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THE MARMARA SEA GATEWAY SINCE ~16 KY BP: NON-CATASTROPHIC CAUSES OF PALEOCEANOGRAPHIC EVENTS IN THE BLACK SEA AT 8.4 AND 7.15 KY BP

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Abstract: The Late Quaternary history of connection of the Black Sea to the Eastern Mediterranean has been intensely debated. Ryan, Pitman and coworkers advocate two pulses of outflow from the Black Sea to the world ocean at ~16–14.7 ky BP and ~11–10 ky BP. From ~14.7–11 ky BP and from ~10–8.4 ky BP, they suggest that the level of the Black Sea fell to ~ –100 m. At 8.4 ky BP, they further claim that a catastrophic flood occurred in a geological instant, refilling the Black Sea with saline waters from the Mediterranean. In contrast, we continue to gather evidence from seismic profiles and dated cores in the Marmara Sea which demonstrate conclusively that the proposed flood did not occur. Instead, the Black Sea has been at or above the Bosphorus sill depth and flowing into the world ocean unabated since ~10.5 ky BP. This conclusion is based on continuous Holocene water-column stratification (leading to sapropel deposition in the Marmara Sea and the Aegean Sea), proxy indicators of sea-surface salinity, and migration of endemic species across the Bosphorus in both directions whenever appropriate hydrographic conditions existed in the strait. The two pulses of outflow documented by Ryan, Pitman and coworkers find support in our data, and we have modified our earlier interpretations so that these pulses now coincide with the development of mid-shelf deltas: Δ2 (16–14.7 ky BP) and Δ1 (10.5–9 ky BP) at the southern end of the Bosphorus Strait. However, continued Black Sea outflow after 9 ky BP prevented the northward advection of Mediterranean water and the entry of open-marine species into the Black Sea for more than 1000 years. Sufficient Mediterranean water to change the Sr-isotopic composition of slope and shelf water masses was not available until ~8.4 ky BP (along with the first arrival of many varieties of marine fauna and flora), whereas euryhaline molluscs did not successfully populate the Black Sea shelves until ~7.15 ky BP. Instead of relying on catastrophic events, we recognize a slow, progressive reconnection of the Black Sea to the world ocean, accompanied by significant time lags.

Keywords: Marmara Sea Gateway, Bosphorus Strait, Black Sea Flood Hypothesis, Outflow Hypothesis, climate change

1. INTRODUCTION

The “Marmara Sea Gateway” connects the Black Sea and Eastern Mediterranean (Figure 1A, B). The gateway consists of (1) a linked set of narrow straits with shallow bedrock sills (the Bosphorus Strait with a sill depth of ~ –40 m; and the Dardanelles Strait with a sill depth of ~ –70 m) and (2) the inland Marmara Sea. The Marmara Sea fills a rugged, tectonically active depression comprising three abyssal basins reaching depths of >1200 m and separated by cross-basin ridges (Aksu *et al.* 2000).

The Marmara Sea Gateway provides an unparalleled natural laboratory in which to study the evolution of Quaternary climate in central and northern Europe. This is because the narrow straits regulate all communication between the Black Sea and the world ocean through the small Marmara Sea, which acts as a sediment trap, registering, like a sensitive tape recorder, paleoceanographic events and paleoenvironmental changes in the catchment area of the rivers that drain into the Black Sea. The volume of the Marmara Sea is only 0.65% of the volume of the Black Sea, so there is enormous amplification in the Marmara sediments of the effects of Quaternary water exchange between the Aegean and Black Seas. The geometry of this gateway is analogous to a vacuum line in a chemistry laboratory, with its series of control valves and condensation traps.

