 17 August 1999 İzmit earthquake, despite its distance of approximately 105 km from the epicenter. The reason for the large impact of the İzmit earthquake on the Avcılar district is still unclear and hence subject of intense discussion (e.g., Aksu et al. 2000; Gürbüz et al. 2000; Siyako et al. 2000; İmren et al. 2001; Le Pichon et al. 2001; Yaltırak 2002; Yaltırak and Alpar 2002; Gökaşan et al. 2002, 2003). Furthermore, the potential risk of tsunami activity in the northern Marmara Sea has recently been highlighted by Özeren et al. (2010).

To unravel the structural framework of the Marmara Sea region, research is at present more strongly focused on the Marmara Sea itself, especially in and around the main basins, rather than on the surrounding land area. Pınar (1942) was the first to propose the existence of an E–W-trending major fault in the Marmara Sea. Since that time, many tectonic models have been devised to explain the geological evolution of the NAFZ in the Marmara Sea. Some authors have suggested that the northern branch of the NAFZ extends into the Marmara Sea as a single shear zone (Pınar 1942; Şengör 1979; Şengör

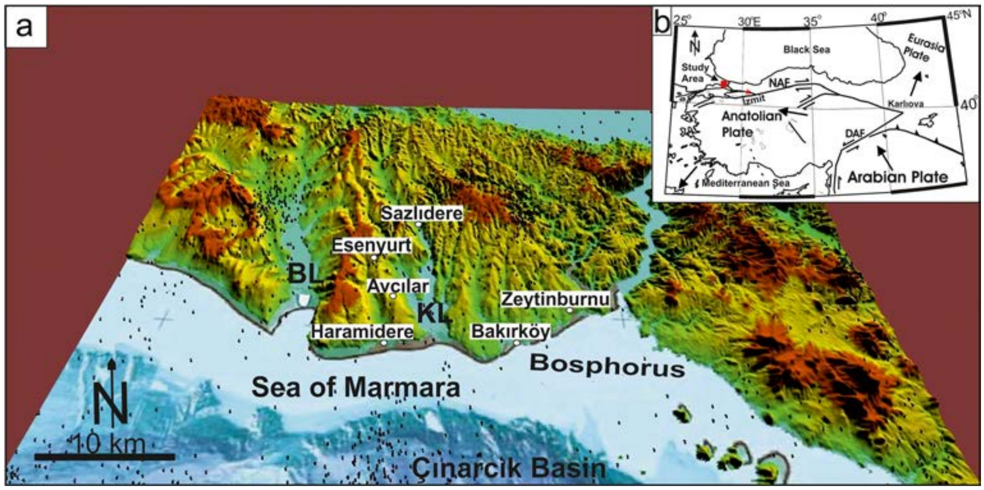

Fig. 1 **a** Map of the study area showing bathymetry, 3D morphology and seismicity (1976–2013 M>2 (*dots*, ISC 2011). The three-dimensional morphology was produced from the SRTM4 data set (cf. Farr and Kobrick 2000), whereas the bathymetric data were extracted from Armijo et al. (2005). **b** Tectonic framework of Anatolia

et al. 1985), whereas others argued that the area is dissected by an E–W-trending graben structure (Ketin 1968; Smith et al. 1995).

The NAFZ in this region has also been considered to represent a combination of en-echelon strike-slip faults and pull-apart basins (Barka and Kadinsky-Cade 1988; Barka 1992; Ergün and Özel 1995; Wong et al. 1995; Armijo et al. 1999). Although the detailed geometry of the New Marmara Fault (NMF) is still being controversially discussed, most authors agree that its western part is represented by an active ENE–WSW-oriented fault extending from the Ganos Mountains to the area offshore of Büyükçekmece Lagoon along the western part of the Marmara Trough (Okay et al. 1999, 2000; Aksu et al. 2000; Gürbüz et al. 2000; Siyako et al. 2000; İmren et al. 2001; Le Pichon et al. 2001; Yaltırak 2002; Yaltırak and Alpar 2002; Gazioğlu et al. 2002; Gökaşan et al. 2002, 2003; Yılmaz et al. 2010). To date, most of these investigations have assumed that the NAFZ does not exist north of the Marmara Trough. However, Gökaşan et al. (2002) identified several NW–SE-striking dextral lineaments in the onland geomorphology, as well as NW–SE-directed strike-slip faults on high-resolution seismic data from the shelf off the Büyükçekmece and Küçükçekmece lagoons, suggesting that these faults are northwestern extensions of the NAFZ rupture along the northern slope of the Çınarcık Basin. Ergintav et al. (2011) mapped some normal faults and NW–SE-oriented strike-slip faults at the entrance of Büyükçekmece Lagoon on the basis of single-channel seismics. Moreover, active faults have been observed on the Istanbul (Thrace) and Kocaeli peninsulas north of the Marmara Sea (Gökaşan et al. 1997; Koral 1998; Demirbağ et al. 1999; Oktay et al. 2002; Dalgıç 2004; Şen 2007), and Şen (2007) also identified two groups of terrestrial faults within the study area, i.e., the now inactive Çatalca Fault Zone (the continuation of the West Black Sea Fault) and several faults near Avcılar. Moreover, seismological records (Gürbüz et al. 2000; Dalgıç 2004; ISC 2011) show evidence of microseismic activity on these peninsulas, particularly around the Küçükçekmece and Büyükçekmece lagoons (seismicity of magnitude >2 on the Richter scale, Fig. 1a). Indeed, Öztin (1994) discusses a historical record of a major surface rupture that apparently occurred along the Avcılar shoreline in 1894.

