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Stratigraphy of the sediment infill in Bosphorus Strait: water exchange between the Black and Mediterranean Seas during the last glacial Holocene

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Abstract The sediment infill over the Paleozoic bedrock in the Bosphorus Strait consists of four sedimentary units which were deposited in the last 26,000 ^{14}C years B.P. The stratigraphy of these units suggests that this part of the Bosphorus was a freshwater lake between 26,000 and 5,300 ^{14}C years B.P., depositing sands with a freshwater mollusc fauna of Black Sea neo-euxinian affinity (*Dreissena rostriformis*, *Dreissena polymorpha*, and *Monodacna pontica*). The first appearance of euryhaline Mediterranean molluscs (e.g., *Ostrea edulis*, *Mytilus edulis*) was observed at 5,300 ^{14}C years B.P. in this part of the Bosphorus. Deposition of coarse *Mytilus*-bank and *Ostrea*-bank units suggests that the establishment of the present dual-flow regime in the Bosphorus took place at about 4,400 ^{14}C years B.P.

Introduction

The Bosphorus Strait (Strait of Istanbul), together with the Sea of Marmara and the Dardanelles Strait, connects the Black Sea with the Mediterranean Sea (Fig. 1). It has a two-layer flow system, with the upper-layer Black Sea waters (S = 18 ‰) and the lower-layer Mediterranean waters (S = 38‰) flowing in opposite directions. A sharp pycnocline occurs between the two layers at 50 m at the Black Sea entrance, and at 20–25 m at the Sea of Marmara entrance to the Bosphorus channel. The upper- and lower-layer current velocities in the Bosphorus vary in the range 10–30, and 5–15 cm s^{-1}, respectively. The present average annual fluxes of Black Sea and Mediterranean Sea waters through the Bosphorus are about 600 and 300 km^3, respectively (Latif et al. 1990; Ünlüata et al. 1990; Özsoy et al. 1995).

The Bosphorus is a meandering strait with a length of 31 km, widths varying from 0.7–3.5 km with a mean depth of 35 m (Fig. 2). It has a very irregular bottom profile with several major deeps and sharp bends along its course. Its maximum depth occurs in a depression situated off Bebek (110 m). There are two sills which are probably composed of late-Quaternary sediments (Gökaşan et al. 1997). One is located off the northern entrance at depths of 57–59 m, and the other is in the southern entrance at 32–34 m (Fig. 2). The northern sill lies within a narrow submarine valley generally known as the pre-Bosphorus channel which forms a natural extension of the strait into the Black Sea (Oğuz et al. 1990). The southern sill extends along the midchannel with a minimum depth of about 28 m. This channel gradually deepens beyond the sill towards the Sea of Marmara, and eventually joins a submarine canyon. The bathymetry of the central section is dominated by a broad channel trending north-northwest to south-southeast parallel to the axis of the Bosphorus.

The basement in the Bosphorus channel is constituted by Paleozoic and Upper-Cretaceous rocks under a sediment infill which locally reaches a thickness of more than 130 m in the southern part (Fig. 3). The thick infill near the south entrance is a sand bar which constitutes the shallowest present-day sill in the strait. The sand bar appears to extend northwards from the Sarayburnu (Saray Promontory), and is probably formed by the piling of coarse sediments by current and wave activity near the mouth of the Golden Horn Estuary.

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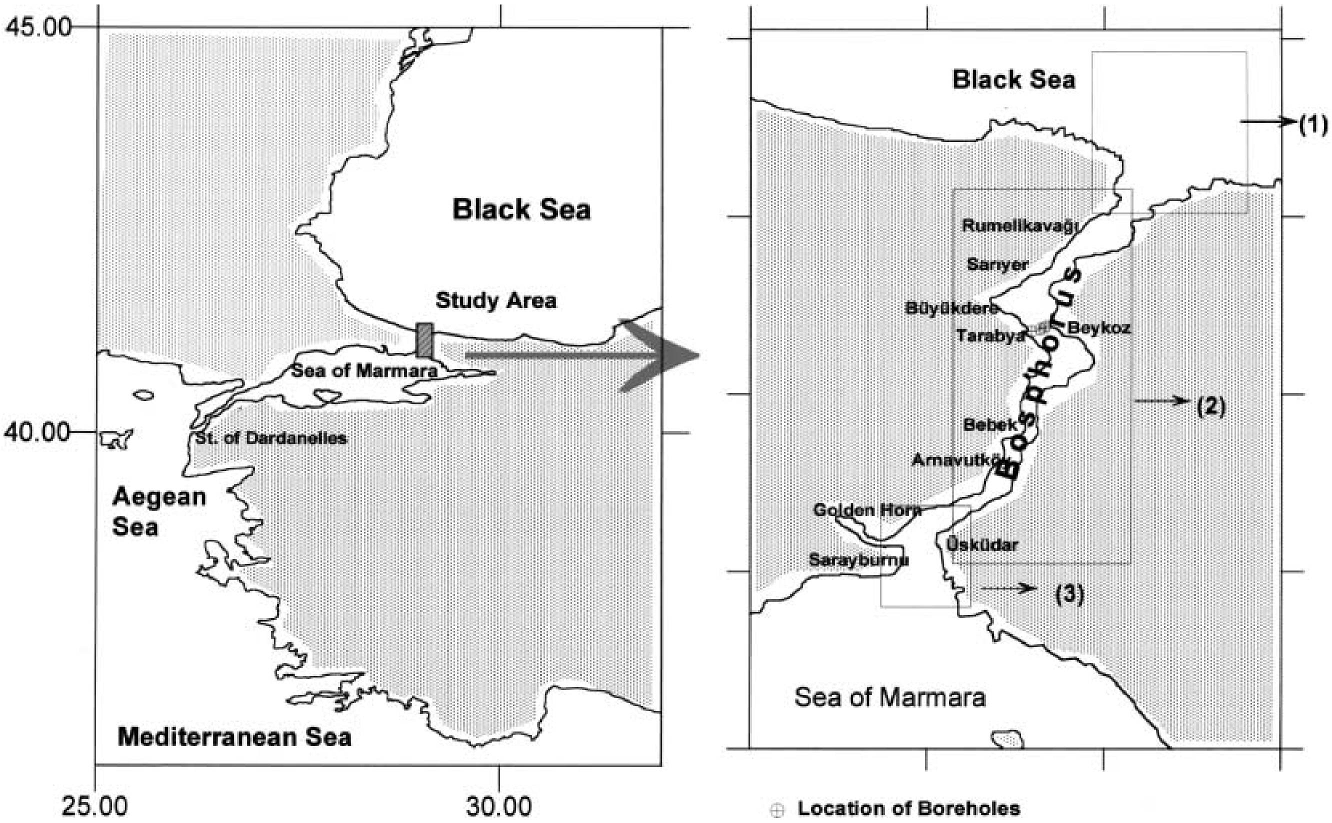