Today, the Black Sea is swollen by the discharge of major European rivers (the Danube, Don, Dnieper, Dniester, Southern Bug), resulting in the net export of ~300 km^3/yr of water through the gateway. This volume represents fifty times the cumulative annual discharge of the small rivers entering the Marmara Sea. Satellite altimetry shows that the surface of the Black Sea is ~30 cm above the level of the Marmara Sea, which, in turn, varies between 5 and 27

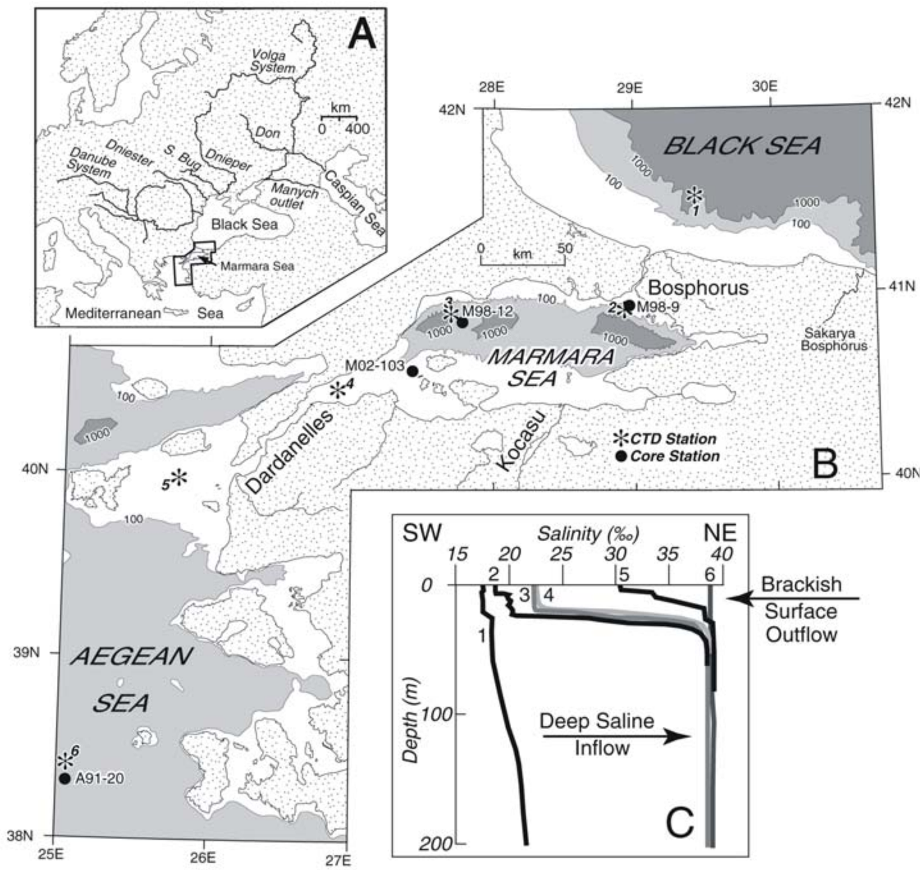

Figure 1. **A:** Location of the Marmara Sea and major European rivers entering the Black Sea. During deglaciation, the Volga system was connected to the Black Sea through the Manych outlet and a link to the Don River. **B:** Simplified bathymetry in meters (Aksu *et al.* 1999); location of cores M98-9, M98-12, M02-103 and A91-20; and location of conductivity-temperature-depth (CTD) stations 1–6, corresponding to data plotted in part C. The Sakarya Bosphorus no longer connects to the eastern end of the Marmara Sea because of Quaternary offsets along the North Anatolian Transform Fault. **C:** Salinity *versus* water depth in the upper 200 m (stations 1, 3, 6) or to the seabed (stations 2, 4, 5), showing sharp salinity-controlled pycnocline at ~20–25 m except in the Black Sea (subtle pycnocline at ~130 m) and the southern Aegean Sea (no low-salinity layer). The low-salinity surface lid originates from Black Sea outflow and promotes permanent stratification which in turn promotes sub-pycnocline oxygen depletion. Salinity (CTD) data from archives of Institute of Marine Sciences and Technology (IMST), Dokuz Eylül University, Izmir.

cm above the level of the northern Aegean Sea (Polat and Tuğrul 1996). These elevation differences drive the outflow across the gateway.

