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Marine Geology 190 (2002) 261–282

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

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Late Quaternary history of the Marmara Sea and Black Sea from high-resolution seismic and gravity-core studies

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Received 5 May 2001; accepted 19 February 2002

Abstract

Lithologic and multi-proxy paleoenvironmental data from 21 dated cores have been used to define three allostratigraphic units (allounits) within the late Quaternary successions of the Marmara Sea and Black Sea. Allounits are bounded by unconformities and their correlative conformities. In both regions, Allounit A extends from the seafloor downward to a ~12–11-ka sequence boundary, which is a major shelf-crossing unconformity in water depths less than ~100–110 m. In deep basins of the Marmara Sea, the lower part of Allounit A, designated Subunit A2, is a laminated sapropel, M1. On the shelf, Subunit A2 consists of backstepping delta lobes and early-transgressive barrier islands and sand sheets. Allounit B has only been recovered in Marmara Sea cores collected at water depths greater than ~90 m, and represents basinal or prodeltaic deposition during the 23–12-ka late Pleistocene lowstand. During the last glacial maximum, the shelves surrounding the Marmara Sea were subaerially exposed, and deltas of Allounit B accumulated along the present-day shelf edge. Following the post-glacial rise of global sea level to −75 m at ~12 ka, the Marmara Sea quickly became inundated and thereafter rose in synchroneity with the Mediterranean. By ~10 ka, the Black Sea rose to start spilling into the Marmara Sea, leading to establishment of a brackish-water lid that has persisted to the modern day. The strongest Black Sea outflow began at ~10 ka and persisted to ~6 ka, promoting the accumulation of sapropel M1 in the deep Marmara Sea, and progradation of an overflow delta just south of the exit from the Bosphorus Strait. Allounit C is a laminated sapropel (M2) in basinal cores, dated at ~30–23 ka. Like M1, it is believed that M2 accumulated during a period of increased brackish-water input into the Marmara Sea mainly from the Black Sea. In the Black Sea, wave erosion kept the shelf stripped of unconsolidated sediments during the falling sea level associated with the last glaciation and subsequent early stages of the post-glacial Holocene transgression. This erosion created a major unconformity, α. Shelf-edge deltas of Allounit B received their sediment during the last lowstand from small rivers that likely coalesced into a single system toward the shelf edge, at modern water depths of −100 to −110 m. These deltas were active until ~11–10.5 ka. Subsequently, sea level in the Black Sea rose to −40 m by ~10 ka, and a set of backstepping barrier islands developed on the shelf as part of the associated transgressive systems tract. Once water level reached −40 m, continued sea-level rise stalled until ~9 ka as the Black Sea began to spill across the Bosphorus Strait into the Marmara Sea.

Keywords: Black Sea; Marmara Sea; allostratigraphy; sequence stratigraphy; transgression; delta; sapropel

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PII: S0025-3227(02)00350-X

1. Introduction

The Black Sea–Marmara Sea–Aegean Sea oceanographic ‘gateway’ (Fig. 1) connects the world’s largest permanently anoxic basin, the Black Sea, to the eastern Mediterranean basin. The Marmara Sea is connected to the Black Sea and the Aegean Sea through the Straits of Bosphorus (= Strait of Istanbul; ~40 m deep) and Dardanelles (= Strait of Çanakkale; ~70 m deep), respectively. Since 1994, approximately 7500 line-km of high-resolution boomer and sparker profiles and 65 short gravity cores were collected across this gateway. The aim of this paper is to document late Quaternary stratigraphic linkages across the Marmara Sea and Black Sea segments of the gateway, where most of our dated cores were collected (Fig. 2). The cores provide ground-truth for the seismo-stratigraphy that has been developed for the gateway, and constrain its geological history since ~40 ka.

The history of connection of the Black Sea to the eastern Mediterranean Sea through the Marmara Sea Gateway is of critical importance in explaining the origin of organic-rich sapropels and sapropelic deposits in the eastern Mediterranean region. There is also an ongoing controversy as to the timing and nature of reconnection of the Black Sea to the Mediterranean Sea during the most recent Holocene sea-level rise. Ryan et al. (1997) claimed that the Black Sea was catastrophically flooded as a sediment-blocked Bosphorus Strait was breached by Mediterranean waters at ~7.1 ka, whereas Aksu et al. (1999), Çağatay et al. (2000), Görür et al. (2001), Kaminski et al. (2002), Hiscott et al. (2002) and Aksu et al. (2002a,b) use a number of sedimentological and paleoceanographic arguments to claim that such a

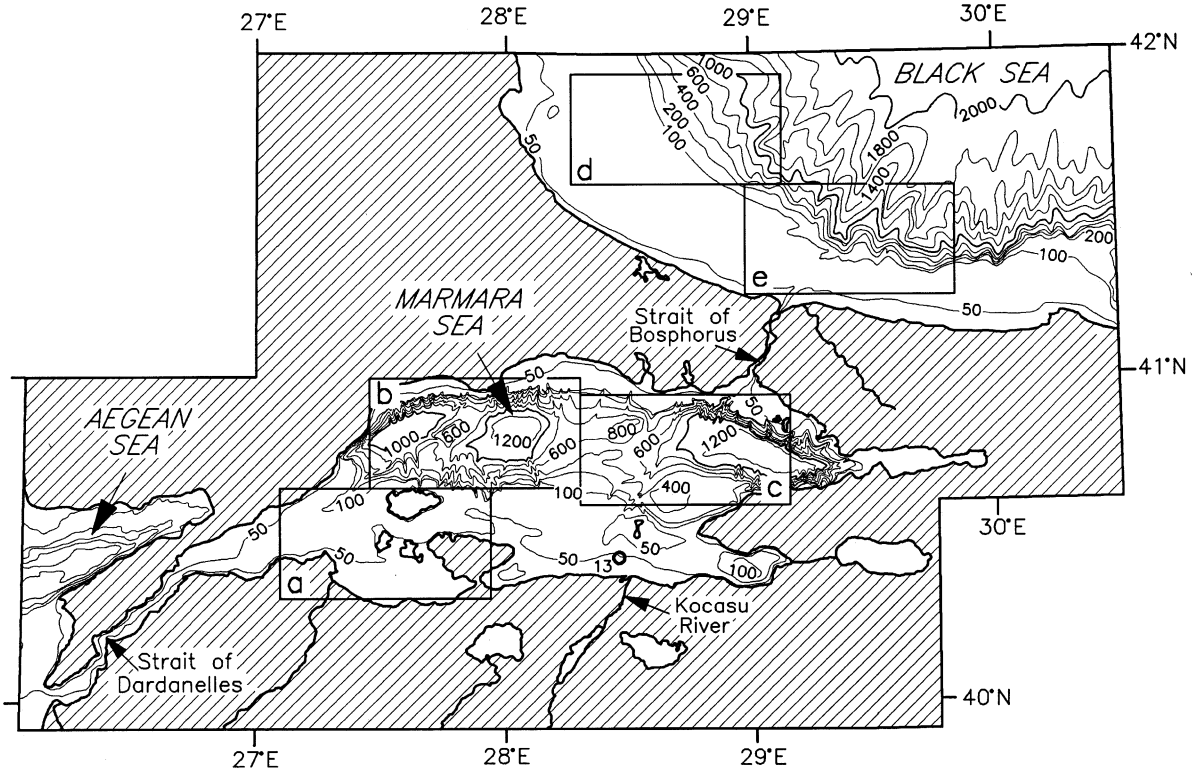

Fig. 1. Location map of the Marmara Sea and the southwestern Black Sea, showing the Strait of Bosphorus (= Strait of Istanbul) and Strait of Dardanelles (= Strait of Çanakkale). Insets a–e are illustrated in Fig. 2. Isobaths are in meters. In the Marmara Sea, three deep basins (1000–1200 m depth) are separated by two intervening saddles (~600 m depth). Circled number 13 just north of the Kocasu River exit is core site MAR97-13.

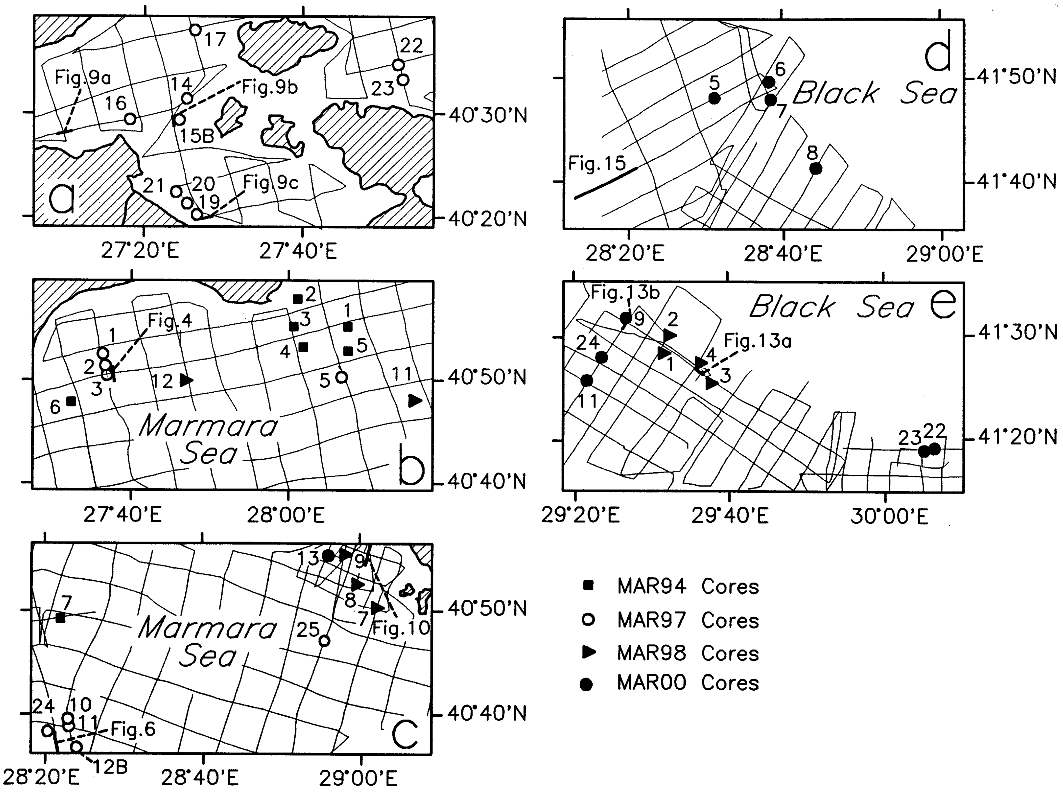

Fig. 2. Index maps showing the location of high-resolution seismic reflection profiles and short gravity cores used in this study. The prefix for each core number (e.g., MAR97-) can be determined from the symbol used. See Fig. 1 for regional context.

flooding event never occurred, and that instead the Black Sea began to export brackish water to the Aegean Sea via the Marmara Sea starting at ~10–10.5 ka. Here, we show the strong support that core data give to the latter hypothesis.