Fig. 1 Locality map of the Bosphorus (Strait of Istanbul). *Framed areas 1*, *2* and *3* correspond to those in Fig. 2

The basement topography of the Bosphorus is rather irregular and displays a southward deepening, with depths locally exceeding 160 m (Fig. 3; Gökaşan et al. 1997). There are three conspicuous basement sills at depths of 80–85 m. One of these sills is located off Rumelikavağı in the north, the other two being situated off Beykoz near the central Bosphorus where they flank a depression.

Previous studies on the origin of the Bosphorus channel have dealt mainly with geological and geomorphological observations on land (Phillipson 1898; Andrussow 1900; Penck 1919; Darkot 1938; Pamir 1938; Erinç 1940; Yalçınlar 1947; Yılmaz and Sakınç 1990; Oktay and Sakınç 1991), seismic stratigraphic aspects (Uluğ et al. 1987; Alavi et al. 1989; Gökaşan et al. 1997), and surface sediments (Ergin et al. 1991). According to most of these, the Bosphorus channel was formed by a combination of faulting and fluvial processes. The history of water exchange between the Black and Mediterranean seas through the Bosphorus has been based indirectly on the global sea-level curve and the study of sediments, mainly in the Black Sea (Degens 1971; Bukry 1974; Deuser 1974; Maynard 1974; Nevesskaya 1974; Scholten 1974; Ross and Degens 1974; Hsü 1978; Stanley and Blanpied 1980; Ryan et al. 1997). These studies show that the Black Sea was isolated from the Mediterranean Sea and became a freshwater lake during the last glacial until the early Holocene when the global sea level fell below the level of the Bosphorus sill. However, the timing of the final inundation of the Black Sea by Mediterranean waters during the early Holocene is still disputable, the ages of this event ranging from about 9,000 to 7,000 years B.P. (Deuser 1974; Ross and Degens 1974; Ryan et al. 1997).

No previous work involving sediment cores reaching all the way to the bedrock has been carried out on the evolution of the Bosphorus channel and its history of water exchange. The present study is based on stratigraphic analyses of cores from five boreholes drilled by the General Directorate of State Hydraulic Works (DSİ) in the central Bosphorus (Fig. 1). These boreholes intercept the late Quaternary sediments and reach the Paleozoic basement. We report the results of sedimentological and paleontological analyses as well as ^{14}C dating of the cores, and use these data to interpret the history of water exchange between the Black and Mediterranean Seas.

Materials and methods

The boreholes were drilled employing both percussion and rotary drilling methods. Section casings were driven up to 5–7 m. The sediment samples were obtained by means of a spoon sampler from within casing at 0.5- to 1-m intervals. The subsamples were lithologically described and studied under a binocular microscope to ascertain their general composition. Aliquots were washed for identification of molluscan and foraminiferal