Within this general context, and using high-resolution seismic reflection and bathymetric data, the present study investigates the possible existence of active faults in Küçükçekmece Lagoon, and any relationship these may have

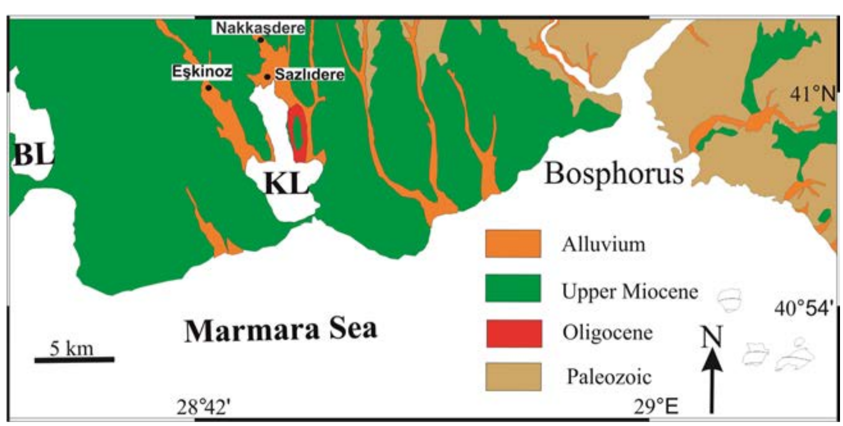

Fig. 2 Geological map of the study area. *KL* Kücükçekmece Lagoon, *BL* Büyükçekmece Lagoon

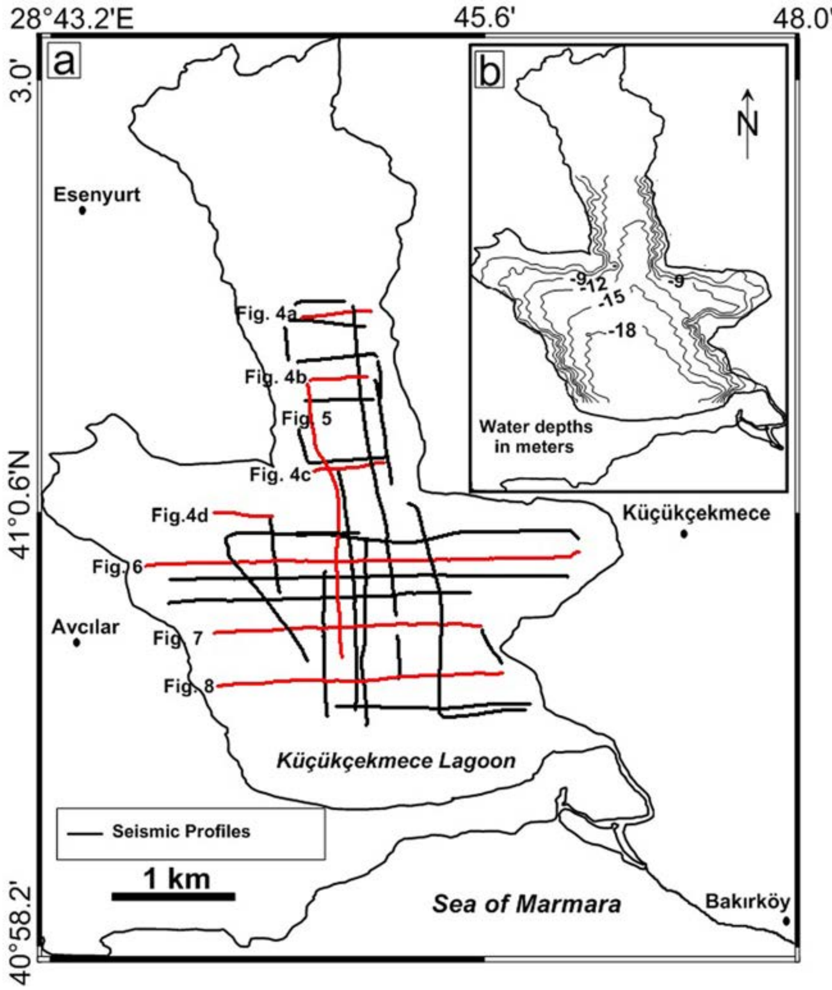

Fig. 3 **a** Location of seismic profiles. **b** Bathymetry of Küçükçekmece Lagoon (depths in meters)