2. Data acquisition and methods

During the MAR94 (1994), MAR97 (1997), MAR98 (1998) and MAR00 (2000) cruises of the R/V *Koca Piri Reis* of the Institute of Marine Sciences and Technology, 65 <2.5-m-long gravity cores were collected from the northeastern Aegean Sea, southwestern Black Sea and the Marmara Sea, using a 4-m-long corer with a 10-cm internal diameter and 400-kg weight. The core sites were carefully selected using ~7500 line-km of high-resolution Huntec deep-tow system boomer/sparker and 40 cubic inch air gun profiles, located by satellite navigation (GPS).

Cores were stored upright onboard ship and were shipped to Memorial University of Newfoundland, where they were split, described and photographed. Sediment color was determined using the 'Rock-Color Chart' published by the Geological Society of America in 1984. Thirty-four of these 65 cores are longer than 1 m and 21 cores have been radiocarbon dated. The ages of several more cores can be deduced from seismic ties to the 21 dated core sites. A full listing of uncorrected radiocarbon ages and calibrated calendar ages (using a reservoir correction of 415 yr) is presented in Aksu et al. (2002a, their table 1). In this paper, we use only uncalibrated ages with no reservoir correction.

3. Definition and origin of stratigraphic bounding surfaces

The gravity cores in the Black Sea were recovered from water depths of 50–110 m, whereas those in the Marmara Sea were raised from water depths of 30–1207 m. The sedimentary facies vary from marginal marine sands and deltaic deposits to hemipelagic muds and organic-rich sapropels in the basins (Abrajano et al., 2002; Aksu et al., 2002a). Because of the extreme variations in water depth and facies across the study area, a lithostratigraphic approach cannot be used to correlate the sedimentary horizons in the cores. Instead, we have picked subaerial unconformities and their correlative conformities (*sequence boundaries*), as well as flooding surfaces, to subdivide the stratigraphy in a consistent manner. The units separated by these surfaces are *allostratigraphic units* (Walker, 1992), referred to here as *allounits*. Each allounit, when traced from shelf to basin, provides a snapshot of sedimentary processes and environmental conditions during a part of the late Quaternary development of the gateway.

Identification and definition of *correlative conformities* is not straight forward. At the landward edge of the shelf, the duration of the subaerial unconformity is greatest, and a considerable thickness of underlying deposits may have been stripped away (Fig. 3). The conformable succession that is time-equivalent to this unconformity is potentially quite thick (circled 1, Fig. 3). For example, the lowstand of the last glacial maximum produced an unconformity that spans ~23–12 ka. Even if we restrict the span of the conformable off-shelf succession to the time of the maximum lowstand, it would still consist of a set of strata rather than a two-dimensional surface (circled 2, Fig. 3). To avoid such ambiguity, and to permit recognition of a single surface in seismic data and cores, we follow the recommendation of Helland-Hansen and Martinsen (1996, p. 680) and place the correlative unconformity at the *maximum regressive surface*, which they define as “a conformable surface, separating regressive deposits below from transgressive deposits above. It corresponds to the time of turn[around] of the shoreline in a maximum seaward position” (circled 3, Fig. 3). For convenience in subsequent sections of the paper, we refer to sequence boundaries using the age of the correlative conformity (e.g., 12-ka sequence boundary), but the reader should be aware that subaerial erosion began earlier when relative sea level first began to fall.

3.1. Marmara Sea

The Marmara Sea experienced a lowstand in the period ~23–12 ka, when the global ocean was lower than the sill depth at the Strait of Dardanelles (Fairbanks, 1989; Skene et al., 1998; Aksu et al., 1999). Deltas along the edge of the southern shelf of the Marmara Sea indicate that water level was ~90 m below its present elevation. Contrary to our assertions in an earlier paper (Aksu et al., 1999), we now believe that this water level points to evaporation of the Marmara Sea so that its surface was ~15 m below the elevation of the Dardanelles sill. This situation persisted until ~12 ka, when the Marmara Sea became reconnected with a rising Mediterranean Sea. This date is based on a global sea level of −75 m at 12 ka (Fairbanks, 1989) and is confirmed by results presented below. The sill depth

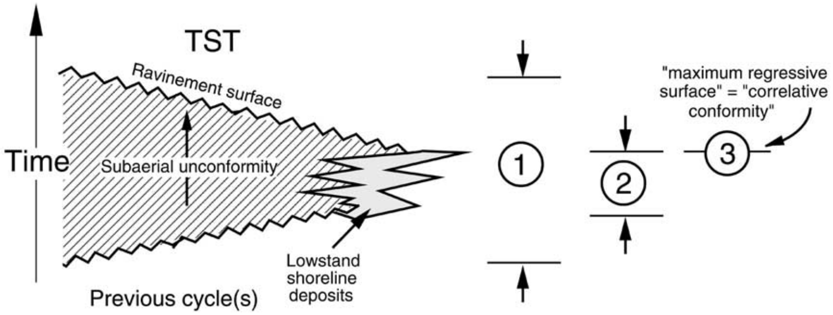

Fig. 3. Definition diagram for the ‘correlative conformity’ that corresponds to a subaerial unconformity. Together, the unconformity and the correlative conformity form the sequence boundary. TST = transgressive systems tract. See text for discussion.

at 12 ka was at −75 m, rather than the present −70 m, because of persistent uplift in the vicinity of the Dardanelles at an average rate of 0.40 mm/yr (Yaltırak et al., 2002).

The ∼23–12-ka lowstand resulted in the development of an erosional unconformity on all shelves of the Marmara Sea (e.g., Aksu et al., 1999, their figs. 8 and 9; Hiscott et al., 2002, their β3 surface). This is a *sequence boundary* in sequence-stratigraphic usage. The deep-water core sites in the Marmara Sea were never subaerially exposed, but cores from these areas show facies changes at ages of ∼12 ka that we interpret as the correlative conformity of the sequence boundary on the shelf. At ∼12 ka, the Marmara Sea was reconnected to the Aegean and Mediterranean seas, perhaps initially with a rapid rise from −90 m to −75 m, drowning the lowstand shoreline. Initially, shallow-marine conditions during the first phases of the Holocene transgression led to diachronous accumulation of sandy reworked deposits in the form of sand waves and barrier islands that rest directly on the unconformity surface in modern water depths less than −80 m. Subsequently, these sandy shallow-marine deposits were stranded by rapidly rising water levels, and are everywhere entombed by a blanket of marine mud, forming a hemipelagic drape (Aksu et al., 1999, their figs. 7–10). We recognize a *marine flooding surface* above drowned barrier islands and backstepping delta lobes, and use this surface as a stratigraphic boundary.

Allounit A extends from the seafloor downward to the ∼12-ka sequence boundary, which is an unconformity in modern water depths less than ∼100 m and a correlative conformity elsewhere. In some cores (see below), Allounit A is divided into two subunits: A1 and A2. Subunit A1 is the Holocene transgressive to highstand mud drape found throughout the Marmara Sea. Subunit A2 is a laminated sapropel in deep basins (M1; Aksu et al., 2002a). On the outer shelf, in water depths of ∼50–90 m, A2 corresponds to early-transgressive backstepping deltas (southern shelf) and stacked barrier islands or marine sand waves (western shelves). Allounit B is only present at water depths greater than ∼90 m, and represents basinal or prodeltaic deposition during the 23–12 ka lowstand when the shelf was exposed to subaerial erosion. Allounit C is a laminated sapropel (M2) like Subunit A2, but the decrease in total organic carbon (TOC) at its top likely resulted from different oceanographic factors than the A2/A1 boundary (see below).

In the following section, we describe the better-dated and longer gravity cores raised from the deep basins, mid-depth saddles, and shallow shelves of the Marmara Sea, and explain significant sedimentological and paleoceanographic changes associated with the contacts of allounits. Because the age of each allounit is approximately the same across the deep and shallow areas of the Marmara Sea, it is possible to interpret its deposits, identified in a set of geographically separated cores, in the context of a linked set of depositional environments extending from shelf to basin. This is akin to the *systems tract approach* of sequence stratigraphers.

3.1.1. Basinal and deep slope settings

Cores MAR97-01, MAR97-02, MAR97-03, MAR97-05 and MAR97-25 (Fig. 4) all sample deep basinal, burrowed hemipelagic muds that are punctuated by thin silt turbidites. The core sites are underlain by a thick succession of acoustically stratified deposits (Fig. 5) younger than ∼3.5 ka (dated in core MAR97-02; otherwise tied to MAR97-02 seismically or sedimentologically). Marine fauna and flora are present throughout. Coccolith abundances in core MAR97-02 double above ∼60 cm core depth, suggesting improved water exchange with the Aegean Sea after ∼2.0 ka. These cored successions are all assigned to Subunit A1.

Core MAR98-12, raised from a saddle between two deep basins (Fig. 2), recovered a more condensed succession than in the deep basins, extending in age to >10.6 ka and into Allounit B (Fig. 6a). In this core and nearby core MAR98-11 (Fig. 6b), Subunit A2 is an organic-rich, laminated sapropel (TOC > 2%) with a basal age of ∼10.6 ka and an upper interpolated age of ∼6 ka. Abrajano et al. (2002) ascribe this sapropel to enhanced preservation of organic matter beneath a brackish-water lid created by the export of relatively fresh water from the Black Sea via

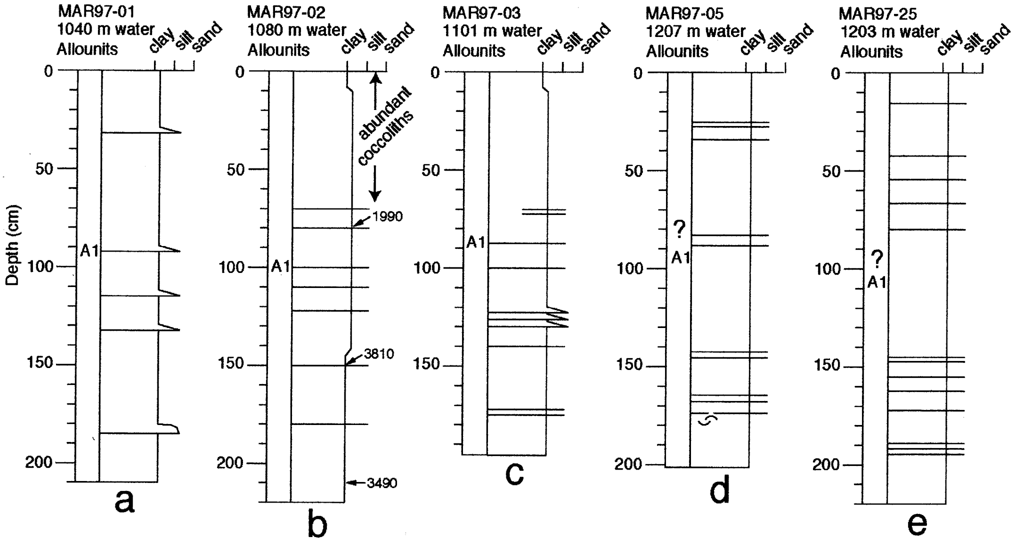

Fig. 4. Summary lithologies and allounits in Marmara Sea basinal cores. Arrows with numbers indicate radiocarbon ages in yr BP, tabulated in Aksu et al. (2002a). See Fig. 2b,c for location.

the Bosphorus Strait; direct sedimentological evidence for this outflow is preserved in a spill-over delta at the southern exit of the strait Hiscott et al. (2002). Coccoliths and planktonic foraminifera are abundant in Subunit A1, but much less common in Subunit A2. They are virtually absent in Allounit B (Aksu et al., 2002a). This is consistent with no connection with the Aegean Sea before ~12 ka.