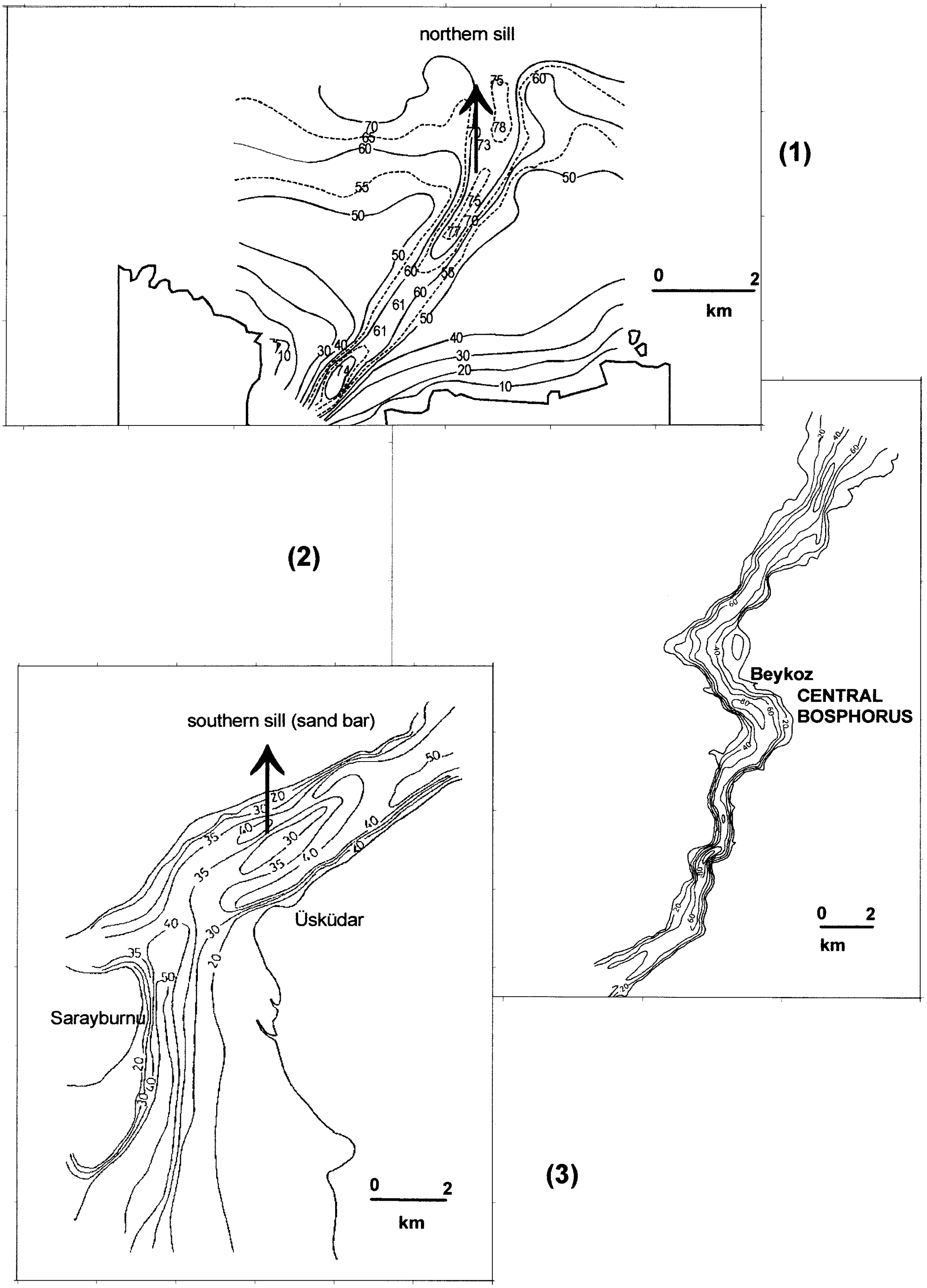


Fig. 2 Bathymetry of the Bosphorus channel, including its northern and southern entrances (see Fig. 1 for the location of *framed areas 1*, *2* and *3*). *Area 1* has been modified after Yüce (1996), *area 2* after Gökaşan et al. (1997), and *area 3* after Latif et al. (1990)

assemblages. Conventional radiocarbon dating was carried out on samples from borehole 14 at the Isotope Geochemistry Laboratory of the University of Arizona. Single shells of oysters were in general sufficient for dating, whereas several shells of the mussel *Dreissena*

