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Black Sea–Marmara Sea Quaternary connections: new data from the Bosphorus, İstanbul, Turkey

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Abstract

Previous studies concluded that the Bosphorus Strait was formed during the Quaternary by fluvial incision of a valley between the Black Sea, to the north, and the Marmara Sea in the south. Hitherto, however, few details of the evolution of this connection have been elucidated from the sediments deposited within the Bosphorus itself. We report here details of sedimentological and palaeontological evidence relating to this history, obtained from five boreholes drilled into the unconsolidated sediment fill in the north-central sector of the Bosphorus, together with nearby geophysical profiles. The Quaternary fill of this part of the Bosphorus comprises two major facies associations. Yellow arkosic sands dominate the lower Facies Association A: these are assigned a Middle to Late Pleistocene age and the contained faunas have a lagoonal to lacustrine character and a Black Sea provenance (Paratethyan affinities). The abruptly succeeding units of Facies Association B comprise fining and coarsening upwards units of coarse to fine shelly and clayey sands that alternate with shell-bearing green clays. These sediments were formed in a range of marine and coastal settings and biostratigraphic evidence and absolute dating demonstrate the Mid–Late Holocene age of this upper unit. Initially brackish faunal assemblages in this upper unit show an upward increase in marine and Mediterranean affinities. Integrating these new data with previously published observations from coeval deposits in the southern Bosphorus and İzmıt Bay (NE Marmara Sea) we conclude that during the Late Pleistocene and Early Holocene a topographic barrier existed in the south-central sector of the Bosphorus, on both sides of which estuarine and lagoonal sediments accumulated, with distinctive Black Sea and Mediterranean faunas. During a significant rise in sea level, between 7000 and 5300 years ago, this barrier was finally submerged, permitting interchange of marine waters between the Mediterranean and the Black Sea and creating the present oceanographic situation. This evolution conflicts with the cataclysmic role of the Bosphorus in the early Holocene as postulated in the 'Catastrophic Flood' hypothesis of Ryan et al. [Mar. Geol. 138 (1997) 119–126; Annu. Rev. Earth Planet. Sci. 31 (2003) 525–554]. It also contrasts with the history recorded from the Gulf of İzmıt, where intermittent connection between these two bodies of water throughout much of the Quaternary is evident.

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1. Introduction

1.1. General

The Bosphorus Strait is generally considered to have played an important role in connecting the marine waters of the Sea of Marmara with the less saline Black Sea during the Quaternary (Fig. 1). Much of the published evidence for this connection is derived from geophysical and sedimentological observations in adjacent areas (see, for example, Ross and Degens, 1974; Stanley and Blanpied, 1980; Evans et al., 1989; Smith et al., 1995, etc.). The aim of the study reported here is to shed light on the history of the Bosphorus using sedimentological and palaeontological evidence obtained from Quaternary sediments deposited within the Strait, supplemented by geophysical profiles (Fig. 2A).

For this purpose samples of the sediments and faunas obtained from five boreholes drilled into the seafloor of the north-central sector of the Bosphorus Strait have been examined and analysed. These boreholes were located in a 1.4 km long transect across the Bosphorus between Selviburnu and Tarabya (Fig. 2B). The locations, water depths and thicknesses of unconsolidated sediment encountered in each of these boreholes are listed in Table 1 (see also Fig. 2A,B).

To assess their wider significance, we have integrated and compared the results and conclusions drawn from these new data with those from previously published studies of the Bosphorus and adjacent areas, many of which are in the Turkish literature, e.g. Derman, 1990; Gülen et al., 1990; Meriç and Sakınç, 1990; Taner, 1990; Ünsal, 1990; Meriç, 1995a,b; Meriç et al., 2000a,b (Figs. 1C and 2C).

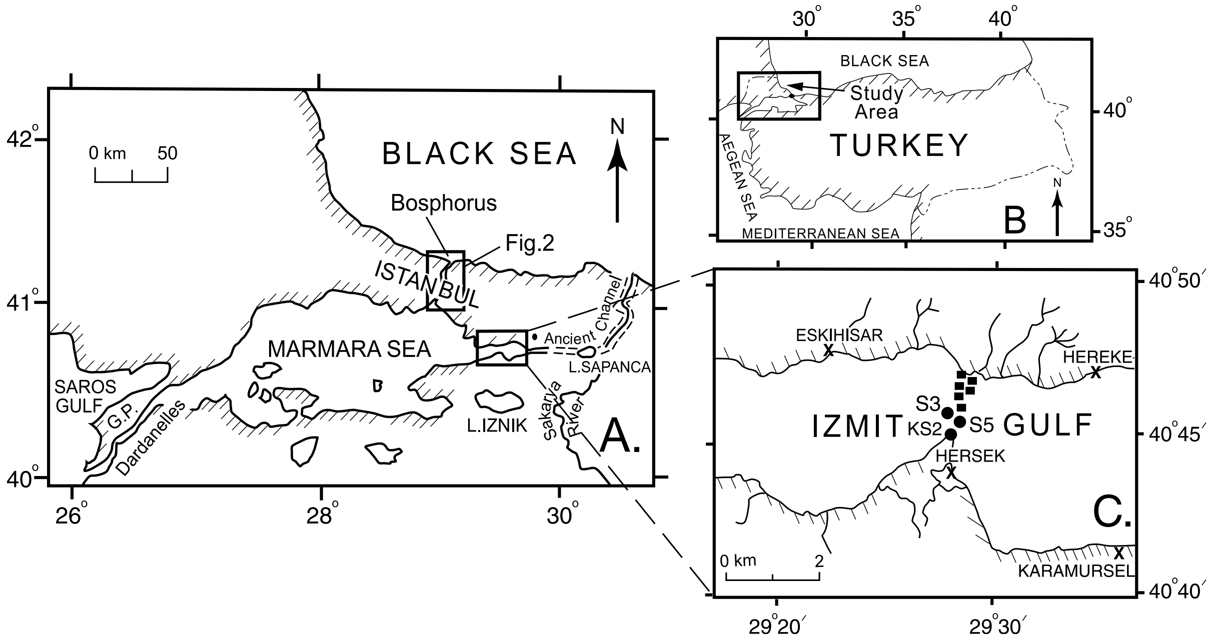


Fig. 1. (A) General location map of the Bosphorus and its relation to adjacent bodies of water. (B) Location of the study area within Turkey. (C) Detail of İzmıt Gulf with location of borehole transect studied by Meriç et al. (1995a,b).

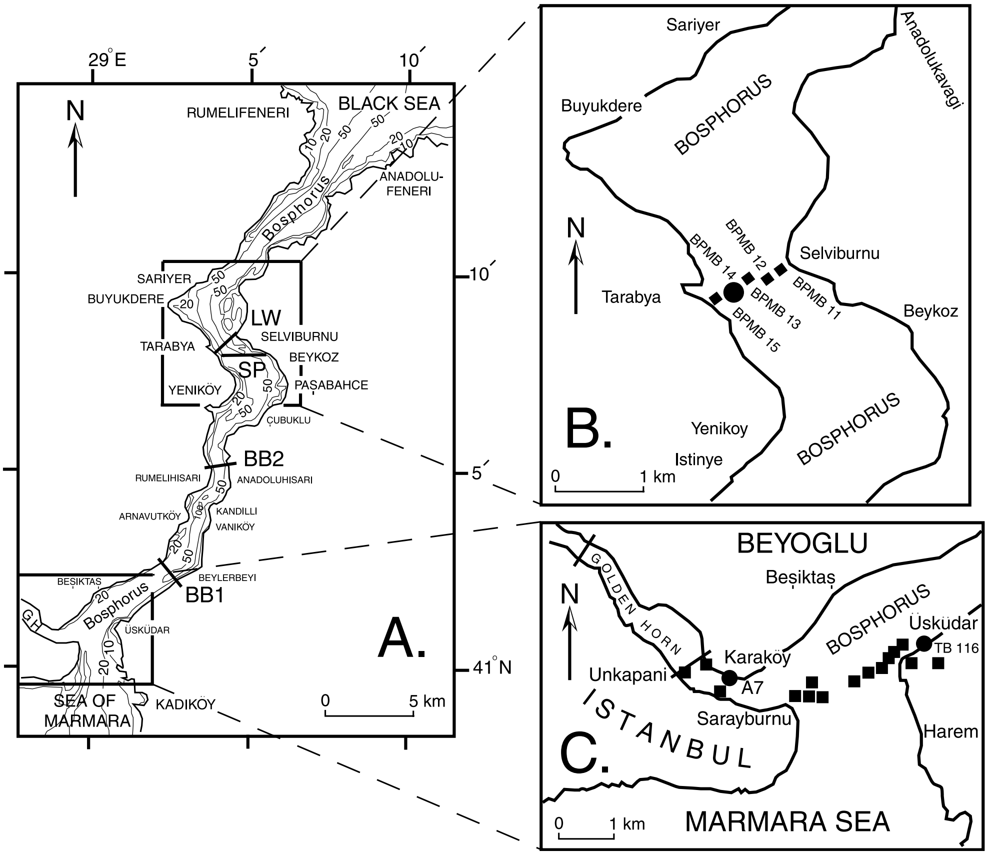


Fig. 2. (A) Bathymetric map of the Bosphorus (from Meriç et al., 2000a). Depth contours are in metres. B1 and B2 are first and second Bosphorus road bridges, respectively; LW is the location of the borehole transect described here; SP is the location of the seismic (air gun) profile of Uluğ (1994) shown in Fig. 5; GH is the Golden Horn inlet. (B) Detail of the central Bosphorus showing location of boreholes drilled by DSI (Turkish State Waterworks) in 1997. (C) Detail of the southern Bosphorus and Golden Horn, showing location of boreholes studied by Meriç (1990).