Finally, Core MAR94-05 recovered ~35 cm of Subunit A1, then much older deposits beneath an unconformity developed on basin slopes (Fig. 6c). Relative to basinal cores (Fig. 4), coccoliths are more uniformly abundant in Subunit A1 at saddle

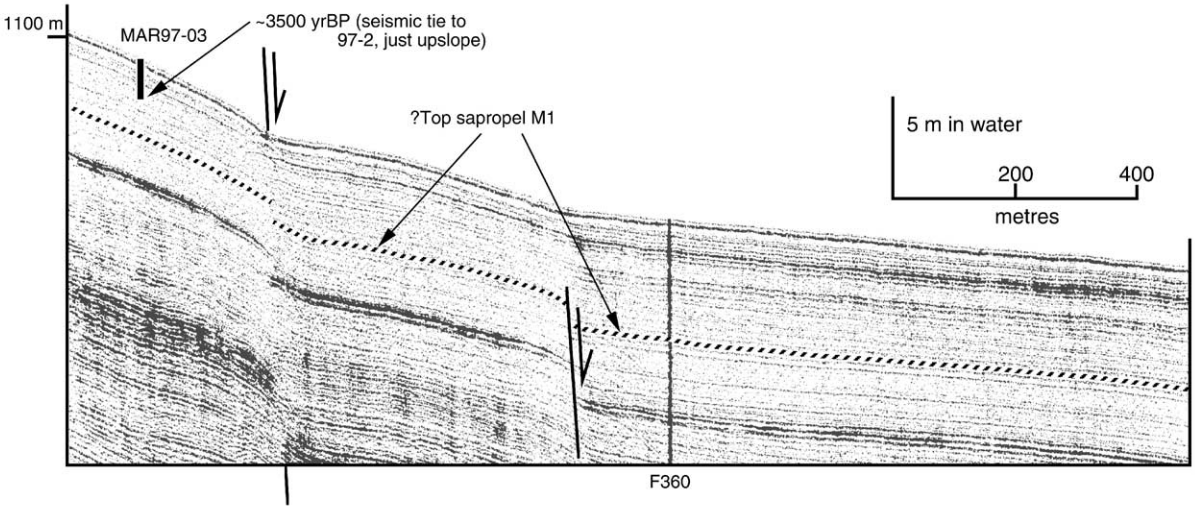

Fig. 5. Huntec deep-tow sparker profile across core site MAR97-03. The ~3500-yr-BP age is based on seismic tie to MAR97-02 ~2 km upslope. MAR97-03 only samples Subunit A1. Based on the ~3500-yr-BP age assignment and an assumed constant sedimentation rate, the top of Subunit A2 (M1 sapropel) is estimated to be at a depth of approximately twice the length of the core. See Fig. 2b for location.

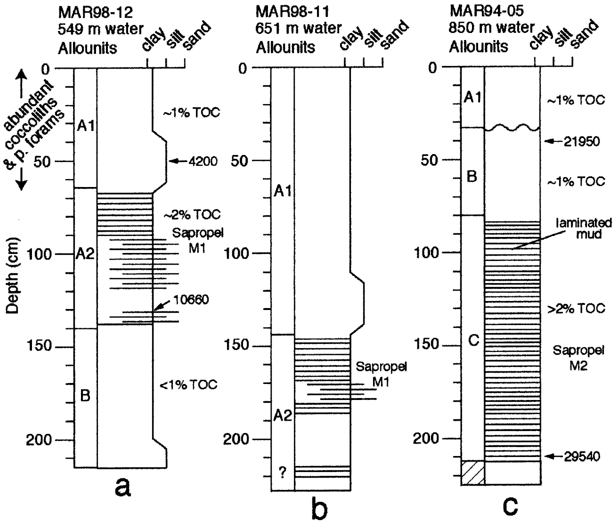

Fig. 6. Summary lithologies and allounits in Marmara Sea saddle cores. Arrows with numbers indicate radiocarbon ages in yr BP. TOC data are from Aksu et al. (2002a). See Fig. 2 for location.

sites, perhaps because of less dilution by turbidite mud that characterizes the deep basins. The youngest sediment beneath the unconformity in this core was deposited during the ~23–12-ka lowstand in the Marmara Sea, and consists of burrowed hemipelagic muds like those at the base of Core MAR98-12; hence, this interval is likewise assigned to Allounit B. The sapropel from 80 to 210 cm in the core is distinguished as a separate unit (Allounit C). Its basal age is ~29.5 ka and its top, assuming constant sedimentation rate between dated horizons, is ~23.5 ka. Planktonic foraminifera are rare in Allounit C and coccoliths are essentially absent. We attribute these low abundances to the presence of a stratified water column with low surface-water salinities, likely the result of strong Black Sea outflow at this time (Hiscott et al., 2002; Görür et al., 2001). The lack of sediments of this age in any other core that we have collected makes it impossible, at present, to correlate the base of the sapropel with a shelf unconformity. The top of this sapropel is likely not associated with a marine flooding event on the shelf because the Marmara Sea should have been dropping towards a lowstand at this time, based on the sea-level curve of Skene et al. (1998).

At the base of Core MAR94-05, there is a thin level of burrowed sediments beneath the sapropel older than ~30 ka. The Marmara Sea basins surely contain widespread sediments of this age and older (e.g., thick deposits in Fig. 5), but we have no core material in these older basinal successions so do not recognize allounits below Allounit C.

3.1.2. Southern shelf deltas

A number of cores were raised from water depths of ~125–50 m on the outer shelf seaward of the rivers that enter the Marmara Sea along its southern margin. These cores sample prodeltaic muds and the transgressive mud drape that formed during the Holocene sea-level rise (Fig. 7). Core MAR97-24 (Fig. 8a) postdates the sequence-boundary unconformity on the shelf, and is assigned to Allounit A (undifferentiated in this area). Core MAR97-12B (Fig. 8c) was raised from a water depth of 78 m on top of a backstepping delta that formed during the Holocene transgression, shortly after the Dardanelles was breached and the Marmara Sea refilled to a depth of −75 m at ~12 ka. The reworked delta top at this site is particularly sandy and prevented greater penetration of the corer during two at-

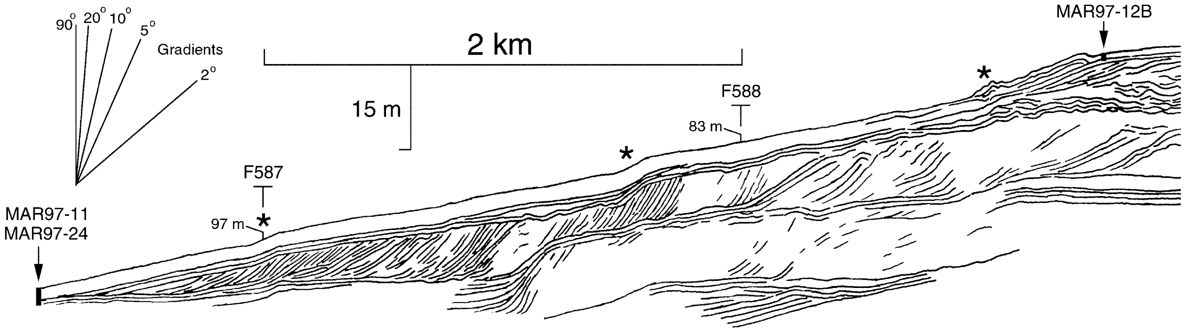

Fig. 7. Detailed line drawing of Huntec deep-tow sparker profile across the southern shelf of the Marmara Sea, showing the location of core MAR97-24 and the projected locations of MAR97-11 and MAR97-12B from nearby positions of comparable water depth and seismic stratigraphy. Rapid raising of the towfish caused a number of apparent changes in seafloor gradient (*) that should be ignored. See Fig. 2c for location.

tempts. The transition to uniform and burrowed muds at a core depth of 30 cm is the flooding surface at the base of Subunit A1.

The longest stratigraphic section that we have obtained in this area is in core MAR97-11 (Fig. 8b), raised from a water depth of 111 m in a setting much like that of core MAR97-24 (Fig. 7, projected location). The upward transition to more uniform prodeltaic mud with higher organic carbon content (like Subunit A2 on deep basin slopes) occurs at ~85 cm depth where the sediment age is tightly constrained to ~12 ka. Hence, we assign the muddy upper part of this core to Allounit A (undifferentiated), and the lower part to Allounit B and the ~23–12-ka lowstand when deltas extended to the edge of the southern shelf (Aksu et al., 1999).