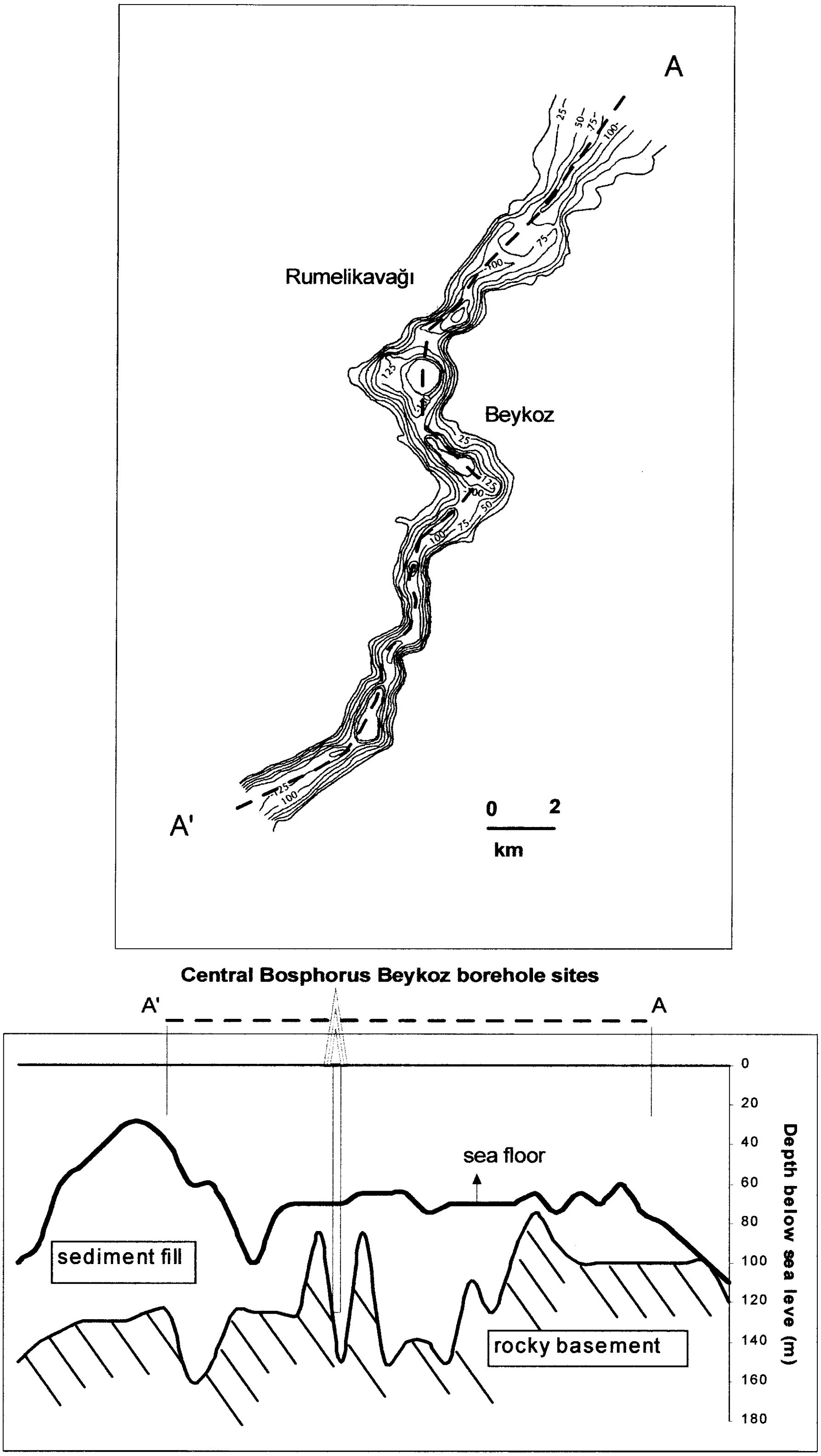


Fig. 3 Longitudinal section through the Bosphorus channel along the *dashed line* A-A′, showing the basement profile and sediment infill (extracted from Gökaşan et al. 1997). The vertical profile of the seafloor has been produced from data in Fig. 2

rostriformis were needed to obtain a sample of adequate size. One *Dreissena* shell from borehole 14 was dated by the AMS method. Ages were calculated as ^{14}C years B.P., corrected for ^{13}C, and expressed at the $\pm 1\sigma$ level for analytical confidence.

Results

The boreholes were located in a 160-m-deep basement depression between Tarabya and Beykoz in the central

Bosphorus (Fig. 4). The sediment infill intercepted by the boreholes consisted of four units (Fig. 5). Its total thickness varied from 4–40 m, with borehole 14 containing the thickest sedimentary record. The highly variable thickness of the sedimentary infill is the result of basement paleotopography. The lithology and fossil assemblages of the various units are described below.