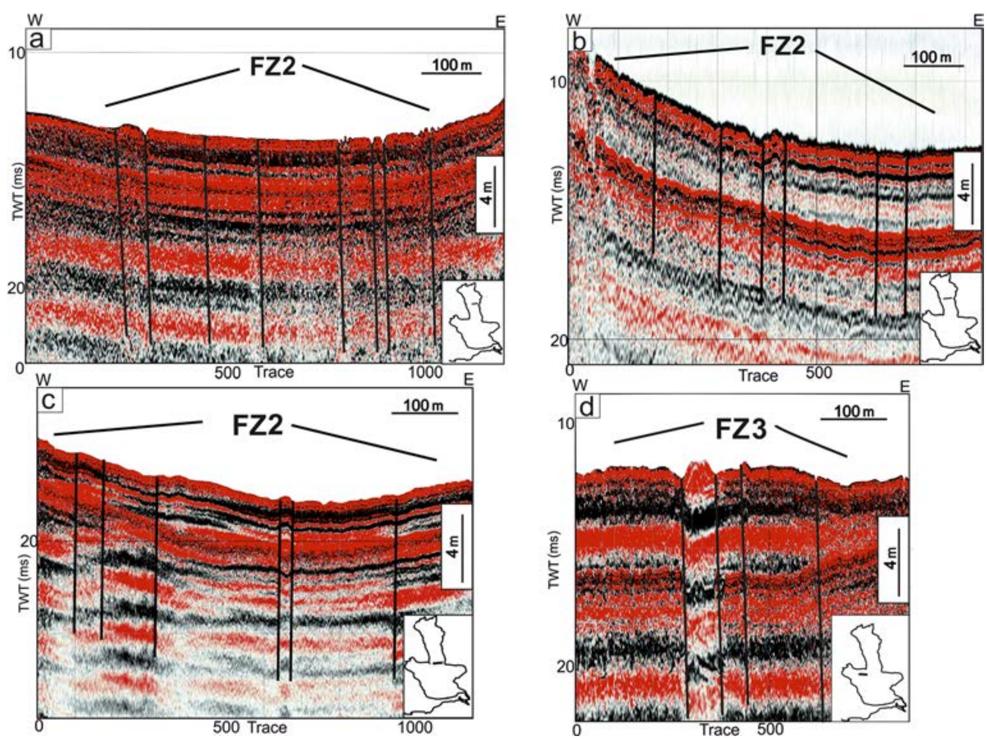

Fig. 4 Active FZ2 (**a**–**c**) and FZ3 (**d**) fault zones identified on seismic profiles from the northern and western parts of the lagoon, respectively

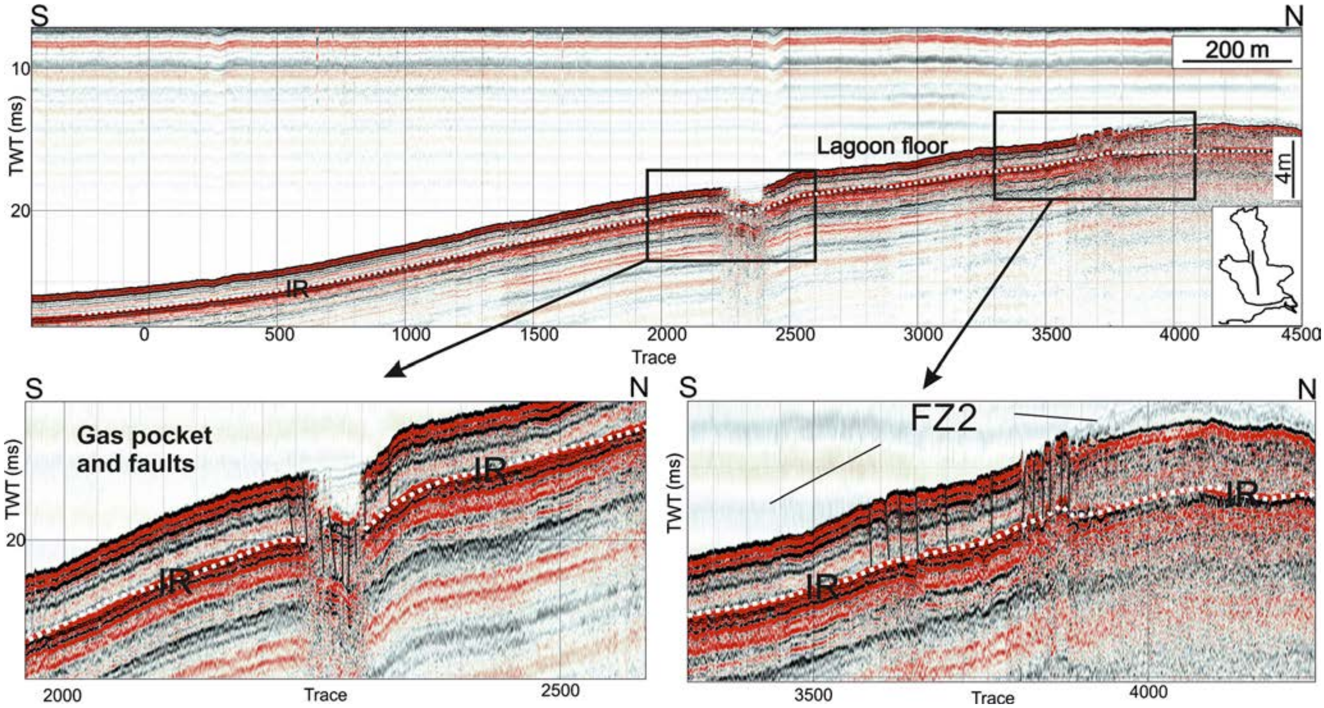

Fig. 5 N–S-oriented seismic profile from the western lagoon area showing the location of probable gas pockets in relation to the FZ2 active fault zone. From the white dashed line (*IR*) downward, the internal sedimentary structures are masked by reverberation sections