1.2. *Morphological and geological setting*

At present the Bosphorus Strait is the sole narrow seaway connecting the Black Sea, to the north, with the Sea of Marmara, to the south (Fig. 1A). Furthermore, the Sea of Marmara is connected with the Aegean Sea (part of the eastern Mediterranean) through the larger Dardanelles Strait (Fig. 1A). The Bosphorus follows a relatively sinuous course for approximately 22 km

Table 1
Localities, water depths, and thickness of unconsolidated sediments recorded in boreholes along the Beykoz–Tarabya transect, north-central part of the Bosphorus İstanbul, Turkey

Borehole no.	Borehole location	Water depth (m)	Thickness (m) of unconsolidated sediment drilled
BPMB-11	41°08′32″N, 29°04′17″E	12.70	09.30
BPMB-12	41°08′30″N, 29°04′12″E	17.00	12.00
BPMB-13	41°08′27″N, 29°04′00″E	42.00	12.00
BPMB-14	41°08′20″N, 29°03′40″E	65.00	39.50
BPMB-15	41°08′22″N, 29°03′47″E	65.00	04.75

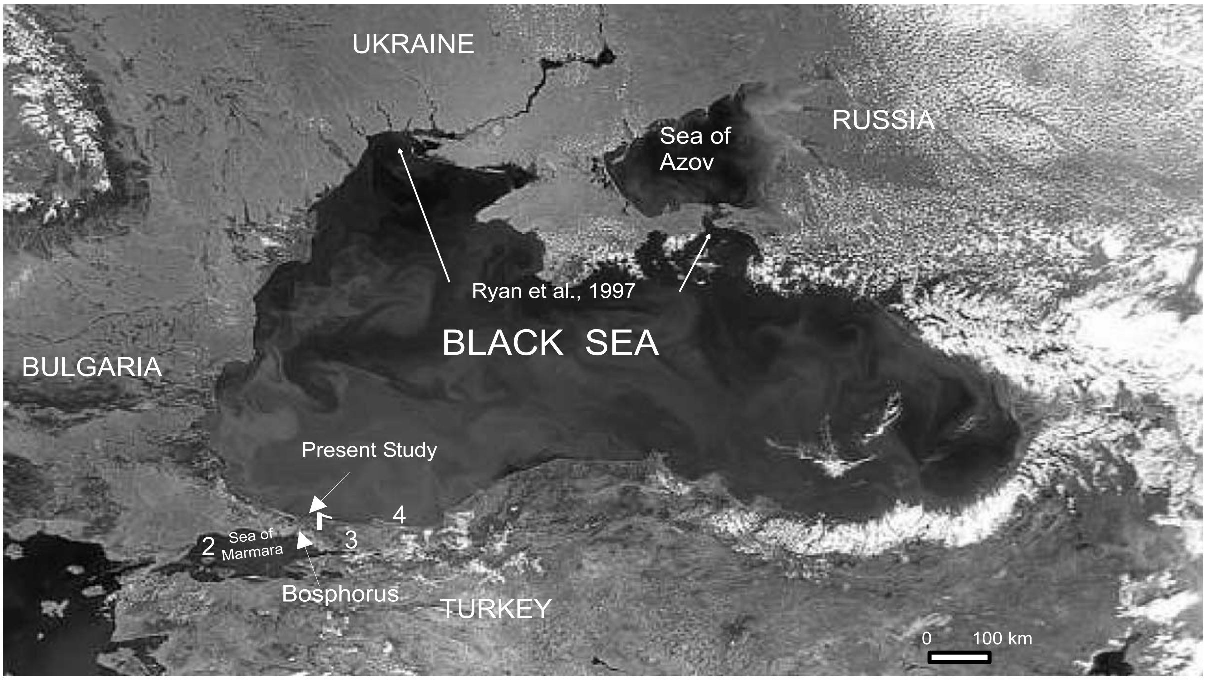


Fig. 3. Satellite image of the Black Sea showing location of this study area and those of some relevant recent studies. Modified from space image provided by the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE. Image captured on June 11, 2000. 1, Gökaşan et al. (1997); 2, Çağatay et al. (2000); 3, Meriç et al. (1995a,b); 4, Görur et al. (2001).

from the latitude of İstanbul to the entrance into the Black Sea and it has an average width of around 2 km. The maximum present water depth within the Bosphorus exceeds 110 m in a restricted basin near Kandilli, south-central part of the Strait, while the sill depth (near İstanbul) is about 35 m (Fig. 2A). This compares with a sill depth of approximately 80 m in the Dardanelles.

The region around the Bosphorus is geologically complex, with a basement consisting mainly of the İstanbul tectonic zone, outcropping in the southern and central parts of the Bosphorus (Önalan, 1982; Gökaşan et al., 1997). This zone includes a structurally deformed sequence of siliciclastic and carbonate rocks ranging from Ordovician to Carboniferous in age, unconformably succeeded by Triassic redbeds and limestones and discordantly capped by Upper Cretaceous to Palaeogene rocks. Near the northern end of the Bosphorus the Palaeozoic rocks of the İstanbul zone are overthrust by Upper Cretaceous ophiolitic and volcano-sedimentary units. Remnants of Upper Miocene Paratethyan limestones are found at elevations up to 200 m above sea level in the southern İstanbul peninsula, implying substantial tectonic uplift over the past 5–6 million years (Gökaşan et al., 1997). Recent uplift is further attested by Quaternary lacustrine and lagoonal deposits that are now exposed at considerable elevations (up to 85 m) in the northern Bosphorus region and along the adjacent Black Sea coast (Oktay and Sakınç 1991 and 1993). Several major faults, mainly ESE–WNW trending and extensional in nature, transect the basement rocks on both flanks of the Bosphorus (Gökaşan et al., 1997). Fractures with similar trend have been observed in reflection profiles from the seafloor of the Strait, together with N–S to NNE–SSW trending faults that affect the Quaternary fill (Yilmaz and Sakınç, 1990; Gökaşan et al., 1997), reflecting the current seismic activity of this entire region (see also Polonia et al., 2002).

Geophysical data show that unconsolidated

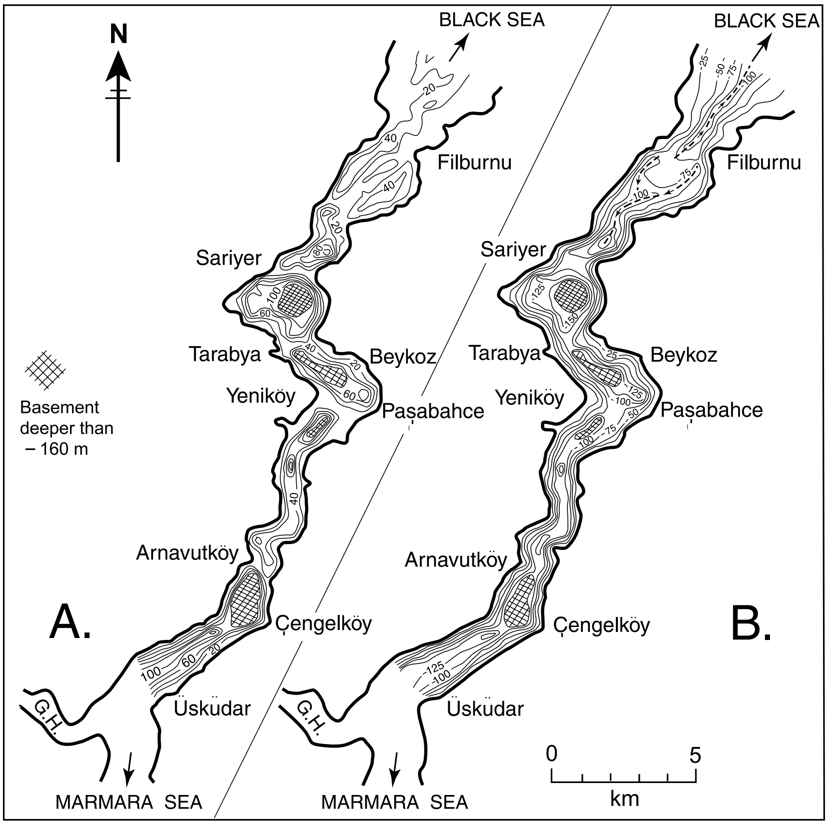


Fig. 4. (A) Isopach map of Quaternary deposits in the central and northern Bosphorus, derived from geophysical profiling (after Gökaşan et al., 1997). Cross-hatched areas denote sediment thicknesses in excess of 130 m. (B) Map showing depth to basement in the Bosphorus (after Gökaşan et al., 1997), determined from geophysical profiling. Cross-hatched areas denote basement depth in excess of −160 m (deeper than the penetrative capability of the profiling system used).

