Seismic stratigraphy and depositional history of the Büyükçekmece Bay since Latest Pleistocene, Marmara Sea, Turkey

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High-resolution seismic data shed light on latest Pleistocene and Holocene sedimentation beneath the Büyükçekmece Bay, northern shelf area of the Marmara Sea, Turkey. Discontinuous fluvio-marine and marine deposits overlying the erosional truncation surface of Oligocene–Lower Miocene deposits are as thick as 30 m and preserved preferentially within the incised valleys that were controlled by some old faults. A series of prograding shoreline, laterally passing to the latest Pleistocene–Holocene valley-fill deposits, are thought to have accumulated mainly during times of shoreline transgression and sea-level rise. The overall morphology and stratigraphic setting observed in the Büyükçekmece Bay and at the southern outlet of the Bosphorus Strait have nearly same characteristics, implying that similar hydrodynamic conditions, erosional and depositional processes were mainly under the control of strong northerly flows during the Late Quaternary. These flows were less powerful in the Büyükçekmece region with decreased sediment input and smaller accommodation space.

Keywords. Büyükçekmece bay; seismic stratigraphy; sea level changes; prograding shoreline; incised valley; Bosphorus strait.

1. Introduction

The Marmara Sea is an intra-continental marine basin connected to the adjacent seas via the İstanbul and Çanakkale (Bosphorus and Dardanelles) straits. Their connections have been cut-off when the sea levels dropped below the respective sill depths (Smith *et al.* 1995; Aksu *et al.* 1999, 2002a, b, c, 2016; Çağatay *et al.* 2000, 2003, 2009; Eriş *et al.* 2007, 2008; Hiscott *et al.* 2002, 2008; McHugh *et al.* 2008; Vidal *et al.* 2010). Reconnection of the Marmara Sea with the global ocean was established with transition to interglacial period,

as evidenced by sapropel deposits indicating suboxic/dysoxic conditions (Çağatay *et al.* 1999, 2000, 2009). According to the continuous sedimentary records given by Çağatay *et al.* (2015), the last lacustrine–marine transition in the Marmara Sea occurred at 12.55 ± 0.35 cal ka BP. During the Last Glacial Maximum (LGM), the margins of the Marmara Sea were sub-aerially exposed (Smith *et al.* 1995; Aksu *et al.* 1999, 2002a, b, c; Çağatay *et al.* 2000, 2009; Eriş *et al.* 2007; McHugh *et al.* 2008).

The northern shelf areas of the Marmara Sea is relatively narrow, varying between 2 and 13 km.

Recent researches on the late Quaternary stratigraphy of this margin have been focused on the general characteristics of the younger and relatively thinner sediments overlying a shelf-crossing acoustic basement (Aksu *et al.* 1999; Olgun 2001; Çağatay *et al.* 2009; Karakılçık *et al.* 2014; Tur *et al.* 2014; Nasıf 2016). In addition, seismic sequences at the southern outlet of the Bosphorus Strait have been discussed deliberately to explain paleo-outflow regime of this water passage (e.g., Aksu *et al.* 1999; Algan *et al.* 2001; Hiscott *et al.* 2002; Gökaşan *et al.* 2005; Eriş *et al.* 2007; Köprülü *et al.* 2016). Due to variable hydrodynamic conditions and high sediment input, the stratigraphic settings of the southern outlet of the Bosphorus Strait is thicker and more complex compared to the other parts of the Marmara Sea (Alavi *et al.* 1989).

Today's Küçükçekmece and Büyükçekmece lagoons (figure 1) were two semi-enclosed bodies of water connected to the Marmara Sea (lake) and fed by rivers at the north. These former coastal estuaries were separated from the Marmara Sea by some partly natural sand bars and manmade road barriers about a century ago. Gökaşan *et al.* (2002) proposed that these shallow water bodies and their shorelines have been shaped by some active NW-trending fault splays connected to the northern strand of the North Anatolian fault system in the eastern Marmara Sea. The Büyükçekmece Bay is located at the southern part of the Büyükçekmece lagoon. There is almost no comprehensive geophysical study in literature about the evolution of the bay. The sedimentation observed in the bay, however, is much thicker if compared to thin Holocene blanket outside the bay. Therefore, the sedimentary successions in the bay interpreted with sufficiently better seismic data may provide a detailed explanation of the late Quaternary evolution. The main scope of the present study is to explain the stratigraphic setting in the Büyükçekmece Bay and to reconstruct its evolution. High-resolution shallow seismic profiles and available sedimentary core data provided necessary information for the construction of sedimentary environments in this bay.