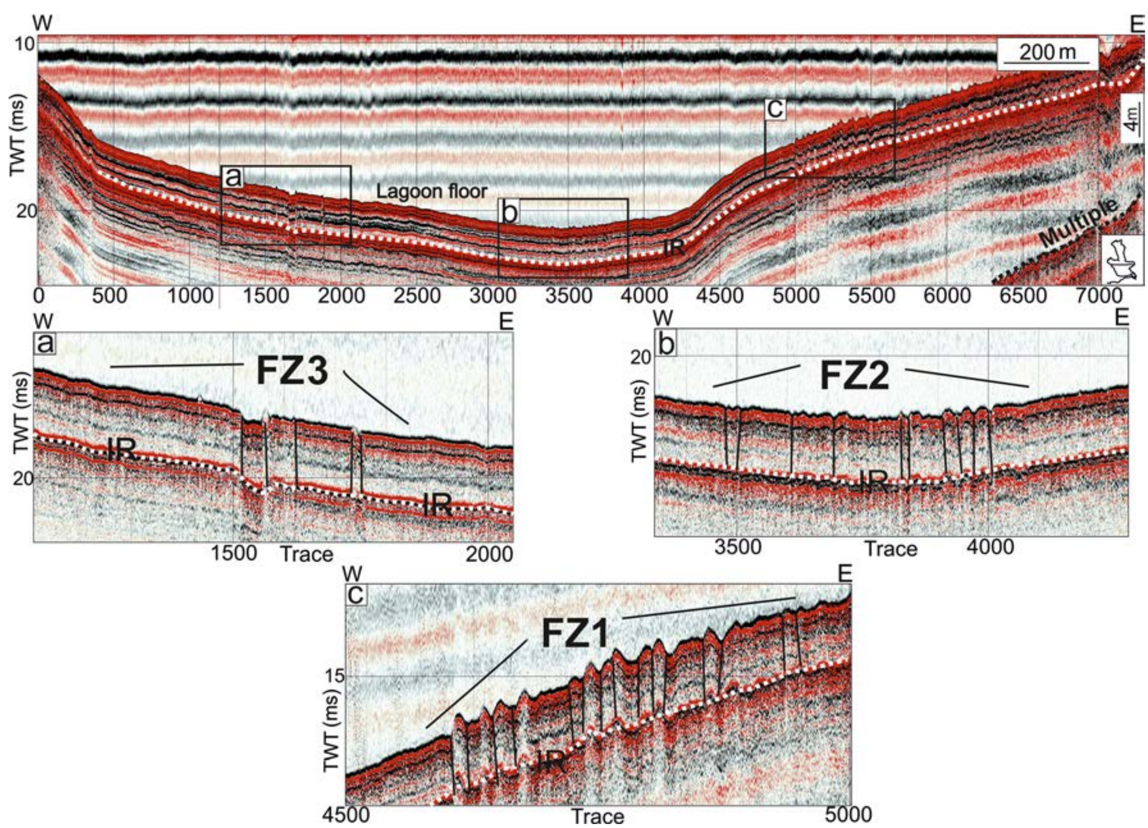

Fig. 6 Active faults (FZ1, FZ2, and FZ3) identified along an E–W seismic profile from the middle part of the lagoon. **a** Blow-up of the FZ3 fault zone located in the western part of the lagoon. **b** Blow-up of the FZ2 fault zone located in the middle of the lagoon. **c** Blow-up of the FZ1 fault zone located in the eastern part of the lagoon. In each case, the internal sedimentary structures are masked by reverberations below the white dashed line (*IR*)

with the tectonic regime of the surrounding land and the rupture of the NAFZ along the northern slope of the Çınarcık Basin.

Geological setting

Küçükçekmece Lagoon is located at the southwestern edge of the Istanbul–Zonguldak tectonic unit. It is confined by the Istranca metamorphic complex in the northwest (Koral 1998), the Thrace basin in the southwest, the Istanbul–Zonguldak units in the north–northeast, and younger sediments of the Marmara Sea basin in the southeast (Fig. 2). The surficial geology of the study area, as recently mapped by Ergintav et al. (2011), shows the occurrence of Paleozoic basement rocks, Cenozoic sedimentary rocks, and Quaternary alluvium. The town of Avcılar is situated within the Miocene-aged Bakırköy Formation, whereas the Küçükçekmece Lagoon itself is embedded within the Middle Eocene to Late Miocene Çukurçeşme, Danişment, and Soğucak formations.