sediments (inferred to be Quaternary) beneath the seafloor of the Bosphorus attain a maximum thickness of more than 130 m in the southern part (Fig. 4A) but exceed 100 m only within a few isolated, fault-controlled depocentres in the central part of the Strait (Gökaşan et al., 1997). In general, the sediment isopachs closely follow the palaeomorphology revealed by basement (bedrock) contours (Fig. 4B), thus suggesting that infilling began when regional base levels or sea level were substantially lower than at present.

Moreover, there are significant differences in the seismic stratigraphy of the young sediment infill between the southern and central/northern sectors of the Bosphorus. In the south, the thick sub-seafloor sequence is locally incised by young channels or disturbed by superposition of lateral fan wedges, but the overall character is of parallel and homogeneous strata (see Gökaşan et al., 1997, their figures 7 and 8). In the central and northern sectors, the sequence is more complex and the Quaternary sediments in most profiles are represented by at least two seismic-stratigraphic units separated by surfaces of erosion or non-deposition (Gökaşan et al., 1997, their figures 4,5 and 9). Moreover, near the northern mouth of the Bosphorus the geophysical profiles show at least two generations of lateral terrace, probably of fluvial origin, attesting to several phases of incision by (presumably) north-flowing stream systems within the present Strait, and probably formed during the Pleistocene.

1.3. Relevant previous studies

The role and history of the Bosphorus has featured in many palaeoceanographic studies of the of the Black Sea and eastern Mediterranean (e.g. Ryan, 1972; Ross and Degens, 1974; Scholten, 1974; Hsü, 1978), and especially in studies concerned with the genesis of the layers of organic-rich dark mud (sapropel) that characterise the Quaternary deepwater sequences of the eastern Mediterranean, including the Aegean Sea, Sea of Marmara and Black Sea (Stanley and Blanpied, 1980; Yaşar et al., 1987; Esin, 1988; Evans et al., 1989; Smith et al., 1995; Aksu et al., 1995; Ergin et al., 1997; Lane-Serff et al., 1997). Until recently there was a broad consensus that, following glacially modulated fluctuations in the relative levels of the Black and Mediterranean seas during the Pleistocene, the present two-layer water exchange system (deep inflow of saline Mediterranean water and surface outflow of brackish Black Sea water) was established gradually during the Early to Mid-Holocene, when the postglacial rise in sea level successively reached the (present-day) sill depths of the Dardanelles (−80 m) and Bosphorus (−35 m).

However, the 'Catastrophic Flood Hypothesis' advanced by Ryan et al. (1997) envisaged a more spectacular role for the Bosphorus connection, involving sudden and catastrophic influx of Mediterranean waters through the Strait into a substantially lower Black Sea lake around 7150 years ago. This hypothesis has been challenged in recent studies by Çağatay et al. (2000), Görur et al. (2001), Aksu et al. (2002) and others. On the basis of geophysical and other data collected from the seafloor of the Marmara Sea and from the Black Sea coast these authors dispute the timing and abrupt character of the latest opening of the Bosphorus and also question the date of inception of the present two-layer water exchange.

To date, few studies have been devoted specifically to determining the nature and evolution of the Bosphorus Strait. Scholten (1974), Gunnerson and Özturgut (1974), Alavi et al. (1989), Uluğ (1994) and Gökağan et al. (1997) have all utilised seismic reflection profiles to detail aspects of the bathymetry, shallow structure and distribution of unconsolidated sediments within the Strait and offered hypotheses concerning its origin.

In their account of the history of the Bosphorus Gökaşan et al. (1997) concluded that the northern part was formed through fluvial and lacustrine processes while the southern sector resulted from faulting. According to these authors the Quaternary history of the Bosphorus can be divided into two stages. During most of the Pleistocene, an embryonic river on the north side of the drainage divide, which was located in the latitude of Sariyer, flowed northwards into the Black Sea (Fig. 2A). Fault tectonics prevailed to the south of this divide and a lagoon or bay was formed, which gradually extended towards the north from the Marmara Sea. Following the last glaciation, fluvial erosion continued in the north and further faulting in the south lowered the intervening barrier. The postglacial rise of sea level then enabled Mediterranean waters to penetrate into the Black Sea. Thus, according to Gökaşan et al. (1997) the Bosphorus attained its present form and connecting function during the Holocene. The study reported here yields evidence that bears directly on this evolutionary model.

2. Materials and methods

The six boreholes along the Beykoz–Tarabya transect that form the basis of this study were drilled in 1997 for the Turkish State Waterworks (DSI, Ankara), using percussion and piston techniques and employing Shelby stainless steel sampling tubes, designed to minimise disturbance.

Following visual examination and recording of sediment colour, texture and structure, as well as megascopic faunal content, about 30 g of sediment was extracted from each of 77 samples collected from boreholes BPMB-11, BPMB-12, BPMB-13, BPMB-14, and BPMB-15. The foraminifera, ostracoda, pelecypoda, gastropoda, and bryozoa collected from these samples were then examined in detail. Sand samples were further studied using grain mounts and impregnated thin sections, while heavy minerals were also separated out.

Shallow seismic reflection profiles were ob-

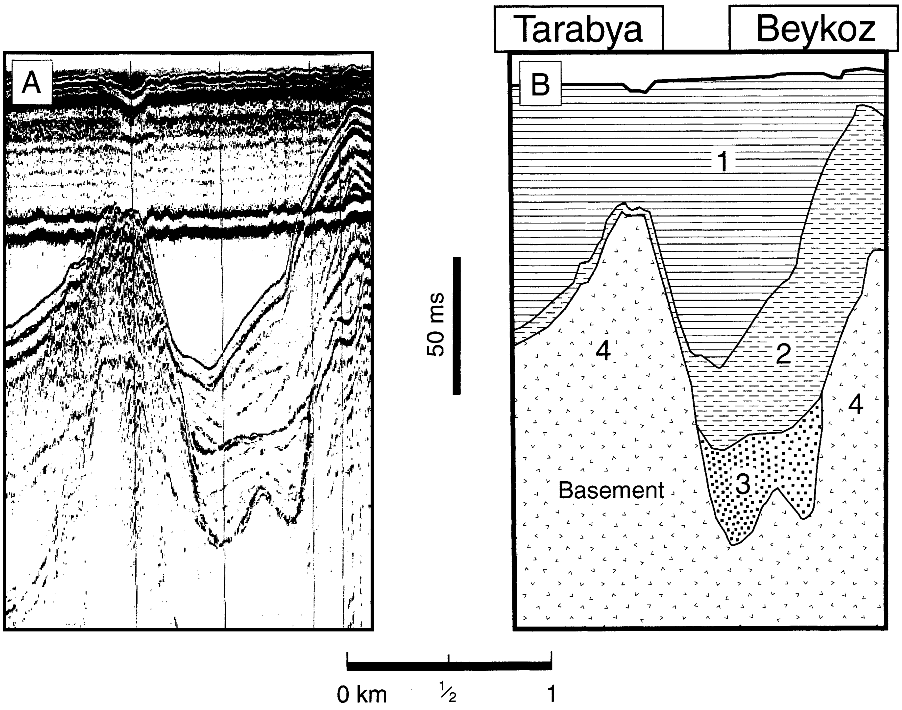


Fig. 5. (A) Air-gun reflection profile of the Bosphorus seafloor between Beykoz and Tarabya, north central Bosporus. See Fig. 2A for location (from Uluğ, 1994). (B) Interpretation of the air-gun profile (after Uluğ, 1994). Unit 1, water; unit 2, Quaternary deposits (Middle–Upper Holocene); unit 3, initial valley fill (Middle Pleistocene); unit 4, basement rocks (Palaeozoic).

tained from the vicinity of the drilling sites (Fig. 2A, SP) during a research cruise of the Dokuz Eylül University Institute of Marine Sciences (Uluğ, 1994), using a PAR 600-B air-gun (40 cubic inches) generating 125–139 atm air-pressure pulses at 0.5 s intervals. The return signals were collected via a 10-element single-channel streamer simultaneously onto an EPC 3200 or Techincs RSB 66W recorder. Depths on the resulting profiles are displayed in milliseconds of two-way travel time and in this region the seismic velocity of the Quaternary sediments is estimated to be around 1800 m/s. (Uluğ, 1994). Profiles from the vicinity of the borehole transect reveal two seismically contrasting units in the unconsolidated sediments (Fig. 5A,B). When compared with the succession recorded in borehole BPMB-14, the upper seismic unit (2) appears to correspond to the topmost 22.0 m of Holocene age sediments, while the underlying seismic unit (3) equates with the lower 17.5 m, of Late or Middle Pleistocene age. Seismic unit 4 correlates with the Palaeozoic/Mesozoic basement (Fig. 5B).