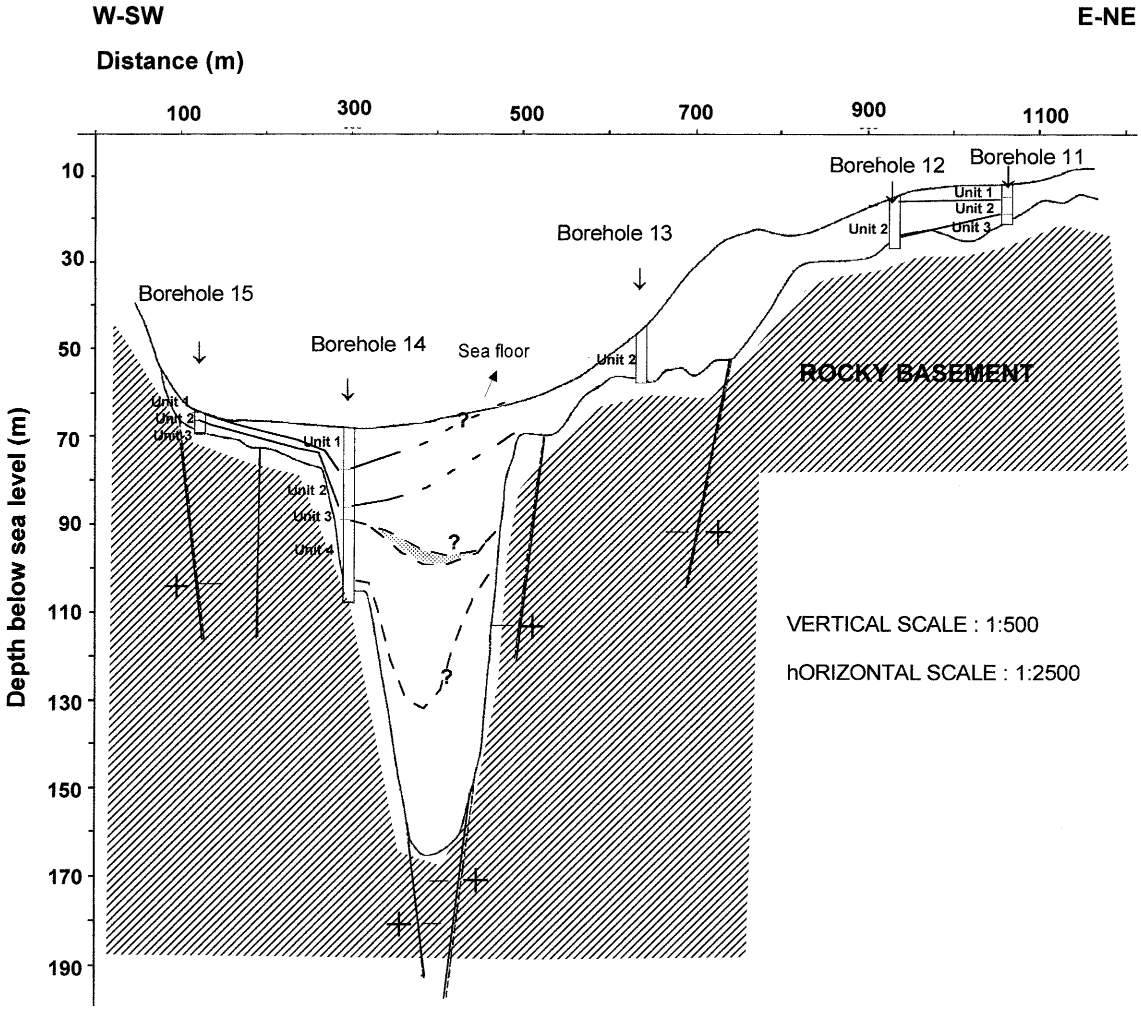
Unit 1 – oyster bank

This unit is represented by an oyster-bank facies consisting predominantly of large *Ostrea edulis* shells in a minor green-gray mud matrix. It contained small amounts of sand, gravel, and rock fragments in boreholes 11 and 15 which were located on either side of the Bosphorus channel. The thickness of this unit varied from 0–9 m. It was absent in boreholes 12 and 13, most probably because of erosion. Common mollusc species found in this layer were *O. edulis*, *Mytilus edulis*, and *Triphora perversa*. This unit contained only a few benthic foraminiferal tests (cf. *Planorbis mediterraneanensis*, *Ammonia beccari*, *Quinqueloculina seminula*, and *Elphidium crispum*). The faunal composition and lithology indicate a fully marine, high-energy depositional environment. Two ^{14}C dates from *Ostrea* shell samples at 5 and 8.5 m below seafloor (mbsf) in borehole 14 are 4,565 ± 85 and 4,040 ± 70 years B.P., respectively (Fig. 5). The reversal of the ages within this unit might be related with sediment slumps occurring at the west side of the depression (Fig. 4; note the increasing thickness of this unit between boreholes 15 and 14) or it can be an erroneous result (see below).

Unit 2 – Mydian bank

The Mydian-bank unit consisted mainly of *M. edulis* shells with lesser amounts of *O. edulis* shells, a few foraminiferal tests, and locally gravel and fine sand containing small amounts of greenish gray mud matrix. It had a thickness of 12 m in boreholes 12 and 13 (Fig. 5). The foraminifer species present were *Globigerina* sp, *Rosalina floridensis, Lobatula lobatula*, and *Ammonia*

Fig. 4 Section across the central Bosphorus showing the distribution of sedimentary units (modified after DSİ 1998). The *dotted pattern* shows the transgressive overlapping layers in the central part which may be missing towards the edges of the depression (see text for explanation)