The bedrock in the study area contains Late Miocene limestones and clastics (Bakırköy, Güngören, and Çukurçeşme formations), which are underlain by the Middle Eocene to Early Miocene Gürpinar Group (Fig. 2). The Çukurçeşme, Danişment, and Osmancık formations include thick fluvial conglomerates and coarse deltaic sands, which have a combined thickness of >250 m. These clastic deposits are exposed in shoreline bluffs around the lagoon and also form the bedrock below the lagoon (Dalgıç 2004). The Holocene sediments in Küçükçekmece Lagoon consist of gravelly sands with minor silt and clay contents. These sedimentary formations are mainly horizontally bedded with a slight (10–15°) dip to the S–W (Duman et al. 2005; Akarvardar et al. 2009). Alluvium of Quaternary age is found throughout the study area, particularly in river valleys and other depressions (Fig. 2).

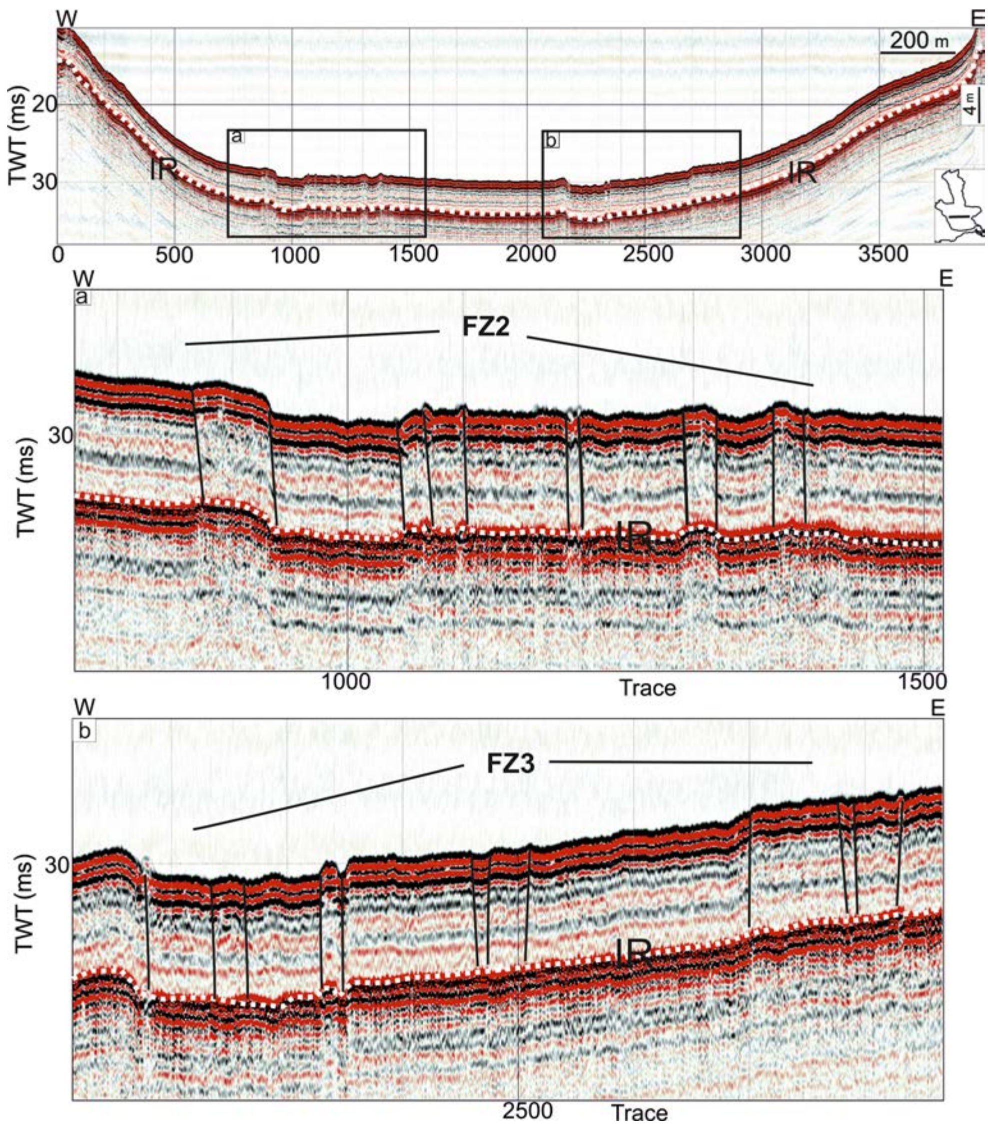

Fig. 7 E–W seismic profile from the southern part of the lagoon. **a** Blow-up of the FZ2 fault zone. **b** Blow-up of the FZ3 fault zone. In each case, the internal sedimentary structures are masked by reverberations below the white dashed line (*IR*)

Materials and methods

Seismic data

A single-channel seismic survey was performed in Küçükçekmece Lagoon using a 50–350 J boomer system. Sub-bottom seismic profiles covering a cumulative distance of 42 km were acquired in May 2012 using an Applied Acoustics AA301 broadband (0.5–10 kHz) boomer sound source with a 6-channel hydrophone array operating with a broad-band electromagnetic pulse-frequency band. Boomer sweeps ranged in frequency from 0.5–6 kHz (Fig. 3a). The maximum vertical resolution of the system is 15 cm. The survey lines were spaced approximately 300 m apart in both N–S and E–W directions.