The present water exchange across the Bosphorus Strait is a two-layer flow. A cooler, lower salinity (17–20‰) surface layer exits the Black Sea, while warmer, higher salinity (38–39‰) Mediterranean water flows northward through

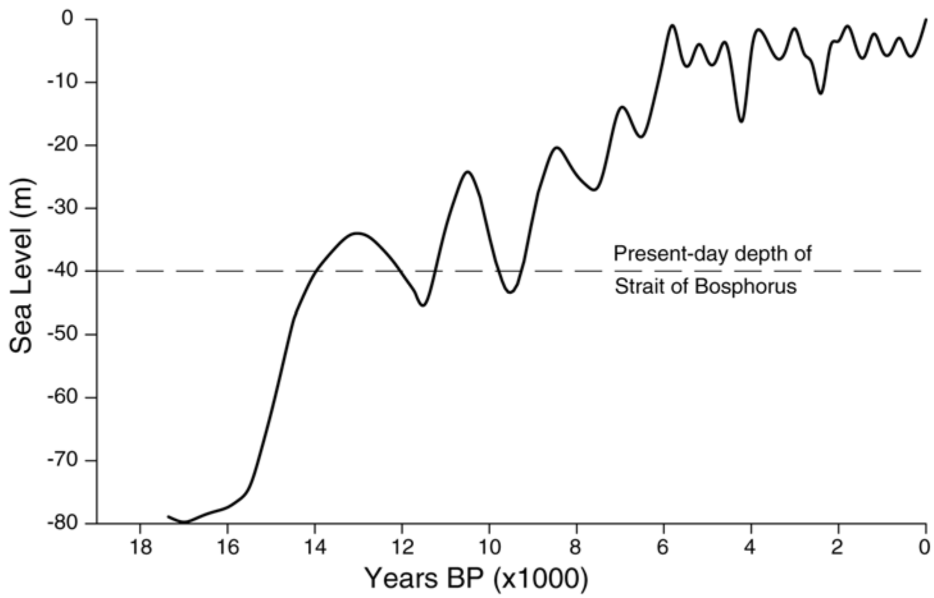

Figure 2. Record of Black Sea water levels compiled from radiocarbon dates on shells collected from former shorelines around the Black Sea coast and inner shelf (after Chepalyga 2002).

the strait at depth (Polat and Tuğrul 1996). The upper tens of meters of the water column in the gateway area (but not in the open Aegean Sea) are strikingly fresher than the deep water because of the Black Sea outflow (Figure 1C). The low-density surface layer prevents ventilation of the deeper water column, promotes organic-matter preservation, and fosters benthic communities adapted to suboxic to dysoxic conditions with 0.1–1.3 ml/l dissolved oxygen.

Throughout the Quaternary, the Black Sea experienced a complex series of transgressions and regressions (Figure 2) (Chepalyga 2002). Transgressions resulted from a combination of melting ice sheets and permafrost in Central Asia (east of the Ural Mountains), wet periods with increased rainfall, cooler time intervals with reduced evaporation across eastern Europe and west-central Asia, and periodic discharges of water from the Caspian Sea through the Manych Depression (e.g., the 16–14 ky BP late Khvalynian flood peak of Chepalyga, this volume). Whenever the sill in the Bosphorus Strait (or Sakarya Bosphorus as in Figure 1B) was subaerially exposed because of low global sea level (glacial stages 6, 4–2; see Yaltırak *et al.* 2002), the Black Sea oscillated independently, whereas at other times like today (interglacial stages), the level of the Black Sea was effectively pinned to the level of the global ocean because of free exchange across the Marmara Sea Gateway. Throughout its Quaternary history, the salinity of the Black Sea has varied from marine to semi-fresh. Salinity estimates used here follow the terminology of Chepalyga (1984): marine (30–40‰ salinity), semi-marine (12–30‰), brackish (5–12‰), semi-fresh (0.5–5‰), and fresh (<0.5‰).

2. RIVAL HYPOTHESES

The means by which the Black and Mediterranean Seas were reconnected after the last glaciation is intensely debated. Ryan *et al.* (1997) and Ryan and Pitman (1998), modified by Ryan *et al.* (2003), proposed their *Flood Hypothesis*, which entailed a catastrophic refilling of the Black Sea basin by marine water at ~8.4 ky BP, an event they estimate to have taken place in less than two years. They link this controversial deluge with the biblical account of Noah's Flood and explain a low Black Sea (Neoeuxinian Lake) persisting well into the Holocene by advocating a dry central European climate. Before this flood, Ryan and coworkers argue for the scenario diagrammed in Figure 3A:

(1) a ~16–14.7 ky BP meltwater-induced outflow from the Black Sea through the Bosphorus channel (= late Khvalynian flood peak of Chepalyga, this volume),

(2) an evaporative drawdown of the Black Sea to an elevation of ~ –105 m from 14.7–12 ky BP,

(3) a ~11.5–11 ky BP Black Sea transgression to –25 to –30 m that caused a second outflow into the Marmara Sea from ~11–10 ky BP, and

(4) a 10–8.4 ky BP evaporative drawdown of the Black Sea until it reached ~ –95 m.