3. Sedimentology

The longest and most complete succession revealed in the five boreholes studied in the north-central sector of the Bosphorus (Fig. 2B) is found in borehole BPMB-14 (Fig. 6). This was studied in detail and lithological correlation was established with the other four boreholes in the transect (Fig. 7). The lower and upper units of unconsolidated sediment above the Palaeozoic basement recovered from borehole BPMB-14 display a very different sedimentological character (Fig. 6). The lower part is here designated Facies Association A, and the upper part is termed Facies Association B. No sedimentary structures were unequivocally recognised in these sequences because, despite the use of the Shelby drilling tubes, the

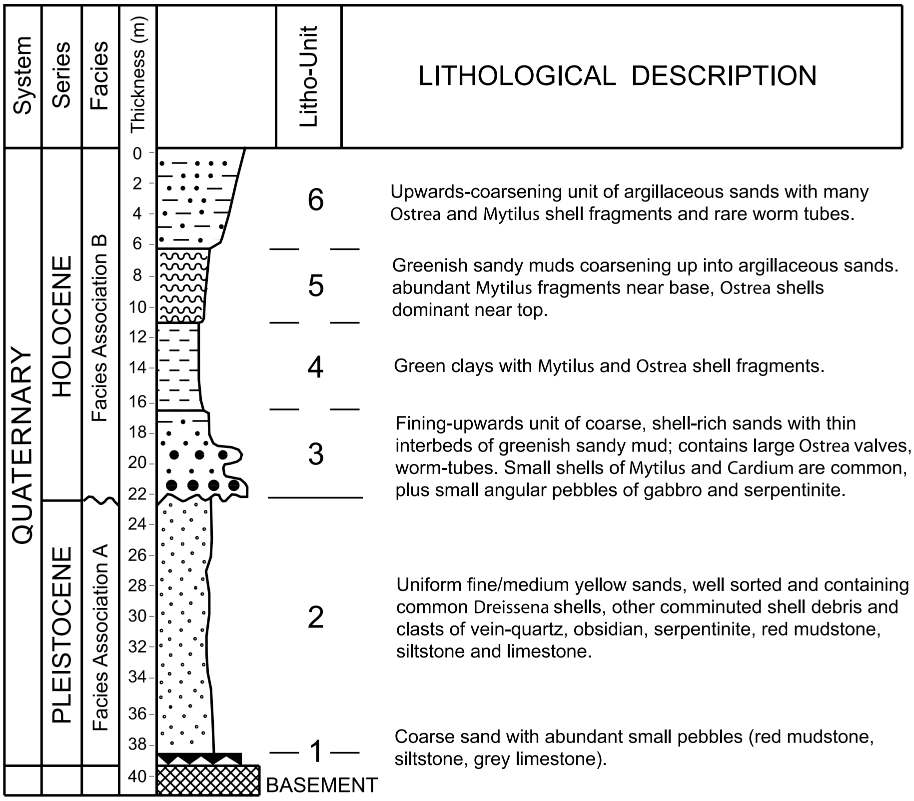


Fig. 6. Sedimentological features of borehole BPMP-14 in the north-central part of the Bosphorus (see Fig. 2B for location).

drilling technique resulted in destruction of these features. Environmental interpretations are therefore based on petrographical, textural and biostratigraphic characteristics.

3.1. *Facies Association A*

3.1.1. *Description*

This association is confined to borehole BPMB-14 and starts with 45 cm of coarse sand (litho-unit 1 in Figs. 6 and 7), containing abundant small pebbles (up to 15 mm diameter) of red mudstone, siltstone and grey carbonates, followed upwards by 17.0 m of relatively uniform, fine to medium, well-sorted yellow sands (litho-unit 2), with abundant comminuted shell fragments (up to 2 mm in diameter), predominantly pelecypods, gastropods and ostracods. Under the microscope the rounded to subrounded sand grains are seen to comprise quartz, plagioclase (anorthite), and shell fragments, together with foraminiferal tests and molluscan shell debris. The heavy mineral fraction is dominated by zircon, garnet and abundant magnetite. Limonitised hematite is present, together with small serpentinite clasts.

3.1.2. *Interpretation*

Such clean sands are typical of shallow water deposits, formed under moderate energy conditions in shoreline settings, or as bars at the mouth of an estuary. By inference, the pebble-bearing, shelly sands forming litho-unit 1 represent a lag-deposit at the base of the beach or bar sequence. Modern Black Sea coastal sands also contain abundant magnetite (Mugan and İpekoğlu, 1995) and Dreissena shells, suggesting that the Facies Association A sands have probably been transported from the shores of the Black Sea.

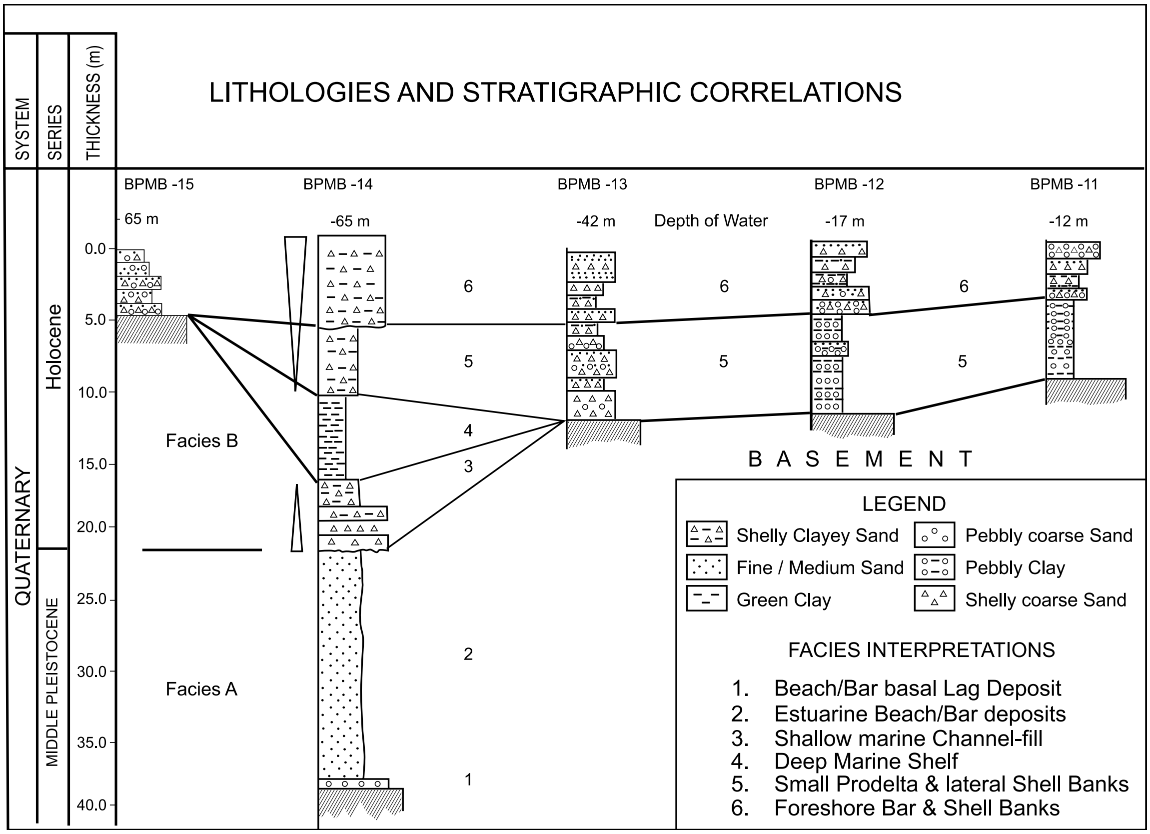


Fig. 7. Lithological characterisitics, correlation and distribution of environmental facies in Quaternary sequences recorded in the borehole transect from the north-central part of the Bosphorus (see Fig. 2A,B for location).