The seismic data were processed with the Coda Survey Engine Seismic+ and Kogeo software, headers and navigation information being extracted by means of the latter software. Seismic data processing steps included band-pass filtering (550–8,000 Hz) and deconvolution to suppress direct wave arrivals and water-bottom multiples. The profiles were imaged to a depth of approximately 10 m below the lagoon floor. However, because the seismic data were severely degraded by strong internal reverberations (IR) that could not be removed by filtering, only the first 5 m below the lagoon floor were useable for interpretation.

Bathymetry

Detailed bathymetric information (Fig. 3b) from the lagoon was obtained from the single-channel seismic reflection data using the Kingdom Suite® seismic package for the extraction of the lagoon floor signal. Depth conversion of seismic data was performed based on a water column velocity of 1,500 m s^{-1} and an estimated sediment velocity of 1,550 m s^{-1}. The bathymetric data were gridded in 50-m cells using a minimum curvature algorithm following tie-line leveling after elimination of spurious depth values.

Results

High-resolution seismic reflection data were interpreted stratigraphically and structurally, and combined with bathymetric features to obtain information on potentially active tectonics in Küçükçekmece Lagoon. The bathymetric map (Fig. 3b) indicates that the water depth is shallow in the northern part of the lagoon, from where it progressively increases to a maximum value of 20 m in a broad, ca. 2 km^2 large basin that forms the southern part of the lagoon. Along some parts of the lagoonal coastline, opposite shores are aligned almost parallel to each other in a general NW–SE direction, which may be an indication of tectonic (fault) control.

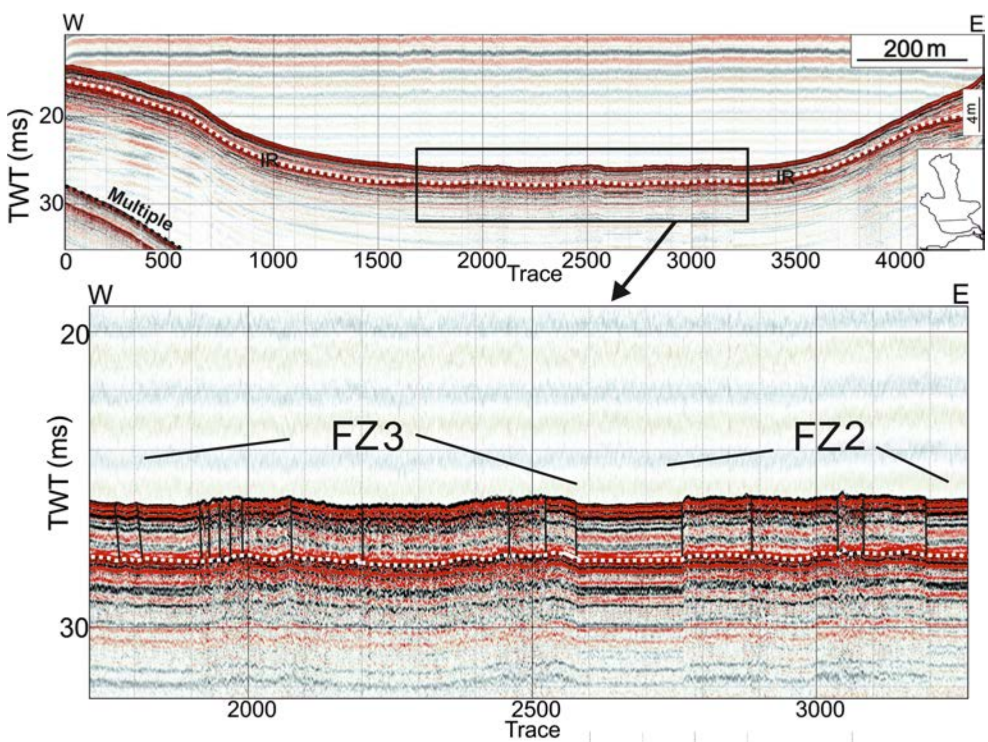

Fig. 8 E–W seismic profile from the southern lagoon basin, the blow-up showing the location of fault zones FZ2 and FZ3

Due to strong internal reverberations (Fig. 4), only the uppermost 5 m of the sedimentary fill were available for interpretation. Throughout the lagoon, the seismic reflections within this uppermost layer reveal horizontal bedding aligned more or less parallel to the lagoon floor (Figs. 4, 5). Such a configuration suggests progressive deposition under low-energy conditions, which normally results in the formation of an even and smooth bed. In the present case, however, the overall smooth lagoon floor is locally interrupted by uneven sections marked by low bumps or depressions associated with vertical offsets in the sedimentary succession below. These are interpreted to indicate the presence of active faults (Fig. 4). In addition, along short sections of some seismic profiles from the southern basin, the bedding is chaotic, the low impedance of the reflections suggesting the presence of gas pockets or gas-charged sediments, a good example being illustrated in Fig. 5. Such zones are invariably deformed by active faults.