2. Materials and methods

Shelf sediments distributed in the Büyükçekmece Bay area and their deposition were studied extensively using (i) two sets of high-resolution seismic data, (ii) sedimentary core data and (iii) by considering the sequence stratigraphic concepts (Vail

1987; Posamentier and Vail 1988; Posamentier *et al.* 1992).

Single channel high-resolution Sparker (72 km-line, 250 ms two-way-time) and Chirp (128 km-line, 100 ms two-way-time) seismic surveys have been acquired in the Büyükçekmece Bay (figure 1) in 2000 and 2015, respectively. The Sparker system is composed of 1.25-kJ multi-electrode spark array and an 11-element, 10-m-long surface-towed hydrophone streamer. Sparker data provided information on sedimentary deposits up to 150 m below the seabed. In order to obtain much detailed sub-bottom survey capability especially for shallow waters, Bathy 2010PTM Chirp sub-bottom profiler and bathymetric echo sounder (2–8 kHz) was used. The transmit pulse repetition rate was 1 Hz depending on the depth range and also on the selected pulse length which is short enough in order to resolve thin layers covering the sub-bottom strata. The vessel speed was held as slow as 2.0–2.5 knot throughout the Chirp survey. The approximate depths were calculated using a typical velocity 1500 ms⁻¹ both for water column and near-surface muddy sediments. Some primary processing such as gain correction, band-pass filter (10/15–1750/1900 Hz) and predictive deconvolution were applied to datasets using free software Kogeo Seismic Toolkit. Kingdom Suite[®] (version 8.5; donated by Seismic MicroTechnology) was used for seismic data interpretation and mapping. The relief maps (unit thickness and surface depth maps) were generated by Global Mapper program and the land elevation data were provided from ASTER 2 data.

3. Results

A total of 200 km-line high-resolution seismic data have been analysed and interpreted to represent the last glacial to recent sediment succession (MIS-2 to MIS-1) and morphological properties of the Büyükçekmece Bay and offshore area.

3.1 Seafloor morphology

The bathymetry map that generated from high resolution seismic data, revealed a NE–SW trending valley system (figure 2). This valley system is widening in the interior of the bay (~3000 m) and it becomes narrower to the south with a control of coastal basement rocks (figure 2). It has an asymmetric cross-section with gentle bounding walls; approximately 1.5°–2° slope along its western side

Figure 1. (a) Location of the Büyükçekmece Bay (BÇ) and Büyükçekmece Lagoon (BL) which are separated by a narrow barrier bar. KL: Küçükçekmece Lagoon. Inset shows a generalized tectonic setting of the region. Shaded box stands for the study area. (b) The cores and seismic reflection profiles acquired by Sparker (yellow lines) and CHIRP (black lines) systems. Heavy lines are seismic profiles illustrated in figures indicated.

Figure 2. Detailed bathymetry of the Büyükçekmece Bay compiled using more than 200 line-km of seismic profiles collected during two cruises. Depths are calculated using 1500 ms^{-1} for water velocity. The seafloor morphology is mainly under the control of a SW-trending valley.

and 3° – 5° slope along its eastern side (figure 2a). The valley system deepens gently to the south with a slope 0.5° – 1° and presents a series of terraces (figure 2b).

3.2 Seismic stratigraphy

The application of sequence–stratigraphic concepts, using high-resolution seismic records as a tool, gives good clues about the spatial and temporal record of the stratal development in response to sea-level changes, and therefore about the surrounding environmental processes occurred during their formation (Van Wagoner *et al.* 1988). A river delta, for example, is a gateway for terrigenous sediment flux and may occur where a river enters a sea, lake or estuary. Therefore, the extensive definition of individual or stacked delta sequences in basins, their morphology and stratigraphy, could provide better understanding of the significant environmental processes within the basin's geological setting, and even tectonics.

The seismic profiles acquired in the Büyükçekmece Bay (see figure 1 for location)

revealed two main seismic units (U1 and U2), which are separated by a characteristic sequence boundary covering the whole study area (figure 3a, b, c, d).

U1: It is the uppermost seismic unit and composed of several different reflection packages, which are represented by weak to moderate, continuous and sigmoidal reflections (figure 3a, b, c, d). The Unit U1 overlies directly on an erosional transgressive surface and reaches a maximum thickness of 30 m (figure 4) at the centre of the bay with respect to the morphology of the underlying valley system (figure 2). This unit represents all the sediment successions that synchronously deposited during the last glacial maximum to present time.