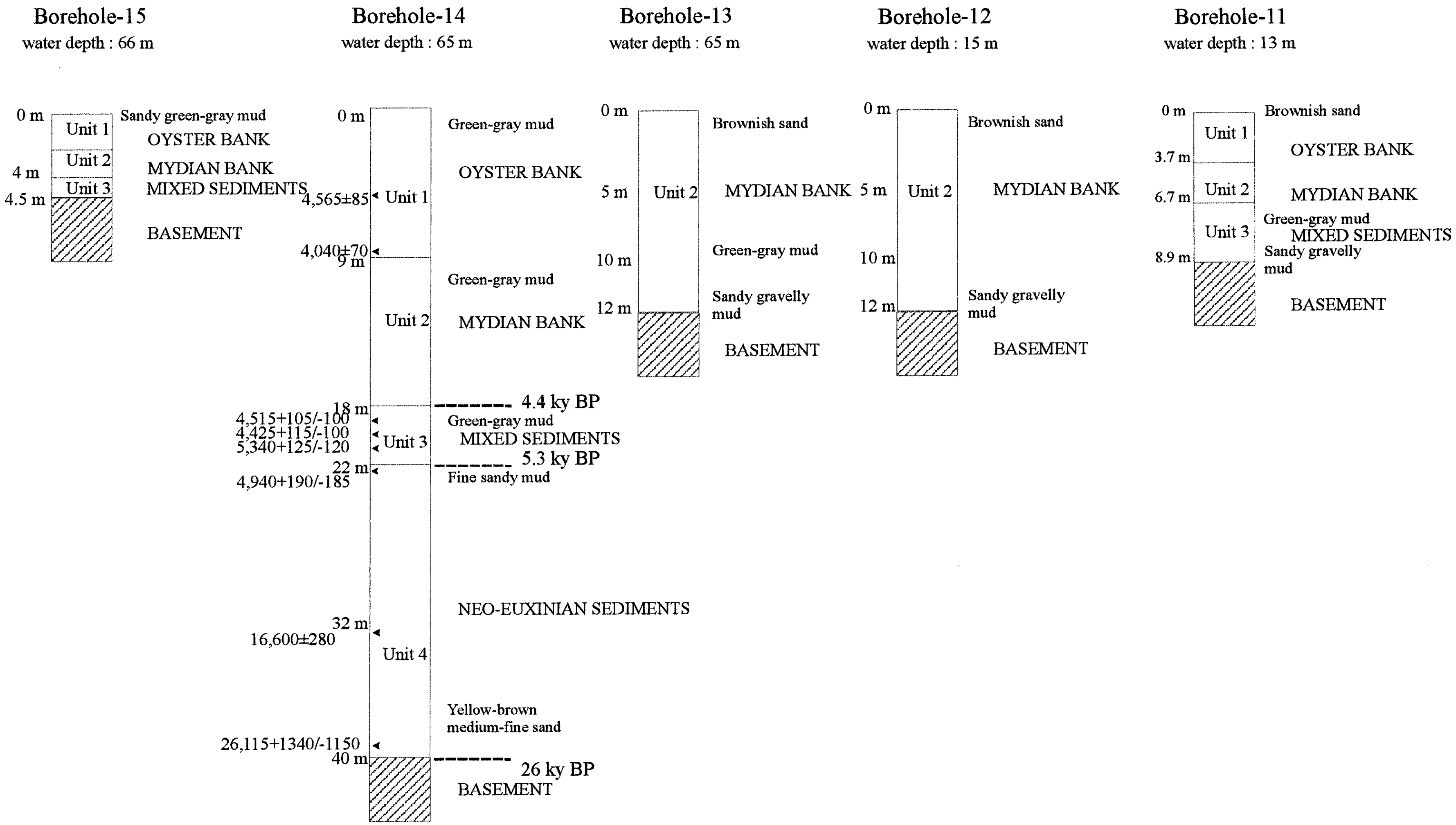


Fig. 5 Stratigraphy of the boreholes from the central Bosphorus

tepida. The lithology and the fossil composition of this unit indicate that it was deposited under marine conditions.

Unit 3 – transitional mixed sediments

Unit 3 consisted of green-gray mud with mollusc shells. It graded down into fine sand near its base. It had a maximum thickness of 6 m between 18 and 22 mbsf in borehole 14. In boreholes 11 and 15 on the channel slopes, this unit was only 1–2 m thick. As in the case of unit 1, boreholes 12 and 13 did not contain this unit. The unit contained few foraminiferal species (*Q. seminula, R. floridensis*, *L. lobatula*, *A. tepida*, and *Globigerina* sp.). The molluscan fauna included species of both marine (*O. edulis* and *M. edulis*) and fresh–brackish water (*Dreissena polymorpha* and *Pontodreissena rostriformis*) affinities. The latter group is characteristic of the Black Sea neo-euxinian sediments deposited from 25,000–9,000 years B.P. These molluscs do not live in the Black Sea today, and are found only in the fresh to slightly brackish waters of estuaries of, for example, the Dnepr, Don and Dnestr Rivers (Arkhangel'skiy and Strakhov 1938). The mixed composition of mollusc shells in unit 3 indicates a transition from freshwater to marine conditions. The fining-upward nature of the unit shows decreasing energy conditions in the course of deposition. ^{14}C dating of shells from this unit produced ages ranging from 4.4–5.3 thousand years (*Mytilus* shell 4,515 + 105/–100; *Ostrea* and *Mytilus* shells 4,425 + 115/–100; *Ostrea* shell 5,340 + 125/–120; *Dreissena* shell 4,940 + 190/–185; Fig. 5).

Unit 4 – neo-euxinic sediments

This lowermost unit above the Paleozoic basement is represented by yellow-brown, well-sorted, medium to fine sand containing mollusc shells. It was encountered only in borehole 14 where it reached a thickness of 18 m. *Ammonia parkinsonia*, a typical fresh–brackish water benthic foraminifer, was found occasionally. The mollusc assemblage consisted only of neo-euxinian freshwater species (*Dreissena rostriformis, D. polymorpha, Monodacna pontica, Thedoxus pallasi, Dreisenna ponticaspia, P. rostriformis*, and *Clessinida* sp), marine Mediterranean mollusc species being absent. The mollusc assemblage and the lithology of this unit show that it was deposited in a high-energy, freshwater coastal environment. *Dreissena* shells at a depth of 32 m and from the base of this unit produced ages of 16,600 ± 280 (AMS) and 26,115 + 1,340/–1,150, respectively.

The two ^{14}C dates obtained close to the boundary between units 3 and 4 differed by less than 400 years. On the basis of these data, we assign the oldest ^{14}C date of about 5,300 years B.P. near the base of unit 3 to this boundary. The age reversals documented at short (0.5–1 m) intervals in unit 3 and at its boundary with unit 4 are caused probably by rapid and chaotic sedimentation. Therefore, the youngest age of 4.4 thousand years recorded in unit 3 can be considered to apply to the unit 2/unit 3 boundary. The age of the unit 1/unit 2 boundary does not seem to be reliably reflected by the age (4000 years B.P.) recorded near the base of unit 1. The age reversal occurring in a 3-m interval in unit 1 suggests an erroneous result or mixing of sediments by slumping and sliding which is certainly possible in such a paleoenvironment. However, the lithological and paleontological consistency within the other units suggests a generally undisturbed stratigraphy.

Discussion and conclusions

Sedimentation over the basement started about 26,000 years B.P. with the deposition of the neo-euxinian sediments of unit 4 in the central Bosphorus, indicating a connection between the Black Sea and the neo-euxinian lake in this part of the Bosphorus. In early neo-euxinian times (30,000–22,000 years B.P.), Black Sea waters must have breached the basement sills in the Bosphorus, flowing into the Mediterranean via the Sea of Marmara (Tchepalyga 1995; Çağatay et al. 2000; Fig. 6a). Between the last glacial maximum and the main period of deglaciation (20,000–10,000 years B.P.), however, the Black Sea level dropped by 105 to 140 m (Ryan et al. 1997; Demirbað et al. 1999), that is, below the basement sills in the Bosphorus. During this period, the depressions in the central Bosphorus became a site of isolated neo-euxinian lake sedimentation. Until about 12,000 years B.P., the global sea level was lower than the bedrock sill depth of the Dardanelles Strait (85 m) and, as a result, Mediterranean waters could not enter the Bosphorus via the Sea of Marmara (Stanley and Blanpied 1980; Çağatay et al. 2000; Fig. 6b). The Black Sea, on the other hand, was receiving glacial melt waters, causing a rise in its water level after the Younger Dryas event (Federov 1971; Stanley and Blanpied 1980). This rise, with a subsequent outflow from the Black Sea, is supported by the formation of sapropels in the Sea of Marmara (Çağatay et al. 2000) and Aegean Sea (Aksu et al. 1995, 1999) at 10,000–6,500 years B.P. (Fig. 6c). With the Black Sea outflow, the neo-euxinian sedimentation apparently continued in the central Bosphorus depressions. Mediterranean waters were prevented from entering the Bosphorus because of the strong opposing Black Sea outflow, as shown by the modeling study of Lane-Serff et al. (1997).