Because the Mediterranean and Marmara water levels had by ~8.4 ky BP already risen to ~ –25 m, well above the present sill depth of the Bosphorus Strait, Ryan *et al.* (1997) hypothesized the existence of a sediment dam to hold back the global ocean. They concluded that the Marmara and Mediterranean catastrophically flooded into the depressed Black Sea basin when this hypothetical sediment dam in the Bosphorus channel was scoured away.

Initially, Ryan *et al.* (1997) relied on radiocarbon dates of the first euryhaline molluscs to populate the drowned shelves of the northern Black Sea as a marker for the time of flooding; these dates clustered at ~7.15 ky BP. Euryhaline molluscs require semi-marine to marine salinity of ~20–40‰ (Knox 1986), conditions only marginally attained in the Black Sea today (Figure 1C). Subsequently, Major (2002) and Ryan *et al.* (2003) shifted the date for flooding to ~8.4 ky BP based mainly on Sr-isotopic data, and they reinterpreted the ~7.15 ky BP shell ages as having resulted from an approximately 1300-year salinization time lag, after which the Black Sea shelf waters attained a salinity level appropriate for colonization by euryhaline fauna well after the actual reconnection took place.

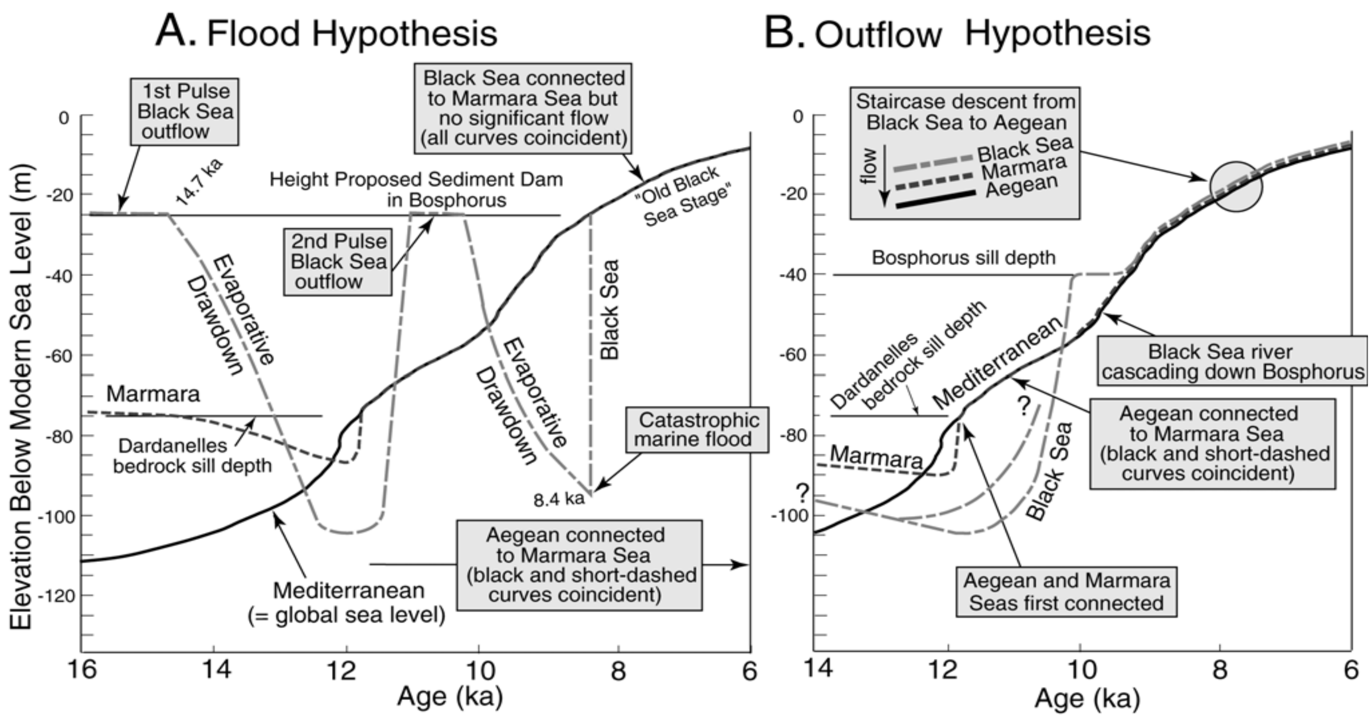

Figure 3. Schematic water-level histories of the Black, Marmara, and Mediterranean (Aegean) Seas according to A. the *Flood Hypothesis* of Ryan *et al.* (2003) and B. the original *Outflow Hypothesis* of Aksu *et al.* (2002a) and Hiscott *et al.* (2002). In both plots, the Mediterranean curve (solid dark line) is the Barbados (global) curve of Fairbanks (1989). When Mediterranean and Marmara curves (dotted dark line) are superimposed (e.g., from ~12–10 ky BP in both plots), the Marmara Sea was an embayment of the Mediterranean.

The flood hypothesis was initially challenged by several authors. Shifting the flood date from ~7.15 to ~8.4 ky BP satisfied the objections of Görür *et al.* (2001), but an extensive Russian literature on regional water-level variations still concludes that the Black Sea reached a level of ~ –30 m by ~10–9 ky BP and has never been lower since (Figure 2). In the Marmara and Aegean Seas, sensitive proxy indicators in sediment cores have been interpreted by Aksu *et al.* (1995, 2002a, b, c), Çağatay *et al.* (2000), Kaminski *et al.* (2002), and Abrajano *et al.