3.2. *Facies Association B*

3.2.1. *Description*

This unit (22.00 m thick in borehole BPMB-14) comprises crude alternations of fossiliferous sands and clays rich in organic matter. In borehole BPMB-14 the darker sediments of Facies Association B are abruptly separated from the yellow-brown sands of Facies Association A by a sharp, probably erosional, contact. In general, the sand samples of Facies Association B are coarser, with more conspicuous (and larger) shell fragments and poorer sorting than the sands of unit A. The interbedded muds are dark grey, with scattered shell debris evident (up to 10 mm in diameter). Excluding the abundant shells, the grain size of the muddy units is predominantly clay but with up to 45% silt-grade material.

The basal part (litho-unit 3 in Figs. 6 and 7) of this stratigraphic unit consists of 4.0 m of calcareous coarse sand, rich in shell fragments. Small pebbles scattered within this basal unit are angular and mainly composed of gabbro, serpentinite, and mudstone. The shells are predominantly *Ostrea*, *Mytilus*, and *Cardium*, encrusted with worm tubes. Litho-unit 3 displays a conspicuous upwards decrease in grain size (fining upward succession) and is gradationally succeeded by 7.0 m of adhesive green clay (litho-unit 4 in Fig. 6) containing *Mytilus* and *Ostrea* shell fragments. *Mytilus* fragments are also abundant in the lower part of the overlying thick (5.0 m) muddy sand interval (litho-unit 5), while *Ostrea* fragments are more abundant towards the top. Green clay matrix constitutes up to 45% of litho-unit 5 but the amount of clay gradually decreases in the uppermost 6.0 m of the sequence (litho-unit 6 in Figs. 6 and 7), simultaneously with an overall upwards increase in mean grain size. The coarser clastics of litho-unit 6 are replete with fragments of *Ostrea*, *Mytilus*, and worm-tubes.

3.2.2. Interpretation

The texture and faunal content of the coarse shell-rich sands of litho-unit 3 demonstrate that they were deposited under predominantly marine conditions as a relatively high-energy deposit. It was previously suggested (Çağatay et al., 2000, p. 202) that this and the succeeding litho-unit were formed by chaotic slumping. However, slumping does not account for the presence of exotic small pebbles in litho-unit 3 or for the observed upwards fining. These lithological features, when taken together with the lateral confinement of this litho-unit (Fig. 7) and the irregular basal surface revealed in local geophysical profiles (Fig. 5), are most plausibly attributed to deposition within a minor channel incised into the underlying Facies Association A sediments. The upwards fining in litho-unit 3 and the accompanying increase in content of green clay result from gradual infilling and abandonment of this channel, probably as sea level continued to rise. The succeeding thick green clays (litho-unit 4) resemble shelly muds described from the modern shelf of the Black Sea (Arthur et al., 1988; Ryan et al., 1997) and were deposited in deeper, lower-energy marine conditions. The two uppermost litho-units form a more widespread regressive, coarsening upwards sequence and probably represent the progradation of a small deltaic mouth-bar (5.0 m thick clayey sand), capped by coarser, shell-rich foreshore sands or wave-reworked shell banks (more prominent in the other boreholes drilled in shallow water; Fig. 7). The faunal evidence demonstrates that the entire Facies Association B interval in all the boreholes is fully to marginal marine in character (see below).

4. Palaeontology

4.1. Foraminifera

The yellow arkosic shelly sands forming Facies Association A in borehole BPMP-14 have yielded foraminifera that can be ascribed to the Black Sea fauna, such as *Quinqueloculina* sp., *Neoeponides* sp., *Cibicides advenum* (d'Orbigny), *Ammonia compacta* Hofker, *A. parkinsoniana* (d'Orbigny), *Cribroelphidium poeyanum* (d'Orbigny), *Porosononion subgranosum* (Egger), and *Elphidium crispum* (Linné). This microfauna represents a Paratethys foraminiferal assemblage (Yanko and Troitskaja, 1987; Yanko, 1989, 1990).

The overlying Facies Association B has yielded forms that represent predominantly Mediterranean but partly Paratethyan assemblages. The lowest litho-unit (3) of this facies contains mostly Mediterranean types and genera of foraminifera (Cimerman and Langer, 1991; Sagarella and Moncharmont-Zei, 1993). *Triloculina marioni* Schlumberger, *Eponides repandus* (Fichtel and Moll), *Vonkleinsmidia* sp., *Rosalina globularis* d'Orbigny, and *Tretomphalus bulloides* (d'Orbigny) are the typical examples for this unit. The succeeding litho-units 4 and 5 also yield typical Mediterranean foraminifera, but their types and genera are more restricted. The uppermost portion of Facies Association B (litho-unit 6) contains abundant and varied species and genera of Mediterranean-type foraminifera, such as *Adelosina pulchella* (d'Orbigny), *Spiroloculina dilatata* d'Orbigny, *Quinqueloculina viennensis* le Calvez J. and Y., *Triloculina morioni* Schlumberger, *Eponides repandus* (Fichtel and Moll), *Stomatorbina concentrica* (Parker and Jones), *Rosalina bradyi* Cushman, *R. globularis* d'Orbigny, *Cibicides advenum* (d'Orbigny), *Lobatula lobatula* (Walker and Jacob), *Astrononion stelligerum* (d'Orbigny), *Elphidium complanatum* (d'Orbigny), and *E. depressulum* Cushman (Meriç et al., 1998; 2000a).

We note that Mediterranean foraminiferal forms increase in abundance from bottom to top in the topmost interval (litho-unit 6). Overall, the foraminiferal assemblages obtained from the BPMP-14 borehole confirm that Mediterranean waters reached the northern Bosphorus in the Mid–Late Holocene

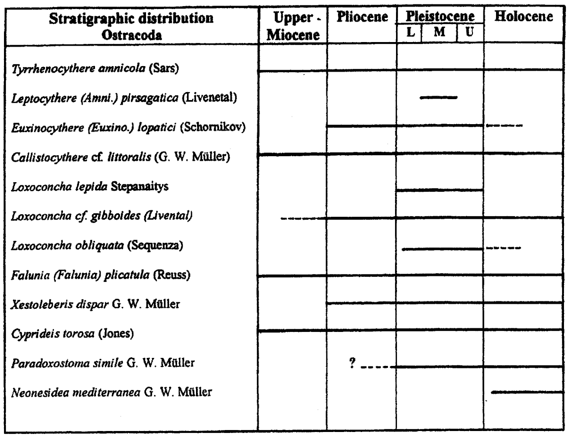
4.2. Ostracods

The lower part of the succession recorded in borehole BPMP-14 (Facies Association A) contains a rich ostracod fauna (56 out of 77 samples contain ostracods) that includes *Loxoconcha lepida* Stepanaitys, *L.* cf. *gibboides* (Livental), *Leptocythere (Amnicythere) pirsagatica* (Livental), *Euxinocythere (Euxinocythere) lopatici* (Schornickov), *Callistocythere* cf. *littoralis* (G.W. Müller), *Falunia (Falunia) plicatula* (Reuss), and *Tyrrhenocythere amnicola* (Sars) (Table 2).

This assemblage is typical of brackish-water environments and contains forms common to Tethys and Paratethys. However, when both the types and numbers of genera present are taken into account, the total assemblage is dominated by Paratethyan forms, notably *Loxoconcha lepida* Stepanaitys, *Leptocythere (Amnicythere) pirsagatica* (Livental), *Euxinocythere (Euxinocythere) lopatici* (Schornickov), and *Tyrrhenocythere amnicola* (Sars).

This assemblage is also characteristic of the *Cryptocyprideis bogatschovi* and *Loxoconcha lepida* Zones (Stancheva, 1989), generally regarded as Mid-Pleistocene (Old Euxinian) in age. *Leptocythere (Amnicythere) pirsagatica* (Livental), present in samples from eight levels in the lower part of Facies Association A (Fig. 8), is also typical of Paratethyan Mid-Pleistocene assemblages (Table 2).