These sedimentary successions are composed of six relatively conformable units of genetically related succession of bed sets; U1a, U1b, D1, D2, D3 and D4 with some characteristic seismic internal reflections, bounded by marine flooding surfaces and their correlative surfaces (figure 3a, b, c, d).

U1a: This unit is characterized by weak to strong, parallel and continuous internal reflections,

Figure 3. Sparker and CHIRP sections and their interpretations. See figure 1 for locations. The position of Core-1 is projected (max. 25 m) on the seismic lines.

Figure 4. Thickness map of Unit 1, according to an assumed acoustic velocity of 1500 ms^{-1} (Aksu *et al.* 2016) for sediment.

with some onlaps on the underlying unit (U1b) and sigmoidal reflections. The unit can be seen within the Büyükçekmece Bay. It is composed from coarse-grained sand (loose to medium dense) and shell fragments at the top of the cores (figure 5).

U1b: Unit U1a is underlain by a relatively conformable Unit (U1b), which is characterized by semi-parallel inner reflections infilling local depressions and onlapping an unconformity surface β and some sigmoidal reflections (figure 3a, b, c, d). The amplitudes are low within the dominant frequency range of the Chirp data, but moderate in the Sparker data. This unit cannot be seen above -35 ms two-way-travel time below mean sea level (-26 m ; $V_w = 1500 \text{ ms}^{-1}$). The deepest part of the basin is masked partly by acoustic turbidities due to shallow gas accumulations. In the gravity core Core-1/2, this unit is composed from gravel (loose to medium dense) and abundant shell fragments (figure 5).

Four separate small subaqueous sigmoidal units have been observed at the western and eastern

sides of the U1b; namely D1, D2, D3 and D4 (figure 6). These units have been characterized by prograding subaqueous clinoforms, a ‘topset–foreset–bottomset’ depositional profile, implying a high-energy (fluvial–riverine) environment. They downlap on to the underlying erosional surface, interpreted as a stable platform, and their topset–foreset rollovers are located close to the shoreline.

D1: The highest subaqueous prograding shoreline unit in elevation is D1 and it is located at the western side of the bay, the topset–foreset transitions between the depths of 26 and 30 ms two-way-travel time below mean sea level (figure 6). The topset–foreset transitions of D1 show an ascending trajectory.

D2: This is a prograding shoreline unit with topset–foreset transitions between the depths of 36 and 46 ms two-way-travel time below mean sea level and it is observed at the eastern side of the bay. The inner reflections along the E–W trending profiles are similar to levee deposits (figure 6), whilst the topset–foreset transitions of D2 show ascending trajectory along the N–S trending profiles (figure 6).

D3: This prograding shoreline unit is located at the western side of the bay, but it is deeper than D1. Its topset–foreset transitions are between 44 and 46 ms two-way-travel time below mean sea level (figure 6). The seismic character of the topset–foreset transitions express an erosive character, as well as sediment by-pass. The clinoforms at the distal part downlap on to the underlying Unit D4.

D4: This unit overlies the erosional truncation surface β that is fault controlled at the western side of the bay (figure 6). The topset–foreset transitions of D4 is between the depths of 57 and 61 ms two-way-travel time below mean sea level and represent an ascending trajectory. The unit first filled an old valley and then eroded due to fluvial forces (figure 3d). Its high-amplitude topset reflections represent a bypass surface.

U2: This unit is the acoustic basement of the CHIRP data. In Sparker profiles, the Unit U2 is represented by locally tilted, folded and faulted reflectors throughout the study area (figures 3a, b, c, d). The most striking faults were observed below the NE–SW extending buried valley in the bay area (figure 3a). The upper surface of U2 is made up of sandy, highly altered and weathered deposits, depending on the bottom part of the gravity core Core-2 (figure 5). This unit corresponds to the Upper Gürpınar formation (Oligocene–Lower

Figure 5. Relations of lithologic definition obtained from the cores (gravity and drilling) and their relation with seismic units. Inset shows the locations of the gravity cores and seismic profiles.

Miocene) observed on land, composed from gravelly clay, occasional sand and silt alternations (Yıldırım *et al.* 2013).

In this scope, the boundary between the Units U1 and U2 represents an ancient subaerial exposure surface (β). Outside the Büyükçekmece Bay, this erosional surface is just below the thin Holocene deposits, and normally concordant with the present bathymetry all across the northern Marmara shelf. This view is different in the Büyükçekmece Bay demonstrating fluvial scoured topographic features and prograding shoreline deposits (figure 7). These

dynamic features must be evolved along a NE-trending valley and under the control of an old fault system located in the deepest part of this valley.