Core MAR97-13 was collected at the most landward of our sites on the southern shelf in water only 51 m deep (Fig. 1). It mostly samples

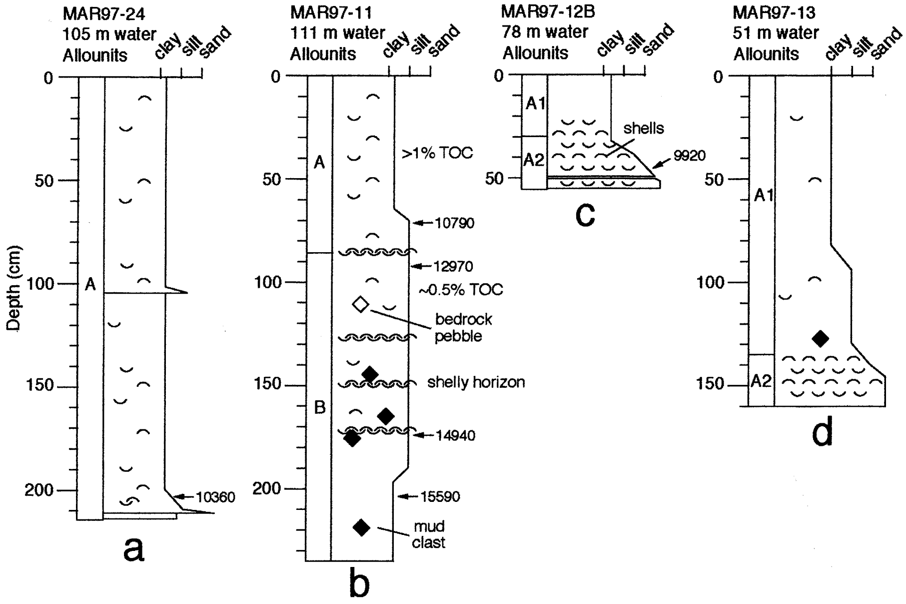

Fig. 8. Summary lithologies and allounits in Marmara Sea southern shelf delta cores. Arrows with numbers indicate radiocarbon ages in yr BP. TOC data are from Aksu et al. (2002a). See Fig. 1 (MAR97-13) and Fig. 2c for location.

the distal prodelta of the modern Kocasu River (Subunit A1). Only the basal shell-bearing sandy deposits are assigned to Subunit A2, presumably the top of a backstepping delta or transgressive sand sheet.

3.1.3. Western shelves of the Marmara Sea at the Dardanelles entrance

Cores in this area (Figs. 2 and 9) are critical to confirming that catastrophic flooding of the Black Sea by the rising Mediterranean Sea did *not* occur at ~7.1 ka. If Mediterranean water transited the Bosphorus Strait with discharges of $\sim 5\times 10^5$ m^3 s^{-1}, as suggested by Ryan and Pitman (1999, p. 160), then the same enormous discharges would have of necessity transited the Dardanelles Strait to feed this flood. Based on the discharge suggested by Ryan and Pitman (1999) and the cross-section at the western edge of the Fig. 2a map for a sea level 15 m lower than the present (appropriate for 7.1 ka; Fairbanks, 1989), the average velocity of the proposed flood would have exceeded 70 cm s^{-1}. For a flat seafloor, the near-bed shear velocity u_* would have been ~4 cm s^{-1}, corresponding to a boundary shear stress of ~1.6 N m^{-2}. Velocities and shear stresses of this magnitude are easily capable of eroding all but the most cohesive silty muds (Blatt et al., 1980, p. 103; Allen, 1984, p. 70). Cohesionless sediments up to 2 mm in size can be rolled by a current this strong. Therefore, a flood of the magnitude suggested by Ryan and Pitman (1999) should have left an erosional record across the shallow shelves at the eastern end of the Dardanelles, where we instead see a rather uniform blanket of burrowed marine mud that onlaps the inferred ~12-ka lowstand unconformity (Aksu et al., 1999, their figs. 8–10). In order to determine whether a vigorous torrent transited the Dardanelles Strait at ~7.1 ka, we need only to determine the basal age of the widespread mud blanket, to see if its deposition started earlier.

Before turning to the core data, an examination of high-resolution boomer profiles confirms that the onset of deposition of the mud drape occurred shortly after breaching of the Dardanelles sill at ~12 ka. The best evidence for this timing comes from facies transitions between the mud drape and barrier islands that had developed after the Marmara Sea level had risen from −90 to −75 m following connection with the Aegean Sea. In the example shown in Fig. 10a, reflections in the low-

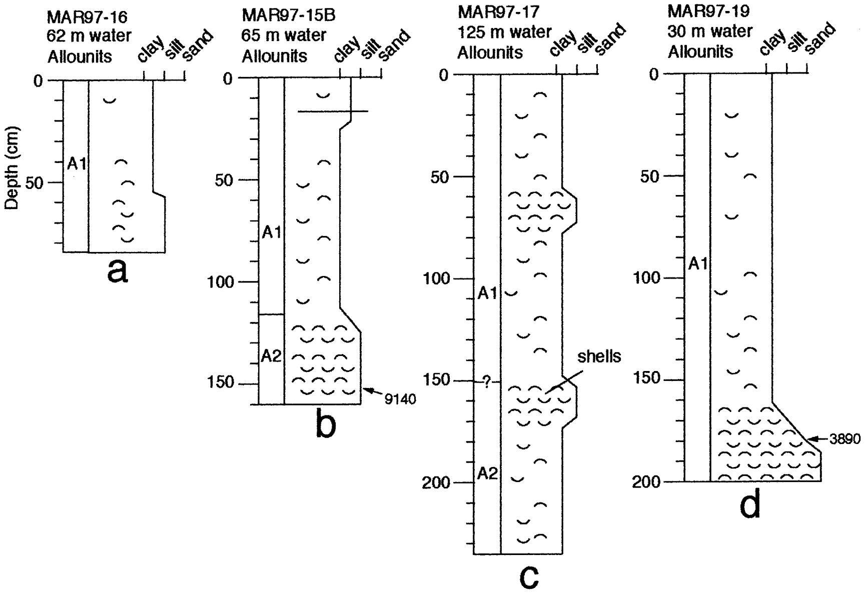

Fig. 9. Summary lithologies and allounits in Marmara Sea western entrance cores. Arrows with numbers indicate radiocarbon ages in yr BP. See Fig. 2a for location.

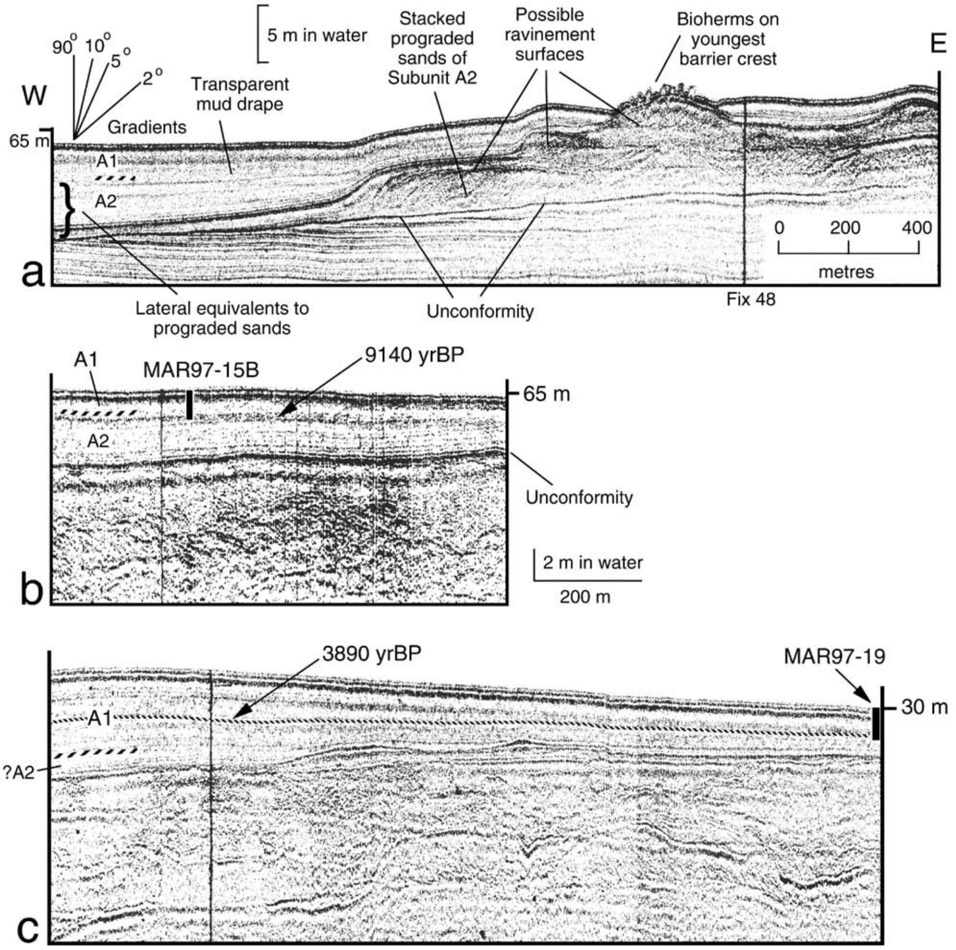

Fig. 10. Huntec deep-tow boomer profiles in the approaches to the Dardanelles showing (a) stacked, drowned, buried barrier islands, overlying the ~12-ka regional angular unconformity and underlying the widespread mud drape, and core sites MAR97-15B (b) and MAR97-19 (c). (b) and (c) share the same vertical and horizontal scales. Note in (a) the basal onlap of the drape and the local lateral facies transition between the base of the drape and stratified barrier–island sands. Ages of seismic horizons in (b) and (c) are based on seismic ties to cores MAR97-15B and MAR97-19, respectively. Inferred boundaries in the seismic data between subunits A1 and A2 respect core depths (Fig. 9) and are consistent with an age of ~6 ka. See Fig. 2a for location.

er part of the mud drape can be traced into clinoforms of backstepping barrier islands equivalent to Subunit A2. These barriers must have formed at the shoreline, but the oldest prograded sand bodies are currently submerged at elevations of approximately −70 m. Global sea level reached −70 m at ~11.5 ka (Fairbanks, 1989). These barrier islands would have been inundated by the time that global sea level reached −50 m elevation at ~10–9.5 ka. Hence, the lower part of the mud drape in the throat of the Dardanelles entrance can be no younger than 9.5 ka, and likely started to form closer to 11.5 ka. This part of the drape corresponds in age to the basal part of Subunit A2 at basinal sites.

Cores MAR97-15B, MAR97-16 and MAR97-17 sampled the Holocene mud drape in water depths of 62–125 m (Fig. 9). In seismic profiles across sites MAR97-15 (Fig. 10b) and MAR97-17, there is a reflective horizon just above the middle of the drape that cores show to be shell-rich (Fig. 9b). A fresh *Turritella* specimen from the bottom of core MAR97-15B is dated at 9140 yr BP, confirming that the mud drape was deposited without interruption at ~7.1 ka. This site cannot have been subaqueous before ~12 ka, so the sedimentation rate in the lower part of the mud drape must have been about three times higher than since ~9 ka. This is consistent with the observation that the lower half of the drape passes by facies change into early-transgressive-phase barrier islands not far from the MAR97-15B core site (Fig. 10a). The mud drape, from a core depth of ~115 cm to its seismically defined base (Fig. 10b) is assigned to Subunit A2. The rest of the drape, younger than ~6 ka, is assigned to Subunit A1 (Fig. 9b).