At about 12,000 years B.P., with the continuous rising of sea level, the Sea of Marmara was flooded with Mediterranean water. The sand bar forming the shallowest present-day sill near the southern entrance (Fig. 2) had probably started depositing earlier than 10,000 years B.P. (Fig. 6b), but had not fully developed until about 5,300 years B.P. This might be the period when the sea level in the Sea of Marmara was at (or lower than) the central Bosphorus basement sill depth (Fig. 6b).

The first euryhaline Mediterranean molluscs (unit 3) appear to have reached the central Bosphorus at about 5,300 years B.P., indicating that the central Bosphorus sill was not breached by Mediterranean waters until that time. This conclusion contradicts the findings of previous investigators (e.g., Degens and Ross 1974; Ryan et al. 1997) which suggest a Mediterranean and Black Sea connection between 9,000 and 7,000 years B.P. Since the evidence of this connection in the Black Sea is indisputable, we propose two alternative explanations for this discrepancy. The first possibility is a transgressive overlap of sedimentary layers deposited between 10,000 and 5,300 years B.P. in the central Bosphorus (Fig. 4). Subsequent concordant layers become thin, or are even missing towards the slope of the depressional basin. As a result, such layers could be missing at borehole 14 which is located at the edge of the depression. Unfortunately, no evidence for such deposition can be found in any available shallow-seismic data (Gökaşan et al. 1997; DSİ 1998) because they lack the necessary resolution. Although such deposition would reflect a relative fall or still stand of sea level, such a model cannot be applied here. It is possible, however, that the inflow of Mediterranean waters at the beginning of their intrusion into the central Bosphorus was at a very low level because of the strong opposing Black Sea flow (Lane-Serff et al. 1997). Besides, the sand bar at the southern entrance of the Bosphorus would not have developed under a strong Mediterranean flow. In a similar context, an erosional event might have removed the sedimentary layers, as suggested by contemporary evidence in the meandering parts of the Bosphorus seafloor (Gökaşan 2000). In fact, the mollusc assemblages and lithology of units 3 and 4 clearly indicate a change in depositional conditions from a more energetic freshwater environment to a less energetic freshwater–marine environment. Chaotic sedimentation and age reversals (unit 3) also support the occurrence of an erosional event for older sedimentary records of Mediterranean inundation.

The second possibility is that the Mediterranean Black Sea connection might have taken a different route. Such potential waterways are the İzmit Bay-Sapanca Lake-Sakarya Valley and Büyük Çekmece Lagoon-Terkos Lake, as has previously been suggested by Pfannenstiel (1944), Ardel and İnandık (1957), Bilgin (1984), and Meriç (1995). However, these alternative