4. Discussion and conclusion

There is no any comprehensive seismic study ever performed on the seismic stratigraphic evolution of the Büyükçekmece Bay, except a number of seismic lines recorded in the previous works carried out on the northern shelf of the Marmara

Figure 6. Seismic expression of the shoreline clinoforms that were represented by the Units D1, D2, D3 and D4 in the text. Dashed arrow lines show the trajectories of the topset foreset transitions, which is eroded in D3.

Figure 7. Map and cross sections showing the morphology and present day depth to the erosional truncation surface β .

Sea. Göktaşan *et al.* (2002), for example, outlined only the sedimentary units above the acoustic basement as a single unit. Karakılçık *et al.* (2014) outlined three distinct Late Quaternary seismic units above the acoustic basement (their SU I) using Uniboom data collected by the Turkish Navy. In the Büyükçekmece Bay, however, they could differentiate only one seismic unit (SU IV), the youngest of their units, directly above the acoustic basement. This most widespread unit with parallel and sub-parallel reflections was interpreted as Holocene deposits. Therefore, the available seismic data obtained from the previous surveys were not sufficient to explain the stratigraphy of the Büyükçekmece Bay in detail, and discuss its depositional history in response to the sea level changes since the LGM.

Considering the overall appearance, reflection characteristic and areal distribution of the seismic units delineated in the present study above the truncation surface β , the Büyükçekmece Bay area was a transitional domain between the terrestrial and marine sedimentation during their deposition following the LGM. The total thicknesses of the Units U1a and U1b reach up to 30 m in the central part of the bay, possibly due to high rates of sediment transportation. The fluvio-marine

and marine deposits in the bay are typically represented by several stages in prograding deposits. Slope erosions and basin deepening due to the secondary faults observed along the NE-trending valley control the external shape and reflection configurations of these units.

The prograding shoreline deposits of D1, D2, D3 and D4 represent an important amount of sediment carried by the rivers flowing into the Büyükçekmece lagoon and then to the Marmara Sea through the valleys carved in the erosional surface (figures 7, 8a, b).

The setting of prograding shoreline deposits and their topset–foreset transitions are the final products of five main factors. They are: (a) the initial bathymetry of the Büyükçekmece Bay, (b) the changes in sediment supply, (c) the suspended sediment concentration that is mostly riverine, (d) the eustatic sea-level changes following the Mediterranean invasion through the Dardanelles Strait and finally, and (e) the total subsidence. The types of shoreline trajectories of D1–D4 depend on the sedimentation and progradation rates during their evolution (figure 6).

The prograding shoreline deposits at the western side of the Büyükçekmece Bay contain some incised valley fills. On the other hand, Unit D2 that

Figure 8. Small-scale cut and fill valleys observed on the (a) CHIRP and (b) Sparker data. Insets show the locations of the sections.

is located at the eastern side is normal distributary channels. The general characteristics of these prograding deposits imply that they were formed by fine-grained sediments transported by riverine discharges. The alluvial material carried by two incised river valleys, observed on the erosional truncation surface β (figures 7a, b, c, 8a, b), are largely responsible for the formation of prograding clinoforms of the Units D1, D2, D3 and D4 (figure 9).

4.1 Integration between the Holocene sea level fluctuations with delta deposition

Considering the sea-level changes during and after the last glaciation (e.g., Lambeck *et al.* 2007; Aksu *et al.* 2016) and wave base level in the Marmara Sea, it will be possible to estimate the ages of development of the prograding shorelines. The wave base level in the modern systems of the Marmara Sea is at the water depths from 10 to 15 m (Aksu *et al.* 1999; Hiscott *et al.* 2002). From their seismic expressions, the development of these late glacial–Holocene prograding shoreline units took place between 7300–7800, 8300–9100, 9000–9100, 9650–9900 BP for D1, D2, D3 and D4, respectively (figure 9). The probable coastal shorelines at those times come to the present day depth contours of 9, 17, 23 and 33 m below the modern

sea level (figure 9). These depth values show that the prograding shoreline deposits must have completed their development within 500–800 years.

The characteristic seismic features of the sediment deposition, incised valleys and erosional surfaces are similar, but in smaller areal scale, to those observed at the southern canyon of the Bosphorus Strait (figure 10) as given by Köprülü *et al.* (2016). The fluvial erosion (see figure 3d) caused by strong flows coming from the northern sector separated the Unit D4 into two parts and prevented further sediment accumulation along the underwater valley.