Core MAR97-19 sampled the mud drape where the present water depth is 30 m. A reflective horizon, like that described above for cores MAR97-15 and MAR97-17, consists of shell-rich muds at the base of the core, dated at 3890 yr BP. When traced a short distance away from the core site where the mud drape is thicker (Fig. 10b), ~50% of the mud drape lies below this reflection. Assuming a constant sedimentation rate (the rate actually likely has decreased with time as sea level rose), the base of the drape has an extrapolated age of ~8 ka. This estimated age is consistent with the fact that global sea level reached a height of −30 m (the water depth at this site) at ~9 ka (Fairbanks, 1989), allowing deposition of the transgressive mud drape to begin by ~8 ka when global sea level had risen a further ~10 m. Most of the mud drape at this locality belongs to Subunit A1 (Fig. 10c).

None of the cores on the western Marmara shelf penetrate to the base of the mud drape;

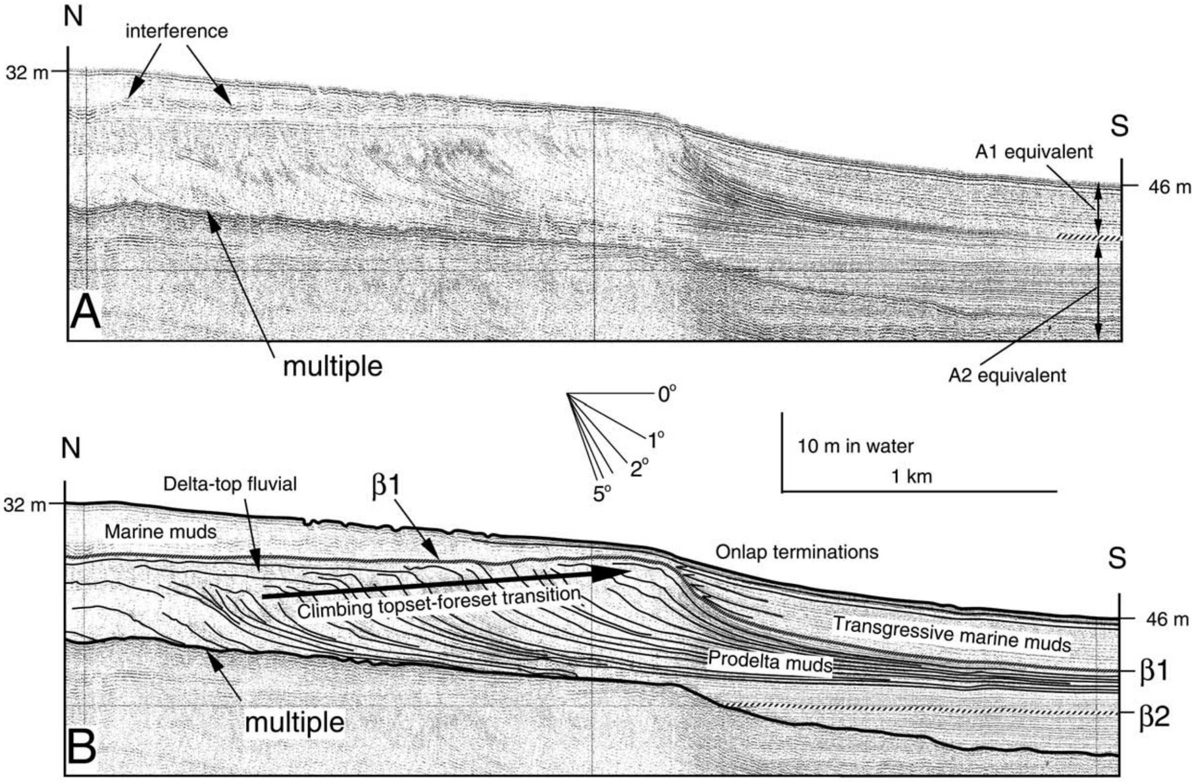

Fig. 11. Huntec deep-tow sparker profile and interpreted line drawing across the youngest delta at the southern exit of the Strait of Bosphorus (Unit 2 delta of Hiscott et al., 2002). The topset–foreset transition climbs consistently from north to south, indicating progradation during a relative sea-level rise. Note the progressive onlap of transgressive marine muds of Subunit A1 over the delta. See Fig. 2c for location. The gradually climbing faint doublet on the left, labelled 'interference', is a multiple from the towfish, and therefore an artefact.

the oldest part of the drape (first onlapping reflections) is in depressions on the unconformity surface where the drape is many meters thick (e.g., Fig. 10c).

3.1.4. Southern exit of the Bosphorus Strait

The shelf south of the Bosphorus Strait is underlain by two south-prograded delta lobes, one dating from 10 to 9 ka and the other from possibly ~30 to 23 ka during oxygen isotopic stage 3 (Hiscott et al., 2002). The youngest of these lobes was initiated when the Black Sea began to flow through the Bosphorus Strait into the Marmara Sea at a sufficiently high discharge to permit the delta to prograde even though sea level was rising, so that the foreset-to-topset transition climbs upward in the direction of progradation (Fig. 11).

Core MAR98-07 was raised near the shelf edge in 94.8 m of water, and penetrated the lowstand unconformity into sediments older than 40 ka, and perhaps older than 160 ka (Hiscott et al., 2002). The lowstand sequence boundary is placed at ~70 cm in the core (Fig. 12a), and deposits above this depth are assigned to Allounit A. We infer the presence of a thin interval of Allounit B deposits at this site based on a single radiocarbon date of 15 210 yr BP. Older deposits contain fresh- to brackish-water shells that are 'chalky' and leached, suggesting that they might have been subaerially weathered (Yim, 1999).

Core MAR00-13 was raised from an erosional trough cut into older deposits, so has an unconformity at its top. The lower part of the core (155–218 cm) consists of interbedded thin silt beds and muds interpreted to be part of the prodelta of the youngest delta lobe. Radiocarbon dates constrain these deposits to the interval ~8.5 ka (interpolated age) to 9.2 ka (Fig. 12b). Above 155 cm, the muds become burrowed and homogeneous, but are still time-equivalent to Subunit A2. Because of few age dates and an unconformity at the core top, we simply assign this core to Allounit A, undifferentiated.

Core MAR98-09 is the last well-dated core in this area. It was collected in the distal toeset of the delta lobe shown in Fig. 10, and consists of Subunit A2 below ~55 cm (the distal toeset) and Subunit A1 above that depth. Subunit A1 is believed to have formed after ~9 ka (mostly after ~6 ka; Fig. 12c) when sea level had risen sufficiently to initiate the deep penetration of a salt wedge into the Bosphorus Strait, perhaps to the point of initiating the first Holocene two-layer flow in the strait (Hiscott et al., 2002). Once the outward flow from the Black Sea became detached from the seabed (by intrusion of a salt wedge), a strait-mouth delta could not persist be-

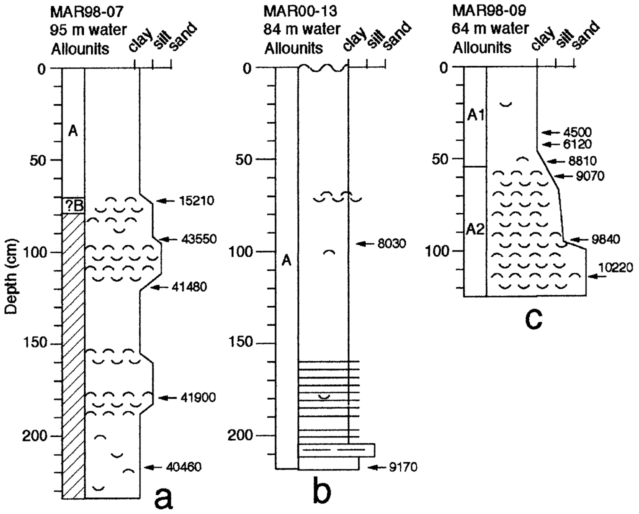

Fig. 12. Summary lithologies and allounits in Marmara Sea delta cores at the southern Bosphorus exit. Arrows with numbers indicate radiocarbon ages in yr BP. See Fig. 2c for location.

cause it would no longer be supplied with bedload. The raw sedimentation rate is 34 cm/kyr below 50 cm depth (contact of allounits A1 and A2) and 3.6 cm/kyr above (Hiscott et al., 2002); hence, the mud drape reflects sharply diminished terrigenous supply as the shelf areas were drowned by rising water levels. This is a special area of the Marmara Sea, because the delta that formed during Holocene transgression was supplied from Black Sea overflow through the strait, and not from a river. Hence, its abandonment took place quite early in the transgression, and the marine flooding surface that defines the base of Subunit A1 is therefore older here than on the southern shelf.

At core site MAR98-09, the lowstand unconformity that defines the base of Allounit A (unconformity β3 of Hiscott et al., 2002) is ~3 m below the bottom of the core. The oldest recovered material from Subunit A2 is dominated by an 'oxic' benthic foraminiferal morphogroup (Aksu et al., 2002a). 'Dysoxic' forms are entirely absent at 120–110 cm, but first appear in small numbers at 100 cm depth in the core and show a steady increase upcore, becoming dominant at 60 cm depth in the core. This faunal change reflects the drowning of the delta as sea level rose, and the onset of stratification of the water column caused by persistent Black Sea outflow.

3.2. Black Sea

The Black Sea also experienced a lowstand in the period corresponding to the last glacial max-

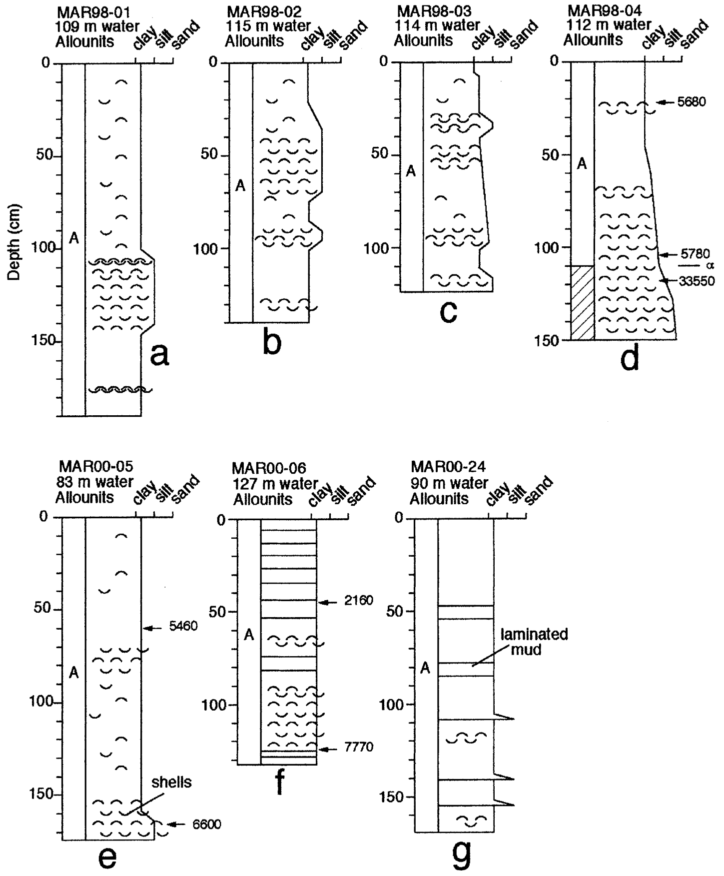

Fig. 13. Summary lithologies and allounits in Black Sea shelf cores, west of the Bosphorus Strait. Arrows with numbers indicate radiocarbon ages in yr BP. See Fig. 2e for location.