Table 2
Stratigraphic range of ostracod species collected from boreholes in the Beykoz–Tarabya transect, north-central part of the Bosphorus



Stratigraphic distribution Ostracoda	Upper - Miocene	Pliocene	Pleistocene			Holocene
			L	M	U	
Tyrrhenocythere amnicola (Sars)	—	—	—	—	—	—
Leptocythere (Amni.) pirsagatica (Livenetal)				—		
Euxinocythere (Euxino.) lopatici (Schornikov)		—	—	—	—	----
Callistocythere cf. *littoralis* (G. W. Müller)	—	—	—	—	—	—
Loxoconcha lepida Stepanaitys			—	—	—	
Loxoconcha cf. gibboides (Livental)	----	—	—	—	—	—
Loxoconcha obliquata (Sequenza)			—	—	—	----
Falunia (Falunia) plicatula (Reuss)	—	—	—	—	—	—
Xestoleberis dispar G. W. Müller		—	—	—	—	—
Cyprideis torosa (Jones)	—	—	—	—	—	—
Paradoxostoma simile G. W. Müller		? ----	—	—	—	—
Neonesidea mediterranea G. W. Müller						—

The Facies Association B sediments in borehole BPMB-14 have yielded ostracods typical of the Holocene. The assemblages recovered indicate that the basal levels (litho-units 3 and 4 in Fig. 6) are slightly more brackish-water in character. However, fully marine Tethyan/Mediterranean forms are dominant throughout this higher sequence, as judged both by particular species and the range of genera.

Falunia (Falunia) plicatula (Reuss) is a Miocene–Holocene type that belongs to both Tethyan (Sissingh, 1972) and Paratethyan (Kristic, 1963) bioprovinces. In the Mediterranean bioprovince, *Neonesidea mediterranea* G.W. Müller (Bonaduce et al., 1975) and *Paradoxostoma simile* (G.W. Müller) are known to be Late Pleistocene–Holocene and Holocene in age, respectively. *Neonesidea mediterranea* G.W. Müller, also observed in Facies Association B from the boreholes BPMB-13, BPMB-14, and BPMB-15, further supports the above observations (Meriç et al., 1998, 2000b).

4.3. Pelecypods

Samples from Facies Association A in borehole BPMB-14 have yielded pelecypods such as *Modiolus (Modiolula) phaceolinus* (Philippi), *Dreissena polymorpha* (Pallas), *D. rostriformis* (Deshayes). It is noteworthy that both freshwater forms like *Theodoxus* sp. and *Valvata* sp., and brackish-water forms like *Dreissena polymorpha* (Pallas) and *Hydrobia (Hydrobia) acuta* (Draparnaud) occur together in this lower interval, which also contains reworked and eroded shell fragments, thought to be older than the Quaternary, based on their shell structure and preservation state. These forms typically represent Central and Eastern Paratethys faunas (Pannonic, Euxinic, and Ponto-Caspic) (Meriç et al., 1998, 2000b).

Many of the pelecypods from Facies Association B are diagnostically Mediterranean in origin. Such forms include: *Anadara diluvii* (Lamarck), *Rhomboidella prideauxi* (Leach), *Modiolus barbatus* (Linné), *Dimya tenuiplicata* (Sequenza), *Lasaea nitida* (Turton), *Gari depressa* (Pennant), *Clausinella fasciata* (Da Costa), and *Corbula (Lentidium) mediterranea* (Costa).

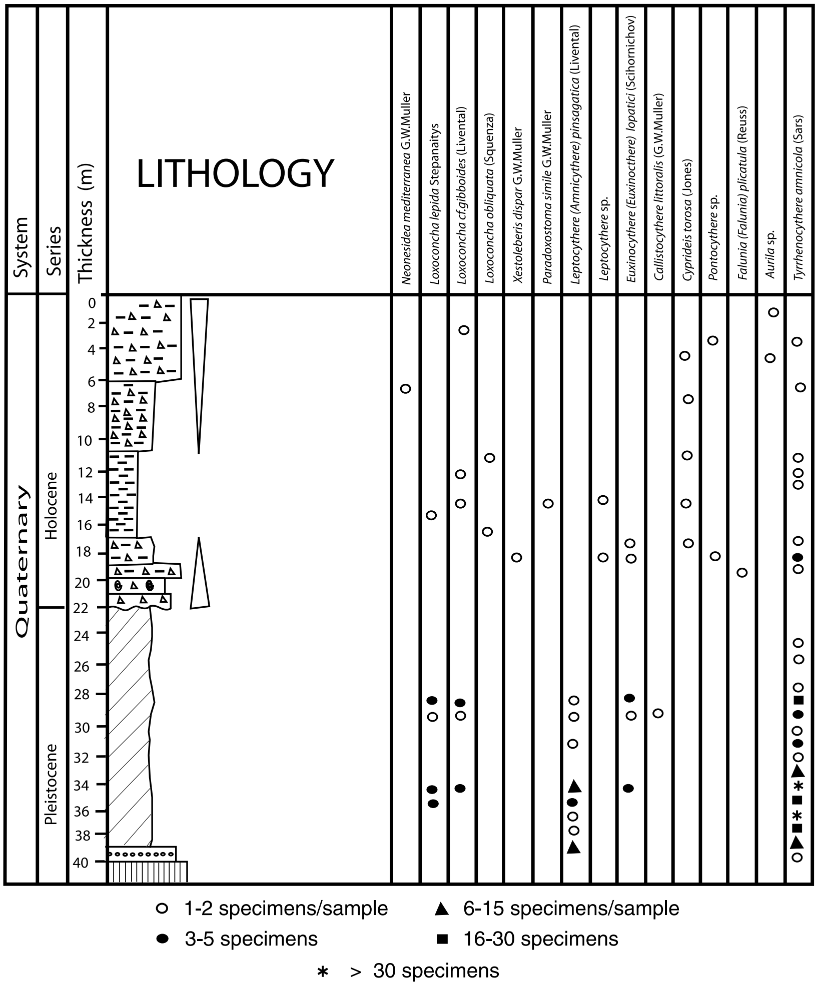


Fig. 8. Occurrence and frequency of ostracod species in samples from the BMPB-14 borehole. Frequency is indicated as follows: open circles, one to two specimens per sample; filled circles, three to five specimens per sample; filled triangles, six to 15 specimens; filled squares, 16 to 30 specimens; asterisks, >30 specimens.

4.4. Gastropods

Samples from Facies Asssociation A in borehole BPMB-14 have yielded gastropods such as *Theodoxus* sp., *Valvata* sp., *Hydrobia (Hydrobia) acuta* (Draparnaud), *Nematurella* sp., and *Pseudamnicola* sp.

Both freshwater forms like *Theodoxus* sp. and *Valvata* sp., and brackish-water forms like *Dreissena polymorpha* (Pallas) and *Hydrobia (Hydrobia) acuta* (Draparnaud) occur together in this older unit, which also contains reworked and eroded shell fragments, thought to be older than Quaternary, based on their shell structure and preservation state. These forms are typical of Central and Eastern Paratethys faunas (Pannonic, Euxinic, and Ponto-Caspic) (Meriç et al., 1998, 2000a).

The gastropods observed in the succeeding Facies Association B include *Diadora italica* (Defrance), *Calliostoma (Callioosotoma) conulus* (Linné), *Gibbula (Tumulus) umblicaris* Linné, *Alvania (Alvania) reticulata* (Montagu), *A. (Acinulus) cimicoides* (Forbes), *Turboeella (Turboella) parva* (Da Costa), *Rissoa querini* Recluz., *Rissoina (Schwarztziella) bryerea* (Montagu), *Pirenella* *conica* (Blainville), *Bittium desayesi* Cerulli and Irelli, *B. lacteum* (Philippi), *B. (Bittium) spina* (Partsch), *Cyclope donovania* Risso, *Triphora (Triphora) perversa* (Linné), *Melanella (Balcis) incurva* (Renieri), *Retusa truncatula* (Bruguière), *Ringicula (Ringicula) conformis* Monterosato, *Chrysallida (Parthenina) initeresincta* (Montagu), and *Turbonilla lactea* (Linné). This assemblage is typical of marine Mediterranean environments.

4.5. Bryozoans

No bryozoans were observed in Facies Association A. However, Facies Association B yielded *Crisia* sp., *Electra* sp., *Cellaria salicornioides* Audouin, *Scrupocellaria scruposa* (Linné), *Caberea boryi* (Audouin), *Schizoporella* sp., *Cryptosula pallasiana* (Moll),*Microporella ciliata* (Pallas), *Smittoidea reticulata* (Mac Gillvray), and *Lagenipora lepralioides* (Norman). These genera and types are Atlantic–Mediterranean forms and their presence clearly shows the influence of Mediterraean waters in the Bosphorus during the Middle–Late Holocene. *Microporella ciliata* (Pallas), observed in these northern Bosphorus Holocene sediments, was not found in previous studies of Holocene sequences in the southern Bosphorus (including the Golden Horn and Anadoluhisari region), or in the İzmıt Gulf. *Caberea boryi* (Audouin) was previously encountered only in the İzmıt Gulf wells (Ünsal and Rosso, 1995; Ünsal et al., 1995).