4.2 Similarities in depositional history between the Büyükçekmece Bay and the southern outlet of the Bosphorus Strait

The region at the southern outlet of the Bosphorus Strait, where the most prominent morphological feature is an asymmetric canyon, is the most important depositional and erosional area along the northern shelf (Aksu *et al.* 1999; Algan *et al.* 2001; Hiscott *et al.* 2002; Gökaşan *et al.* 2005; Eriş *et al.* 2007; Köprülü *et al.* 2016). Under the strong two-layer current system, the western slope of this canyon is steeper than the eastern one. The canyon in the Büyükçekmece Bay is similar to the

Figure 9. Map shows the paleo-river suggested in this study and relation with the prograding shoreline deposits in the Büyükçekmece Bay. Figures show the depths (in metres below present mean sea level) to the top surface of the prograding shoreline deposits. The development of the Units D1–D4 depends on the sea-level rise in Holocene (MIS-1) proposed by Lambeck *et al.* (2007) and Aksu *et al.* (2016).

Bosphorus canyon, but it is smaller. It looks like a mirror image of the Bosphorus canyon drawn along a WE-trending profile, but with a steeper eastern slope (figure 10). Such a morphological feature indicates an outflow to the south, therefore a significant erosion, along the fault-controlled valley in the Büyükçekmece Bay (figure 3a).

The sources and evolution mechanism of the deltaic sequence at the southern outlet of the Bosphorus Strait is still unknown and a subject of debate today (Unit 1b, Köprülü *et al.* 2016). The topset–foreset transitions of this deltaic accumulation, which is thicker than 30 ms two-way-travel time below mean sea level, have an ascending character (Hiscott *et al.* 2002) and its long-distance spatial continuity shows high amount of terrestrial input during the deposition against the sea-level rise (Köprülü *et al.* 2016). The delta (Unit 1b) is located between 38 and 58 m below the modern sea level (Köprülü *et al.* 2016).

The sigmoid Units D3 and D4 observed in the Büyükçekmece valley are similar to the deltaic Unit 1b (sD3 and sD4 in AA' section in figure 10) in terms of depths below sea level and reflection characteristics. The main differences between the units are in their sizes and geometry, which are directly related with the rate of sediment input against the sea-level rise in the Marmara Sea. The topset–foreset transitions of Unit D4 have also an ascending character similar to those in Unit 1b. The top of Unit D4 is about 42.75 m below the modern sea level and effects of wave erosion can be seen on its frontal lobe (figures 3b, 6). This unit retreated backward rapidly according to the sea level rise and then continued its accumulation under the name of Unit D3 with some downlap terminations on the Unit D4. The topset–foreset transitions of Unit D3 have a descending character, implying sediment by-pass towards the deep basin. The top of Unit D3 is at 33 m below the

Figure 10. The comparison of the interpreted stratigraphic sketch section we deduced from the Büyükçekmece Bay with that at the southern outlet of the Bosphorus Strait (Köprülü *et al.* 2016) demonstrate similar morphologic settings and seismic units.

present mean sea level. The subunit D1 is similar to the seismic image of fluvial depositions (Unit 1a of Köprülü *et al.* 2016 at the mouth of the Kurbağalıdere River; here named sD1 for comparison) observed at the eastern part of the Bosphorus Strait, whereas it is overlain here by marine origin sediments due to lack or low rate of terrestrial sediment input. Finally, Unit D2 in the eastern part of the Büyükçekmece Bay is similar to the sand bars (see sD2 on the cross-section A–A') observed on the western side of the Bosphorus Strait (Alpar *et al.* 2012) in terms of their depths below the present mean sea level and reflection characteristics. Similar to the swale behind the Ahirkapi sandbar (Köprülü *et al.* 2016), a fluvial erosion area is located between the complex Unit D2 and the land (see also figure 3b).

From the point of their morphological characteristics and Late Quaternary depositional properties, the depositional basin in the Büyükçekmece Bay is rather similar to that at the southern outlet of the Bosphorus Strait (figure 10). Their morphological physiography and depositional spaces are like a mirror reflection of the other. In the light of these findings, we propose that the hydrodynamic conditions, erosional and depositional processes in

the Büyükçekmece valley during the Late Quaternary were mainly under the control of strong flows coming from the north similar to those along the Bosphorus Strait. The faults at the southern end of Bosphorus, which were developed depending on an anti-clockwise rotation mechanism generated by the dextral shear (Yılmaz 2007), controls the morphotectonic development and present morphology of this outlet area. Therefore, the outflows in both cases, Bosphorus and Büyükçekmece Bay, are along the eroded valleys that are controlled by old faults (figure 10). The differences in the younger units show that the northerly flows in the Büyükçekmece region were less important compared to the Bosphorus flow, but more vulnerable to the sea level rise, possibly due to decreased sediment input.

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