imum, some ~23–11 ka, when the global ocean was lower than the sill depth at the Bosphorus Strait (Fairbanks, 1989; Pirazzoli, 1996; Aksu et al., 2002b) and evaporation exceeded river input plus precipitation over the isolated sea. Some authors refer to the Black Sea as a freshwater lake at this time, but it was likely brackish (Mudie et al., 2002). Lowstand deltas along the southwestern Black Sea indicate that water level was ~100–110 m below the present (Aksu et al., 2002b). Delta progradation at low sea level continued until ~11–10.5 ka, after which the Black Sea rose to begin flowing into the Marmara Sea at ~10 ka (Hiscott et al., 2002). The presence of an overflow delta at the southern end of the Bosphorus Strait by ~10 ka and evidence of persistent brackish-water input from micropaleontological and geochemical proxies in cores from the Marmara and Aegean seas (Aksu et al., 1995; Aksu et al., 2002a) require this early connection.

The lowstand of the last glacial maximum resulted in the development of an erosional unconformity across the entire southwestern Black Sea shelf (e.g., Aksu et al., 2002b, their **α** reflector, their figs. 6–8 and 10–12). This is a *sequence boundary*. From ~10.5 to 10.0 ka, the Black Sea level rose ~60 m, drowning the lowstand shoreline and developing transgressive systems tract deposits on the southwestern Black Sea shelf, including a series of back-stepping beaches and barrier islands (Aksu et al., 2002b). Subsequently, these coastal deposits were drowned in-place by rising water levels, and are everywhere covered by a thin veneer of marine mud, forming a hemipelagic drape (Aksu et al., 2002b). The base of this mud drape is a *marine flooding surface*.

Black Sea Allounit A extends from the seafloor downward to the ~11-ka sequence boundary which is an unconformity in modern water depths less than ~110 m. Allounit B is only present along the shelf edge at water depths greater than

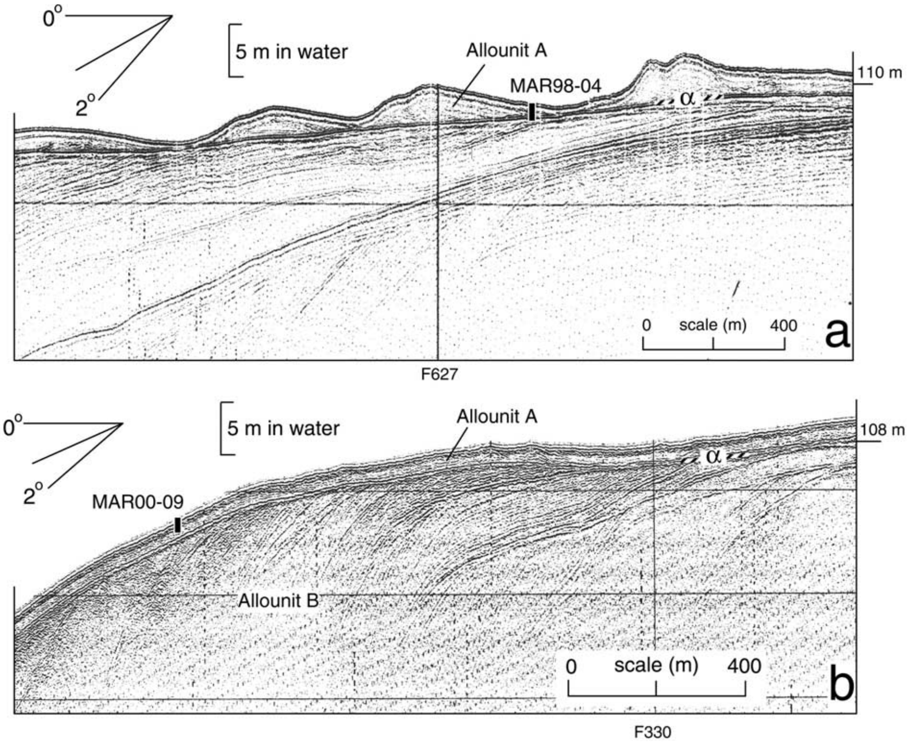

Fig. 14. Huntec deep-tow boomer profiles in the southwestern Black Sea showing core sites MAR98-04 (a) and MAR00-09 (b). In (a) there are a number of sediment waves. In (b) a thin veneer of transgressive-phase mud (Allounit A) overlies the shelf-crossing regional unconformity, **α**, and seaward-prograding clinoforms of a shelf-edge delta (Allounit B). See Fig. 2e for location.

~90 m, and represents deltaic deposition during the last glacial maximum (Δ_1 of seismic unit 1A of Aksu et al., 2002b). It has not been cored.

3.2.1. Southwestern Black Sea east and west of the Bosphorus Strait

A number of cores were raised from the southwestern Black Sea. Cores MAR98-01, MAR98-02, MAR98-03, MAR98-04, MAR00-05, MAR00-06 and MAR00-24 (Fig. 13) sample burrowed hemipelagic muds, punctuated by shelly zones, younger than ~7–8 ka. In seismic profiles, the cored deposits consist of a number of seaward-prograded imbricate wedges and mounds. One type of mound has the cross-sectional geometries, conical shapes, and piercement relationships characteristic of mud volcanoes or diapirs (Aksu et al., 2002b). Other features have linear crests and resemble barrier islands/beaches, sediment ridges (Fig. 14a), sediment waves, and current-generated marine bars (Aksu et al., 2002b). At the shelf edge where cores MAR00-07, MAR00-08 and MAR00-09 were collected (Figs. 2 and 15), Allounit A forms a thin veneer of mud on top of the clinoforms of a set of shingled shelf-edge deltas (Fig. 14b). Linear extrapolations based on several radiocarbon dates point to the cessation of delta progradation in the southwestern Black Sea at 11.0–10.5 ka (Aksu et al., 2002b).

In general, the oldest dates we have obtained for shells above the lowstand sequence boundary on the shelf are ~6.5 ka, except for a date of 7770 yr BP ka near the base of Core MAR00-06 (Fig. 13f). Where the unconformity is penetrated by Core MAR98-04, it is overlain by sediments no older than ~5.8 ka (Fig. 13d). The paucity of shelf sediment dating from 10.5 to 6.5 ka is attributed to the migration of sediment waves (e.g., Fig. 14a) and strong local scouring in a wave-dominated setting. The modern shelf, in similar fashion, is swept clean of sediments in water depth <65 m, leaving extensive bedrock surfaces at or very near the seafloor, except at the mouths of rivers. Large areas on the inner shelf and some parts of the outer shelf have less than ~1 m of sediment cover (Aksu et al., 2002b; their figs. 2 and 10). The wave-dominated conditions on the shelf likely mean that, in these areas, the sediment above reflector **α** is not yet part of the geological record, but instead might be remobilized during severe storms. Hence, these thin veneers are inferred to still be part of the *active layer* on the shelf. The extent of the hiatus in deposition at **α** is demonstrated by high-resolution boomer profiles in areas of thicker sedimentation, at water depths of approximately 60–65 m. In Fig. 16, a reflector that occurs ~8 m above the base of the post-**α** succession (Fig. 16a) descends to rest on the scoured bedrock surface in water depths less than ~60 m (Fig. 16b). Hence, several thousands of years of deposition on the shelf are absent landward of this point. We believe that the same situation holds wherever the post-**α** succession is thin, including those places where we attempted to core to the vicinity of **α** to test the age of the deposits below the unconformity (e.g., core site MAR98-04; Fig. 13d). Elsewhere, failed core attempts recovered nothing more than core-catcher samples of coarse to very coarse sand from a transgressive lag that has remained in the active layer since ~10.5 ka. As a result, the fact that relatively short gravity cores collected shelf sediments no older than ~6.5 ka does not indicate that the shelf was not inundated until this time. Instead, the demise of the shelf-edge deltas at ~11–10.5 ka and evidence from the northern Marmara Sea that the Black Sea had risen to the sill depth of the Bosphorus (−40 m) by ~10 ka constrain the onset of transgression to 11–10.5 ka. Sea-level rise produced a transgressive

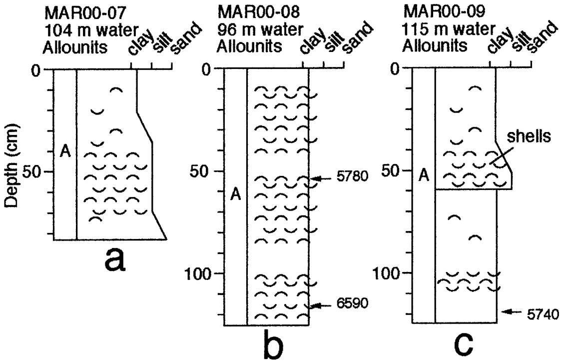

Fig. 15. Summary lithologies and allounits in Black Sea lowstand delta cores. Arrows with numbers indicate radiocarbon ages in yr BP. See Fig. 2d,e for location.