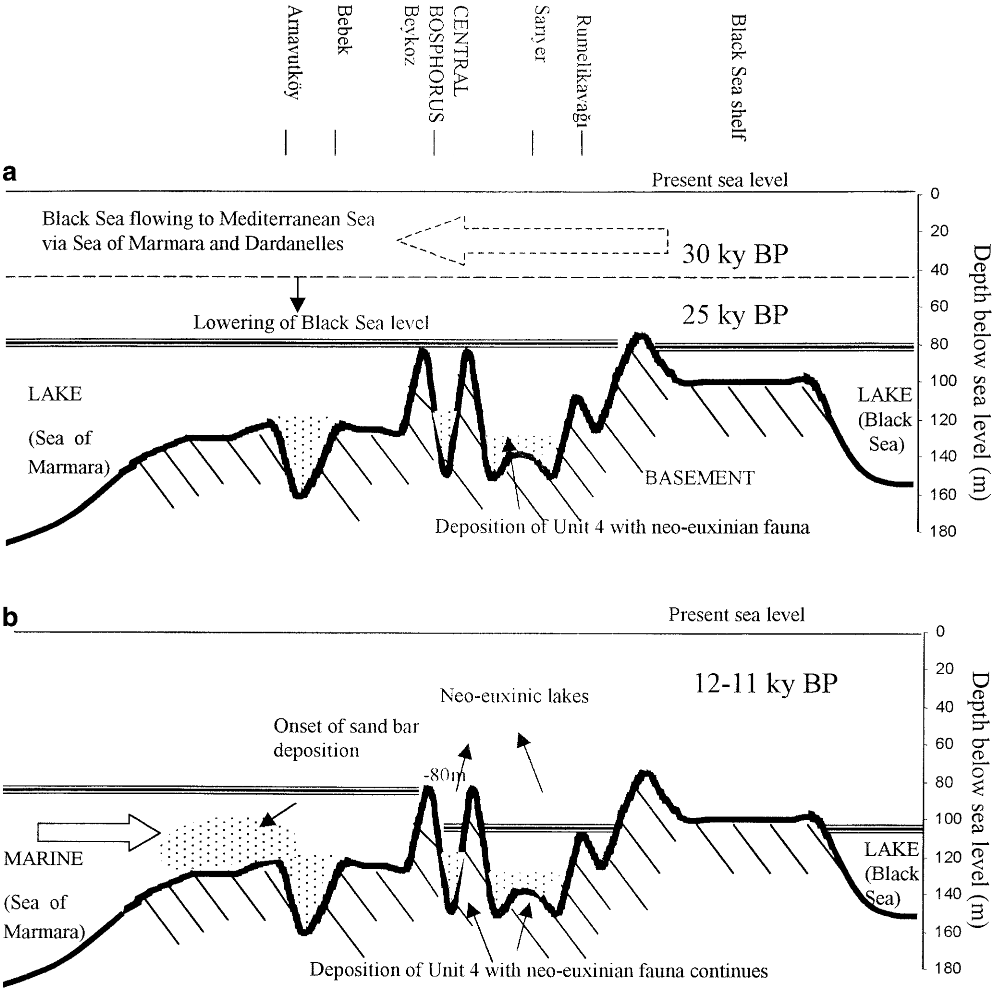
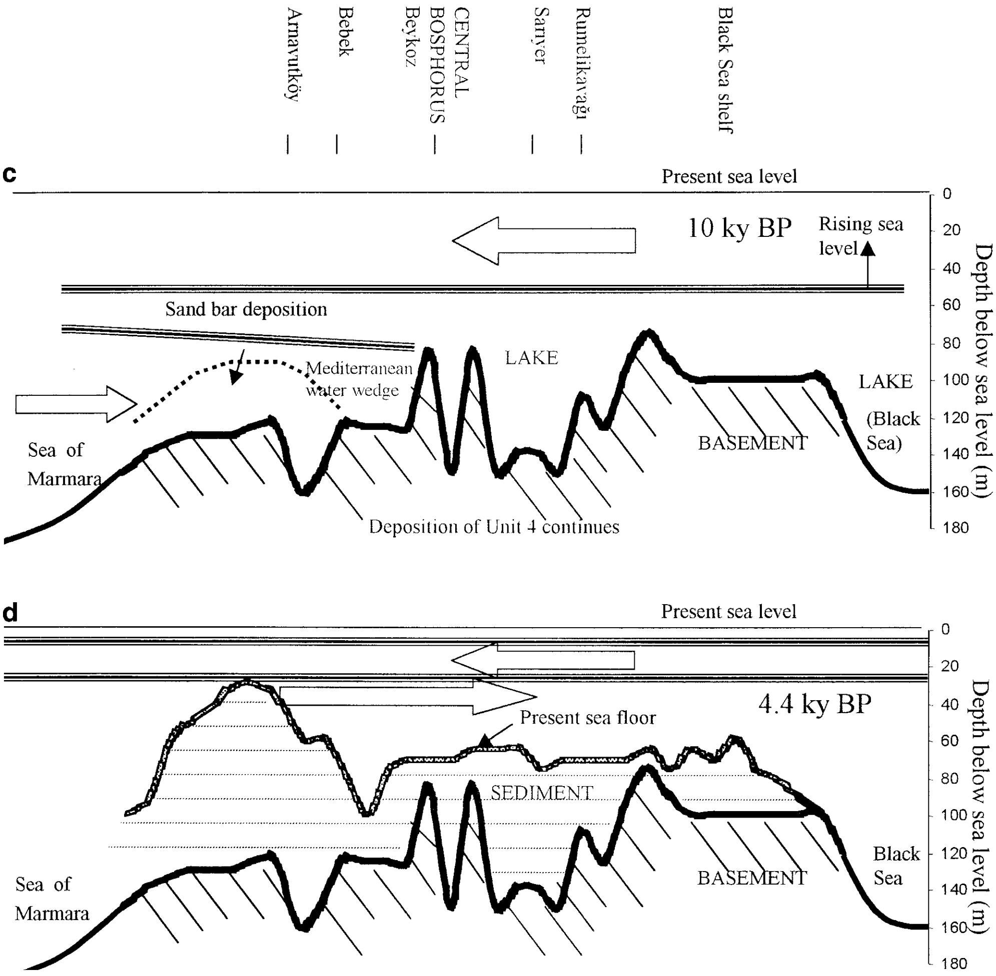


Fig. 6a–d Schematic illustrations of water exchange from 30,000 years B.P. to the Present between the Mediterranean and Black Seas through the Bosphorus. **a** Lowering of sea level prevents breaching by Black Sea freshwater at the northern entrance of the Bosphorus. The deep parts of the Bosphorus and the Sea of Marmara become isolated lakes. **b** Rising Mediterranean waters enter the Sea of Marmara via the Dardanelles Strait, but are prevented from entering the central Bosphorus because of the basement sill at 80 m. **c** The Black Sea water level starts to rise, and water eventually flows into the Sea of Marmara through the Bosphorus. Sand bar deposition is promoted near the southern entrance (*dotted line*). Because the rate of the Mediterranean sea-level rise is slower than the rise of the Black Sea water level, Mediterranean waters are prevented from entering the central Bosphorus due to excess outflow of Black Sea waters. **d** Establishment of the modern two-way flow regime at 4.4 thousand years B.P.

Fig. 6a–d (Contd.)



routes remain to be investigated by future drilling and geological studies.

The deposition of the *Mytilus*- and *Ostrea*-bank units, which began at about 4,400 years B.P., shows that the strong present-day two-way flow regime in the Bosphorus had started by that time (Fig. 6d). The change from *Mytilus*-bank to *Ostrea*-bank deposition indicates a deepening of the depositional environment.

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