5. Discussion

5.1. Evidence from Bosphorus Strait

The sedimentological, faunal and geophysical evidence presented above indicates that Quaternary sediments deposited within the north-central part of the Bosphorus comprise two main units that differ markedly in age, environmental characteristics and provenance. The lower stratigraphic unit (Facies Association A) is a succession of lacustrine beach or coastal sands, radiocarbon-dated as Late Pleistocene (26–16 kyr BP; Çağatay et al., 2000) but including Black Sea faunal elements of Middle Pleistocene age, which may be reworked. The shelly sands and muds of Facies Association B have yielded absolute ages and biostratigraphic evidence of Mid- to Upper Holocene age (see Fig. 9). Deposition of this unit apparently commenced around 5300–6000 yr BP, the contained faunas are predominantly Mediterranean and the sediments record a range of shallow marine and coastal environments. The above evidence indicates that the sharp boundary separating these major units represents a significant time gap.

A similar unconformity has been recognised throughout the central and southern Bosphorus (Uluğ, 1994; Gökaşan et al., 1997). In the geophysical profiles the Holocene unit appears to down-lap on to this unconformity surface, suggesting that it represents a depositional hiatus, although minor localised channelling is also observed on this surface (Fig. 5; cf. Gökaşan et al., 1997, their figures 4, 8 and 9). This minor channelling supports the interpretation of the basal litho-unit (3) of Facies Association B as a channel lag.

In the southern Bosphorus the arrival of Mediterranean waters has been dated by electron spin resonance (ESR) analyses on mollusc shells at 7400 ± 1300 yr BP (Meriç and Sakınç, 1990; Göksu et al., 1990) (see Fig. 9). ESR dates such as 6100 ± 1300 and 5700 ± 1800 yr BP that characterise the Middle Holocene were also obtained from the upper levels of sequences in the Golden Horn (Fig. 2C; Yanko, 1990; Meriç, 1997a,b) and the faunal evidence here demonstrates the rapid change from fluvial–brackish through marine–brackish to fully marine conditions during the Mid-Holocene (Meriç, 1997a,b). In a well drilled just offshore from Üsküdar, in the southern Bosphorus, (Fig. 2A,C), a mollusc assemblage including *Bittium reticulatum* (de Costa) and *Piranella conica* (Blainville), recovered from the lower part of the drilled succession(Taner, 1990), yielded ESR dates of 6100 ± 1300 and 5100 ± 1200 yr BP and thus attests to the existence of brackish-water conditions here in the Middle Holocene (see Fig. 9; Göksu et al., 1990).

Meriç et al. (2000b) have recorded the presence of *Lingulodinium machaerophorum* (Cooks and Ei-

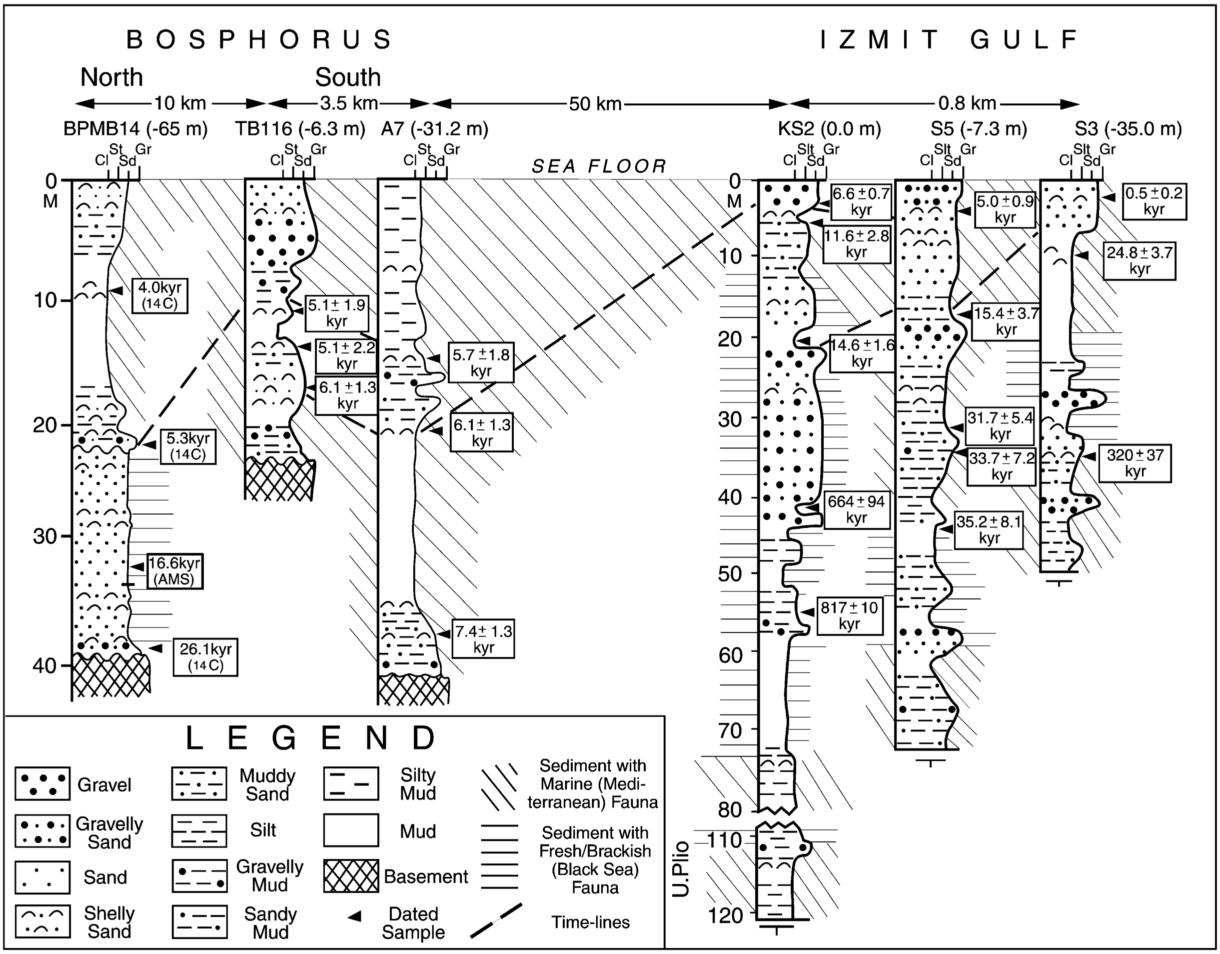


Fig. 9. Diagram illustrating chronostratigraphic, lithostratigraphic and palaeoecological relationships among Quaternary sequences deposited in the Bosphorus and Gulf of İzmıt, utilising data from representative boreholes. Locations of İzmıt Gulf boreholes KS2, S5 and S3 are shown in Fig. 1C; location of BPMB-14 in Fig. 2B; locations of boreholes TB116 and A7 in Fig. 2C. Radiocarbon dates (calibrated and reservoir-corrected) for BPMB-14 are from Çağatay et al. (2000); data for TB116 and A7 (including ESR dates) are from Meriç et al. (1990); and data for KS2, S3 and S5 (including ESR dates) are from Meriç et al. (1995a,b). See text for explanation.

senack) and *Cymatiosphaera* sp. in sediments considered to be coeval with Facies Association B in the Anadoluhisari region (central Bosphorus), indicating that a brackish-water depositional environment also persisted there into the Mid-Holocene. These findings indicate that during the Middle Holocene much of the Bosphorus and the Golden Horn were still influenced by rivers conveying low-salinity waters but nevertheless there was continuous connection with the Marmara Sea (Taner, 1990).

5.2. Evidence from Sea of Marmara and Gulf of İzmıt

A much longer Quaternary history is recorded in sediment successions recovered from the Kadıköy–Kuşdili wells on the northern coast of the Marmara Sea, where a 45 m thick Quaternary sequence yields ESR dates such as 925 000 (± 101 000), 786 000 (± 88 000) yr BP from lower levels and 308 000 (± 35 000)–209 000 (± 21 000)–204 000 (± 18 000) yr BP from the middle parts

(Meriç et al., 1996) and thus records much older intervals (Lower Pleistocene and Middle Pleistocene, respectively).

Sequences of similar, and even older, dates have been discovered in boreholes drilled across the inner part of the Gulf of İzmıt (Figs. 1C and 9). These reveal substantial thicknesses (up to 118.0 m) of Late Pliocene–Pleistocene and Holocene sediments and show no evidence of the sub-Middle Holocene unconformity encountered in the Bosphorus. Indeed, microfaunas and macrofaunas obtained from several levels within these İzmıt Gulf sediments include typical Black Sea elements and demonstrate that in this area there was intermittent connection between the Black Sea and the Marmara Sea throughout much of the Pleistocene (Meriç, 1995b; Tchapalyga, 1995).