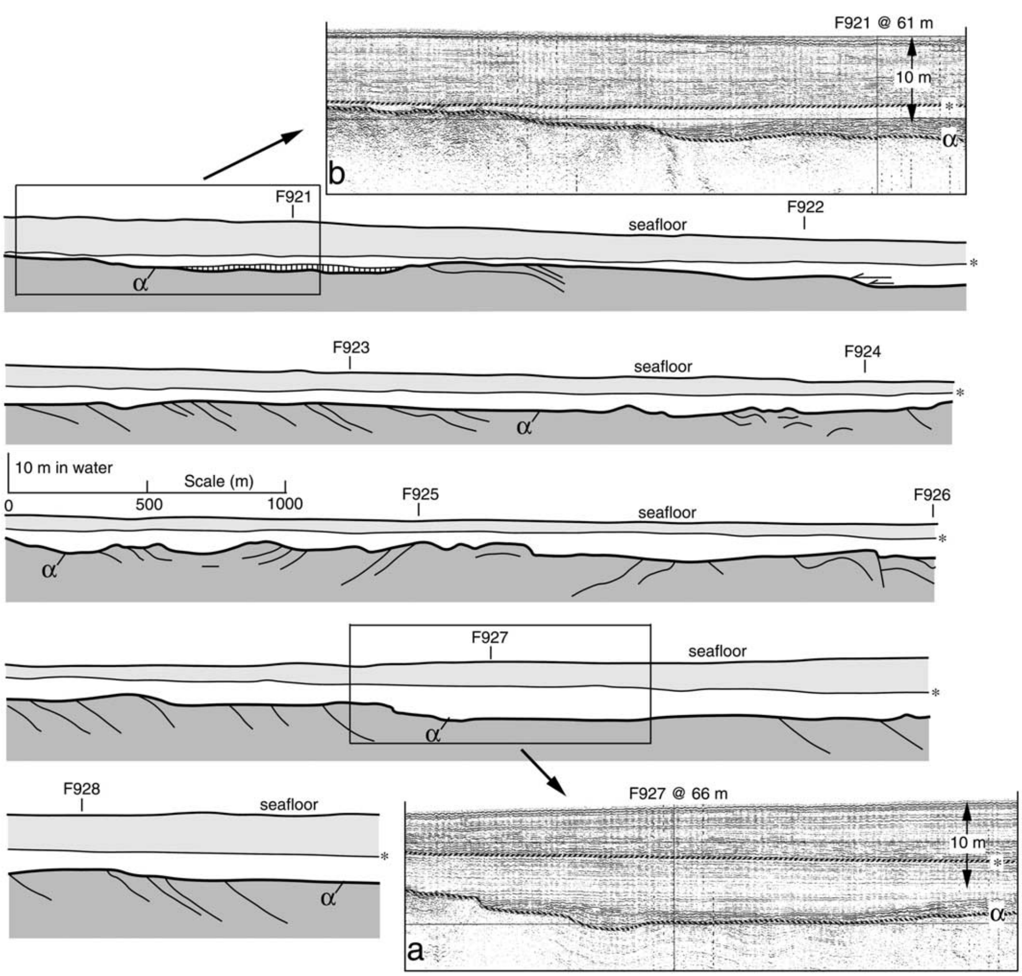

Fig. 16. Line drawing of a ∼14-km-long Huntec deep-tow boomer profile across the southwestern Black Sea shelf showing the notable thinning of the basal transgressive unit by progressive onlap over the regional shelf-crossing unconformity, **α**. (a) and (b) are short segments of this profile. The reflector (*) is common to all parts of the figure, and serves to demonstrate the onlap. See Fig. 2d for location.

systems tract on parts of the outer shelf, with superb examples of backstepping barrier islands attesting to a steady, persistent water-level rise (Aksu et al., 2002b).

After the Black Sea had risen to begin overflowing into the Marmara Sea at ∼10.0 ka (Hiscott et al., 2002; Aksu et al., 2002b), its rise would have stalled at −40 m elevation (the sill depth of the Strait of Bosphorus) until global sea level passed that elevation at ∼9.2 ka (Fairbanks, 1989). While at −40 m, we believe that large areas of the southwestern Black Sea shelf were wave swept and sediment starved, except where the initial phase of the transgression had left thicker wedges of muddy sediments that we have not yet been able to fully core.

4. Linked depositional systems and paleoceanographic evolution of the gateway

Allounits provide the opportunity to reconstruct paleoenvironmental, paleogeographic, and paleoceanographic conditions from shelf to basin. In the Black Sea, wave erosion during falling sea level and the early stages of transgression was very efficient in keeping the shelf stripped of previously deposited unconsolidated sediments. Hence, most of the southwestern Black Sea shelf is underlain by a major unconformity, α, and all deposits above α belong to a single allounit, A. Beyond the shelf edge in this part of the Black Sea, slopes are so steep that boomer profiling provides little information, so we have not been able to trace Allounit A into equivalent slope and basinal successions. As a consequence of these two attributes of the southwestern Black Sea (severe wave erosion and steep basin-margin slopes), seismic and core data only permit an understanding of the timing and characteristics of deposition at the shelf edge during the last lowstand (uncored Allounit B, described as seismic unit 1A by Aksu et al., 2002b), and across the shelf during the subsequent Holocene transgression (Allounit A). Shelf-edge deltas likely received their sediment from the ancestrial courses of small modern rivers that, at times of lowered sea level, coalesced into a single channel belt toward the shelf edge (Aksu et al., 2002b). After ∼11–10.5 ka, the shelf was rather rapidly inundated so that the water level reached −40 m by ∼10 ka. The sea-level rise was gradual enough, however, to permit the development of a set of backstepping barrier islands as part of the transgressive systems tract (Aksu et al., 2002b; their figs. 20 and 22). Over large parts of the shelf, and particularly where water depths today are < 65 m, wave erosion and resuspension prevented the accumulation of a significant sedimentary cover.

In the Marmara Sea, in contrast, recovery of dated cores from a wide range of depths allows reconstruction of conditions along a number of shelf-to-basin transects. We have chosen two transects to illustrate changing paleoenvironmental conditions: Transect I from the southern shelf lowstand deltas to the deep basins at ∼1200 m depth, and Transect II from the Black Sea overflow deltas south of the Bosphorus Strait to the same deep basins.

4.1. Marmara Sea Transect I, southern shelf to deep basins (Fig. 17)

Late in oxygen-isotope stage 3 (59–23 ka), while the level of the Mediterranean Sea stood at approximately −30 m (Skene et al., 1998), sapropel M2 accumulated in the deep Marmara Sea. By analogy with sapropel M1 (Aksu et al., 2002a), we infer a period of increased fresh- to brackish-water input into the Marmara Sea at that time, either from the Black Sea or the rivers of the southern shelf of the Marmara Sea. The most likely source was the Black Sea, because the combined discharge of the southern shelf rivers is today only ∼2% of the volume of brackish-water input from the Black Sea, yet even today the Black Sea input is insufficient to promote sapropel deposition in the deep basins of the Marmara Sea. Only exceptional discharges from the Black Sea are capable of triggering and maintaining the strong stratification required for sapropel deposition. The transition from Allounit C to B is characterized by increases in marine microfauna and microflora, which we ascribe to the decreasing influence of the brackish-water surface layer. The Black Sea fell well below the sill depth of the Bosphorus Strait by oxygen isotopic stage 2 because of reduced riverine input and increased evaporation (Pirazzoli, 1996; Ryan et al., 1997; Aksu et al., 2002b).

During the lowstand of the last glacial maximum, most of the southern shelf of the Marmara Sea was subaerially exposed, and deltas of Allounit B were situated immediately landward of core site MAR97-11, providing prodeltaic muds to this core site and basinal areas. Following the postglacial rise of global sea level to −75 m at ∼12 ka, the Marmara Sea became inundated rather quickly from −90 m depth to −75 m depth. The inflow cut an erosional notch in bedrock at the eastern end of the Dardanelles Strait (Aksu et al., 1999, their fig. 6) and drowned an erosionally dissected landscape. Approximately 2000 yr later, the Black Sea rose to start spilling into the Marmara Sea, leading once again to establishment of a brackish-water lid that has persisted to the modern day (Aksu et al., 2002a). The strongest Black Sea outflow began at ∼10 ka and persisted to ∼6 ka, promoting the accumulation of sapropel M1 in the deep Marmara Sea, and progradation of an overflow delta just south of the exit from the Bosphorus Strait (see below). These deposits

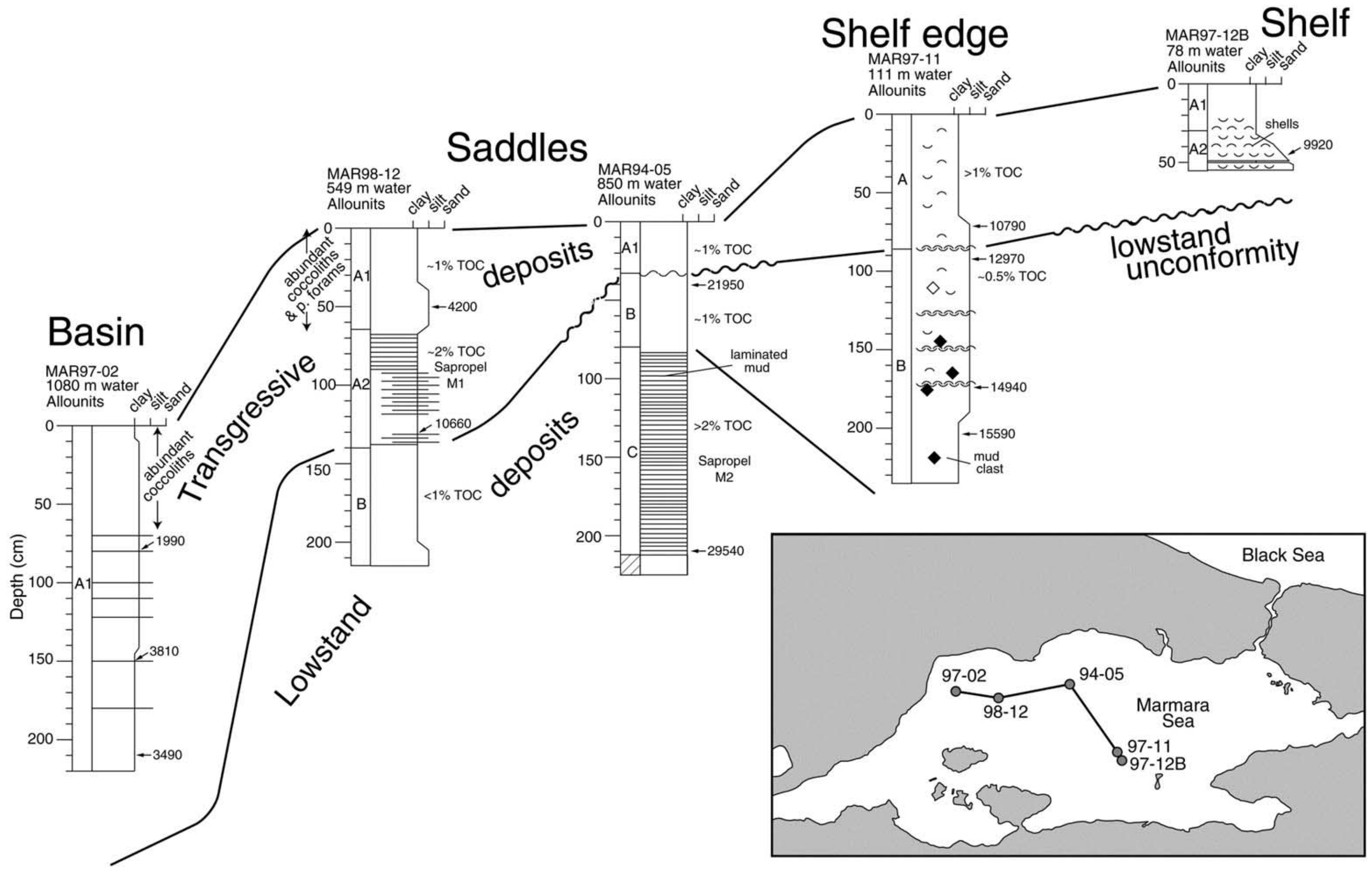

Fig. 17. Schematic cross-section along Transect I, showing the correlation of allounits across the western basin, to the saddle which separates the western and central basins, to the southern shelf. Inset shows the location of the transect.

belong to Subunit A2, as do the backstepping deltas on the southern shelf that formed during the diachronous transgression (base of Core MAR97-12B).