Overall, three discrete fault zones, marked FZ1, FZ2, and FZ3 from east to west, have been identified. Along the shallow-water profiles in the northern part of the lagoon, only fault zones FZ2 and FZ3 were traversed (Figs. 4, 5). Fault zone FZ1 is located further east and therefore only encountered along the longest E–W profiles reaching into the eastern embayment of the central lagoon (Figs. 3, 6). As in the case of fault zones FZ2 and FZ3, the uplifting of sediments between faults is interpreted as being indicative of local compression along the fault zone (Fig. 6c). The southernmost E–W profiles, by contrast, are again shorter and thus only reveal fault zones FZ2 and FZ3 (Figs. 7, 8). The faults are essentially vertical and can, in most cases, be traced from depth to the lagoon floor, an exception being places where they are masked by overlying gas pockets (e.g., Fig. 5).

As illustrated in the summary diagram of Fig. 9, the individual fault zones identified on successive E–W-oriented

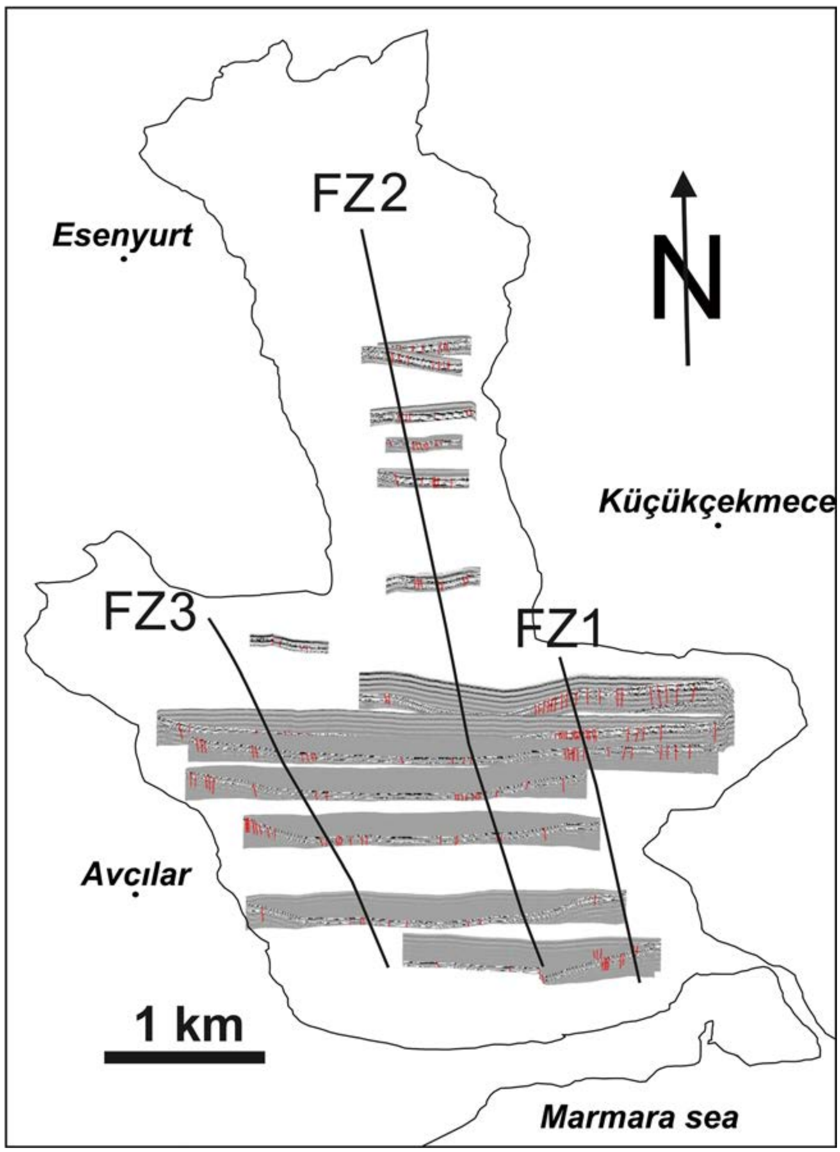

Fig. 9 Three-dimensional structural view of Küçükçekmece Lagoon showing the location and trend of the three active strike-slip fault zones identified on the seismic profiles

seismic profiles are clearly aligned in a general NW–SE direction. They are interpreted as representing strike-slip fault systems that may be associated with the northern branch of the NAFZ.