Importantly, the occurrence of the pelecypod *Dreissena* in the Quaternary sediments of the Bay of İzmıt indicates the existence of brackish-water conditions, probably of Black Sea provenance, here during the Early and Mid-Pleistocene (ESR dates of 817 000 ± 105 000; 664 000 ± 94 000; 320 000 ± 37 000; 186 000 ± 20 000 yr BP; see Fig. 9).

The presence of *Dreissena polymorpha* (Pallas) in the Chauda (Bacunian) terraces of the Dardanelles and of *D. rostriformis pontocaspia* (Andrussow) in the older sediments encountered in the İzmıt Gulf boreholes indicates that both these parts of the Sea of Marmara were under the influence of Ponto-Caspic waters in the Mid- to Late Pleistocene (Taner, 1983). İslamoğlu and Tchepalgya (1998) also identified these two characteristic Black Sea species in the Late Pleistocene of the Black Sea Basin. Thus the evidence from İzmıt Gulf demonstrates that during the Pliocene–Holocene interval there has been frequent and prolonged interconnection between the Black and Marmara/Aegean seas, whereas the Bosphorus yields evidence of such a connection only within the Holocene.

5.3. Evidence from the Black Sea area

On the Crimean shelf, on the northern coast of the Black Sea, two different units of Quaternary age were identified by Ryan et al. (1997). The lower unit, interpreted as lake-shore facies, comprises shell-bearing gravel, sand and muds containing *Dreissena rostriformis* (Deshayes), a typical Caspian Sea pelecypod, plant debris and *Viviparus viviparus* (Linné), a typical fluvio-lacustrine gastropod. The calibrated age of this unit by the AMS ^{14}C method ranges between 14 700 ± 65 and 10 400 ± 100 yr BP, i.e. Late Pleistocene (New Euxinian) (Ryan et al., 1997). The overlying Crimean shelf unit includes several sapropelic layers, providing the first indication of the post-glacial events (Ryan et al., 1997). Euryhaline marine dinoflagellates and diatoms were observed in this upper portion, together with marine molluscs such as *Cardium edule* Linné, *Mytilaster lineatus* Gmelin, *Mytilus galloprovincialis* Lamarck, *Hydrobia ventrosa* (Linné), and *Abra ovata* (Philippi). This upper unit had been dated as Holocene by previous workers and the absolute (calibrated) age by ^{14}C method is 7150 ± 100 yr. Ryan et al. (1997) thus deduced that during the Late Pleistocene and earliest Holocene the Black Sea was a large lake with its surface up to 150 m below present sea level, initially fed by glacial melt waters until around 9500 years ago. They concluded that Mediterranean waters finally entered the Black Sea through the Bosphorus about 7150 years ago, and that this influx occurred on a catastrophic scale, resulting from sudden overtopping of the south Bosphorus sill at a present depth of 35 m as global sea level rose in the Holocene (see also Ryan et al., 2003).

However, the timing and abrupt nature of this marine influx are disputed by Görur et al. (2001), who studied the coastal plain and offshore sedimentary successions around the mouth of the Sakarya River, on the southern Black Sea coast, about 130 km east of the Bosphorus (Figs. 1A and 3). These authors concluded that there was a gradual rise in the level of the Black Sea lake from some time prior to 8000 yr BP until it attained a surface level of −18 m around 7200 yr BP, when the most recent influx of Mediterranean waters began.

Further evidence for a higher level of the Black Sea in the early Holocene has been adduced by Aksu et al. (1999, 2002), who identified from high-resolution geophysical profiles a 15 m thick prograding delta lobe in the northern part of the Marmara Sea. According to Aksu et al. (1999, 2002) this delta was built by vigorous westward outflow from a higher-level Black Sea during a period of rising sea level between 10 and 9 kyr BP, although the possible contribution of rivers draining the southern slopes of the Kadıköy region (ancestral Kubağali Dere, etc.; Fig. 2A) to this delta growth should not be ignored. Similarly, Çağatay et al. (2000) consider that the formation of a sapropel layer in the deep Marmara Sea during the period 10 600–6400 yr BP reflects water-column stratification and seafloor anoxicity, which they attribute to prolonged freshwater influx from a Black Sea whose surface at that time must have been at or above the Bosphorus sill depth of −35 m.

Evidence from Quaternary sequences in other parts of the Black Sea and its periphery, summarised by Yanko-Bombach et al. (2002), demonstrate that the Black Sea surface rose from −65 to −35 m in the interval from 9400 to 8000 yr BP, then dropped back to around −40 m in the Pontian regression (8000–7500 yr BP), but rose once more during the Kalamitian transgression (7200–5000 yr BP), when Mediterranean species finally became fully established across this region. Tchapalyga (1995) also has pointed out that the Late Pleistocene and Early Holocene of the Black Sea region was marked by spasmodic but significant fluctuations in water level and the periodic appearance of Mediterranean species, tolerant to higher salinities.

In summary, the evidence strongly suggests that previous studies may have placed undue emphasis on the Bosphorus as the sole or main waterway connecting the Mediterranean and Black Sea during the later Quaternary. It is also likely that models for this connection that involve purely eustatic oscillations in local sea level and that stress the role of present-day sill depths in the Bosphorus and Dardanelles are too simplistic, especially in view of the seismically active nature of the Bosphorus/North Marmara region and the Quaternary fault movements recorded in local geophysical profiles. For example, it is improbable that the depth of the south Bosphorus sill, lying within the ambit of the North Anatolian Fault System, has remained at −35 m throughout the entire span of the Late Pleistocene and Holocene.

Other routes for previous Black/Marmara Sea connections thus need to be considered, as Meriç et al. (1995b) and Çağatay et al. (2000) have argued. The İzmıt Gulf–Lake Sapanca–Sakarya Valley waterway represents a viable longer-term alternative (Pfannensteil, 1944), as suggested by the borehole records from the İzmıt Gulf (Fig. 9) that demonstrate the persistence of Mediterranean faunas since 10 000 yr BP, significantly longer than is evident from the Bosphorus. Present-day morphology suggests that a northward connection from the Büyük Çekmece Lagoon, west of İstanbul, also appears feasible, but as yet this hypothesis lacks supporting evidence. Of course, the record of the central and northern Bosphorus boreholes may be incomplete, and Mediterranean waters might have passed through the Strait in the Early Holocene without leaving a sedimentary record anywhere in this region. However, this appears implausible in view of the lack of palaeotopographic relief below the Mid-Holocene unconformity disclosed by the geophysical profiles.

6. Conclusions

(a) Borehole and related geophysical evidence from the north-central Bosphorus reveals the presence of two distinct stratigraphic units in the preserved Quaternary sub-seafloor sediments: A lower, laterally confined unit (Facies Association A) comprising beach/bar arkosic and shelly sands that have yielded Mid-Pleistocene ostracod shells (possibly derived) but which are radiometrically dated (^{14}C) as Late Pleistocene (Çağatay et al., 2000). This is abruptly succeeded by a more diverse and heterolithic unit, comprising shelly and muddy sands, clays and minor gravels (Facies Association B) and representing a range of shallow marine and coastal environments and formed since the Mid-Holocene (^{14}C dates of 5000–6000 yr BP; Çağatay et al., 2000).

(b) The surface separating these two major units is correlated with an unconformity recognised in geophysical profiles from the central and northern Bosphorus (Gökaşan et al., 1997).

This unconformity appears to represent a significant depositional hiatus.

(c) Faunal elements preserved in the lower (Pleistocene) sediments are exclusively of Ponto-Caspian (Black Sea) affinity and are typical of lacustrine and lagoonal settings. Both macro- and micro-faunas recovered from the upper unit (Mid–Late Holocene) display characteristic Mediterranean assemblages and are ecologically consistent with both fully marine and more restricted coastal settings.

(d) Thus the northern and north-central sectors of the Bosphorus formed an estuarine/lagoonal arm of the Black Sea during much of the Pleistocene. Presumably at that time these sectors were separated from the southern, fault-bounded portion of the Strait (and the Marmara Sea) by a topographic barrier of some sort. The first evidence for the role of the northern Strait as a link in the Aegean–Black Sea marine connection system dates from around 5300 years ago. This is significantly later than the date of the cataclysmic influx required by the 'Catastrophic Flood' hypothesis of Ryan et al. (1997, 2003) (and perhaps 2000 years after Mediterranean waters arrived in the southern Bosphorus).

(e) Thus the assumption that the present-day Bosphorus sill depth was a critical factor in the interchange of Black Sea and Aegean waters throughout the Late Quaternary requires re-appraisal. Concomitantly, the role of other potential connection routes, such as the Gulf of İzmıt–Sapanca Lake–Sakarya Valley, requires further evaluation.

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