Allostratigraphic Subunit A1 corresponds to a time of diminished brackish-water outflow from the Black Sea, and increased influence of Mediterranean water in the Marmara Sea, so that microfossil contents increase in cores and a hemipelagic, burrowed mud drape has accumulated in all areas (e.g., Figs. 9 and 10). Bottom-water oxygen contents have remained relatively low (Aksu et al., 2002a) because of continued water-column stratification caused by Black Sea outflow. Because of weaker stratification than during the time of deposition of sapropel M1, organic carbon contents of the A1 muds are ~1% or less. Accumulation rates in the deep central basins have remained high (Figs. 4 and 5), with an interbedding of hemipelagic muds and thin silt turbidites.

4.2. Marmara Sea Transect II, Bosphorus overflow deltas to deep basins (Fig. 18)

A delta lobe (Fig. 11) began to prograde at the

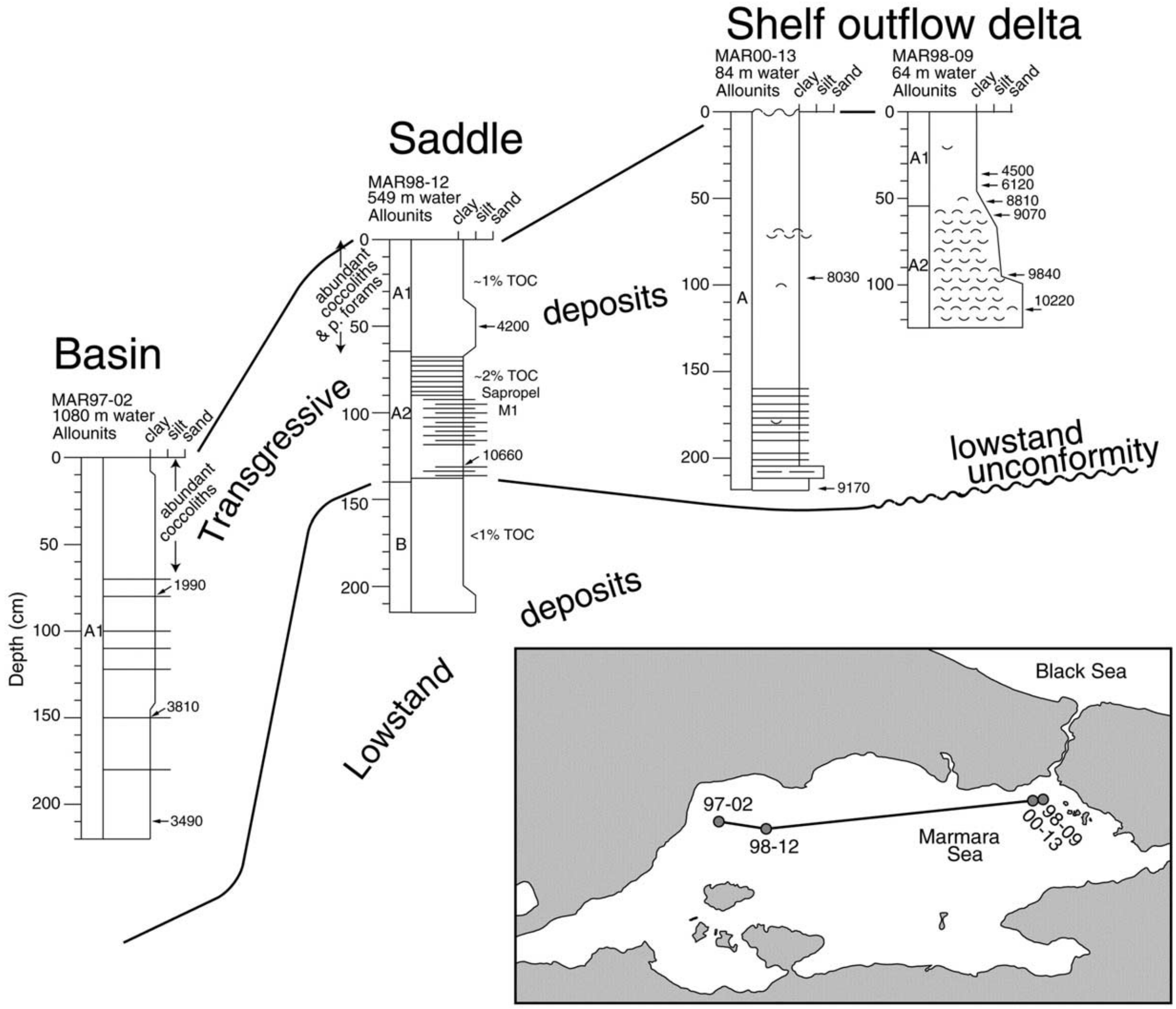

Fig. 18. Schematic cross-section along Transect II, showing the correlation of allounits across the western basin, to deep-water saddle sites, to the vicinity of the Bosphorus Strait. Inset shows the location of the transect.

southern end of the Bosphorus Strait at ~10 ka (Hiscott et al., 2002), and persisted until ~9 ka. This lobe and coeval to somewhat younger deposits (to ages of ~6 ka) constitute Subunit A2. Prodeltaic sand and silt beds and laminae were recovered in Core MAR00-13, and date from the terminal stages of delta growth. Hiscott et al. (2002) propose that this delta lobe was abandoned not because Black Sea outflow declined at ~9 ka, but rather because rising sea level led to penetration of a salt wedge deep into the Bosphorus Strait, so that bedload supply to the delta was cut off. The continuation of sapropel deposition in the basinal areas (M1) confirms that vigorous Black Sea outflow did not decline until ~6 ka, after which diminished water-column stratification increased the oxygen content of bottom waters, allowing burrowers to colonize the seabed sediments and enhancing the degradation of organic carbon.

After ~9 ka, a rather uniform mud drape characterizes the Bosphorus exit. Muds of Allounit A began to accumulate later at the Bosphorus exit than in Transect I or at the western end of the Marmara Sea (Figs. 9 and 10) because of the continuation of deltaic sedimentation near the Bosphorus Strait. However, if Transect I were extended farther onshore toward the modern southern coast of the Marmara Sea, there would be an increase in the deltaic character of Allounit A, eventually passing into the modern prodelta of the Kocasu River (MAR97-13, Fig. 8d). The major difference between the two transects is that deltas are still active along the southern shelf because they are river-fed, whereas delta lobes no longer exist south of the Bosphorus Strait because the 10–9-ka delta was fed entirely by outflow from the Black Sea before a two-layer flow had been established in the Bosphorus Strait. Since the establishment of two-layer flow, there is no sediment supply to construct a delta because the Black Sea outflow has no contact with the floor of the strait. Instead, the floor of the strait is only influenced by a northward flowing Mediterranean water mass.

5. Conclusions

(a) Three allounits are identified in the cored late Quaternary successions in the Marmara Sea. Allounit A extends from the seafloor downward to the ~12-ka sequence boundary, which is an unconformity in water depths less than ~100 m and a correlative conformity in deeper areas. Allounit B is only present at water depths greater than ~90 m, and represents basinal or prodeltaic deposition during the 23–12-ka lowstand. Allounit C is a laminated sapropel (M2).

(b) Two allounits are identified in the Quaternary succession in the Black Sea. Allounit A extends from the seafloor the ~11-ka sequence boundary which is a major shelf-crossing unconformity, **α**. Allounit B is only present along the shelf edge at water depths greater than ~90 m, and represents deltaic deposition during the last glacial maximum; it has not been cored.

(c) In the Black Sea, wave erosion during falling sea level and the early stages of transgression kept the shelf stripped of previously deposited unconsolidated sediments, developing a major unconformity, **α**. Shelf-edge deltas developed during a lowstand of −100 to −110 m that lasted until ~11–10.5 ka. While sea level rose to −40 m by ~10 ka, a set of backstepping barrier islands developed as part of the transgressive systems tract.

(d) From ~30 to 23 ka, sapropel M2 accumulated in the deep Marmara basins during a period of increased brackish-water input into the Marmara Sea mainly from the Black Sea. The transition from Allounit C to B is characterized by the decreasing influence of a brackish-water surface layer, probably because of the lowering of the Black Sea level toward the last glacial maximum and a reduction in its outflow. During the lowstand of the last glacial maximum, most of the southern shelf of the Marmara Sea was subaerially exposed, and deltas of Allounit B were situated along the present-day shelf edge. Following the post-glacial rise of global sea level to −75 m at ~12 ka, the Marmara Sea became inundated rather quickly from −90 to −75 m depth. The inflow cut an erosional notch in bedrock at the eastern end of the Dardanelles Strait and drowned an erosionally dissected landscape, leading to the beginning of diachronous deposition of a widespread mud drape starting at ~11 ka in deeper areas. Beginning at ~10 ka, the Black Sea rose to start spilling into the Marmara Sea, promoting the accumulation of sapropel M1 in the deep Marmara Sea and progradation of an overflow delta just south of the exit from the Bosphorus Strait. Persistent Black Sea outflow since ~10 ka has promoted and maintained dysaerobic conditions at the seafloor.

Acknowledgements

We thank Prof. Dr. Erol Izdar, the Director of the Piri Reis Foundation for Maritime and Marine Resources Development and Education, and Prof. Dr. Orhan Uslu, the Director of the Institute of Marine Sciences and Technology, for their support and encouragement. We extend our special thanks to the officers and crew of the R/V *Koca Piri Reis* for their assistance in data acquisition, in particular Captains Mehmet Özsaygılı (MAR98) and Ramiz Akdemir (MAR00) and the Chief Engineer Ömer Çubuk. We acknowledge research and ship time funds from the Natural Sciences and Engineering Research Council of Canada (NSERC) to A.E.A. and R.N.H., travel funds from the Dean of Science, Memorial University of Newfoundland, and a special grant from the Piri Reis Foundation for Maritime and Marine Resources Development and Education. Journal reviewers David Piper and Yoshi Saito provided many helpful suggestions that have improved the paper.

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