Discussion and conclusions

The interpretation of seismic profiles and bathymetric features of the Küçükçekmece Lagoon indicates that the study area is deformed by active fault zones (FZ1, FZ2, and FZ3) that extend in a NW–SE direction. The character of these fault zones suggests that they are strike-slip faults. Moreover, evidence for compression in the sediments along these fault zones may be indicative of shortening in an approximately E–W direction in this area (Figs. 4 to 8). Some previous onland and offshore studies support the existence of such active faults in this region. Thus, Gökaşan et al. (2002, 2003) mapped NW–SE-directed lineaments that follow the parallel drainage pattern and morphological scarps characterizing the land surface to the north of the Marmara Sea (lineament L2 on Fig. 10a). The same authors also identified the offshore continuation of these faults on seismic records (fault F2 on Fig. 10a). The active faults identified in the present study actually match the location and orientation of the L2 and F2 lineaments. To confirm that there is a link between the former and the latter, possible landward and seaward extensions of the active fault zones (FZ1, FZ2, and FZ3) identified in the Küçükçekmece Lagoon should be investigated in the future, and their role within the general tectonic framework of the Marmara Sea and surrounding land area discussed.

Moreover, the right-lateral displacement of the Marmara Sea coast at the southern exit of Küçükçekmece Lagoon strongly suggests that the FZ1, FZ2, and FZ3 fault zones represent right-lateral strike-slip fault zones (Fig. 10a). Although the young active faults in the soft bottom sediments of the lagoon may be interpreted as merely representing local deformations, their alignment with surrounding structural features and their proximity to the main Marmara Fault, which delimits the northern boundary of the Çınarcık Basin, strongly suggests that these active zones may be related to the NW–SE-oriented branches of the NAFZ. This is supported by their correlation with the NW–SE-oriented strike-slip faults (flower structures) identified by Gökaşan et al. (2002, 2003) on the continental shelf off the Küçükçekmece and Büyükçekmece lagoons.

If the above interpretation is correct, then the northern branch of the NAFZ does not bend offshore off Avcılar and the Küçükçekmece and Büyükçekmece lagoons but, on the contrary, continues northwestward into the land mass north of the Marmara Sea (Fig. 10b). This would explain the extraordinary damage in the Avcılar district close to Küçükçekmece Lagoon caused by the 1894 (Öztin 1994) and 1999 earthquakes, the latter having had its epicenter in the Marmara Sea some 105 km to the east, and also the high microseismic activity around the Büyükçekmece and Küçükçekmece lagoons (Fig. 1; Gürbüz et al. 2000; Dalgıç 2004; ISC 2011).

As already pointed out above, this model needs to be confirmed by further structural and seismological studies. The clarification of the tectonic setting of this region is all the more important because of the high seismic hazard risk potential to the densely populated Istanbul metropolitan area.

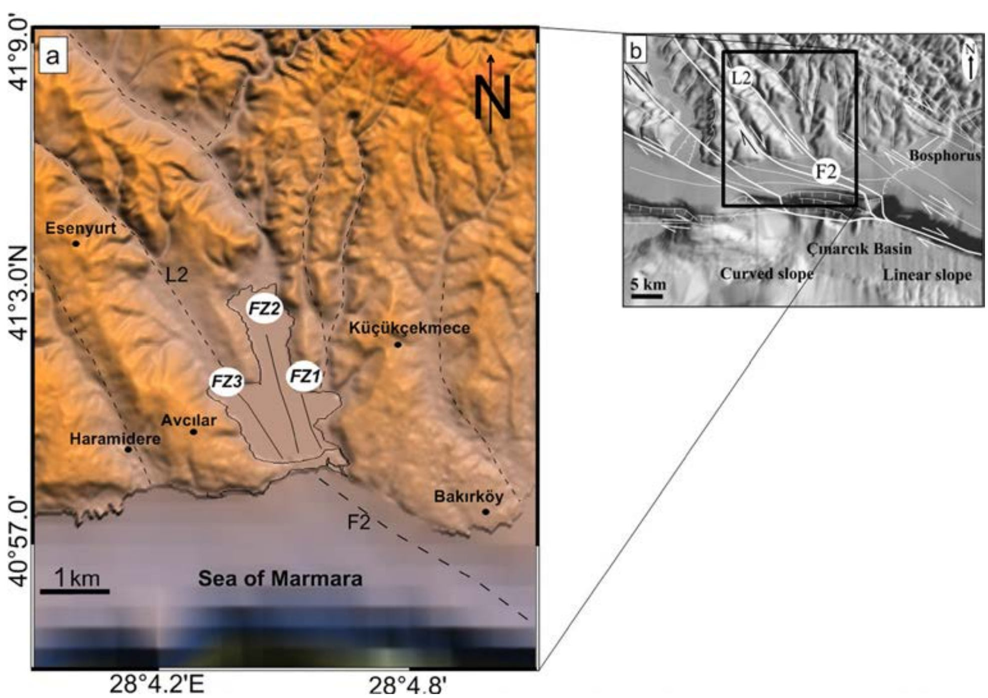

Fig. 10 **a** Overview map showing the active fault zones in the Küçükçekmece Lagoon relative to the F2 fault on the adjacent continental shelf. **b** Regional fault map of Gökaşan et al. (2002). Note that the major NNW–SSE-trending fault, representing the F2 fault (offshore) and lineament L2 (onshore), matches the trend of the active faults identified in Küçükçekmece Lagoon

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