* (2002) as evidence that the Black Sea has been continuously exporting low-salinity water through the Marmara Sea Gateway since ~10 ky BP, or perhaps earlier. This is the basis for our *Outflow Hypothesis* (Figure 3B). Physical sedimentological evidence from bedform asymmetry and deltaic progradation at the southern end of the Bosphorus Strait supports this interpretation (Aksu *et al.* 1999; Aksu *et al.* 2002a; Hiscott *et al.* 2002). These last authors named the youngest delta (~10–9 ky BP) at the strait exit "delta 1," or Δ1.

We began to study the gateway area in 1995 and have acquired approximately 8500 line-km of airgun, sparker, and Huntec boomer profiles (vertical resolution ~10–20 cm), about 126 gravity and piston cores, and 78 radiocarbon dates from cores. A case has been built for continuous Black Sea outflow since ~10 ky BP that is rooted mainly in our large dataset from the Marmara and Aegean Seas, and less so from the Black Sea itself. Ryan *et al.* (2003) criticize our efforts to deduce the behavior of the Black Sea largely from adjacent waterways, but the unique configuration of the Marmara Sea Gateway perhaps makes it a better place to monitor the reconnection history than within the Black Sea itself. As an analogy, if one wants to know the number of spectators in a stadium, a count at the exit as people enter or leave is more reliable than an attempt to estimate the number of spectators from within the stadium. Our evidence from the connecting link between the Aegean and Black Seas leaves little doubt that the last phase of Black Sea outflow began as early as ~11–10 ky BP and has continued to the present.

Ryan *et al.* (1997) and Ryan and Pitman (1998) instead proposed that the Black Sea was in a protracted phase of evaporative drawndown from ~14.5–7.15 ky BP, ending with a catastrophic flood when the rising Mediterranean and Marmara Seas breached the sediment dam in the Bosphorus Strait. In their present version of events, Major (2002) and Ryan *et al.* (2003) acknowledge outflow at ~11–10 ky BP but insist that it then stopped, first because evaporation lowered the level of the Black Sea and terminated the earlier connection during the interval 10–8.4 ky BP, and subsequently because the Black Sea remained sufficiently evaporative that it continued to receive net inflow from the Aegean Sea through the Bosphorus Strait. They suggest that this latter situation continued until ~3 ky BP, when the Black Sea's tributary rivers eventually attained near-modern discharges and the climate shifted to modern humidity and rainfall

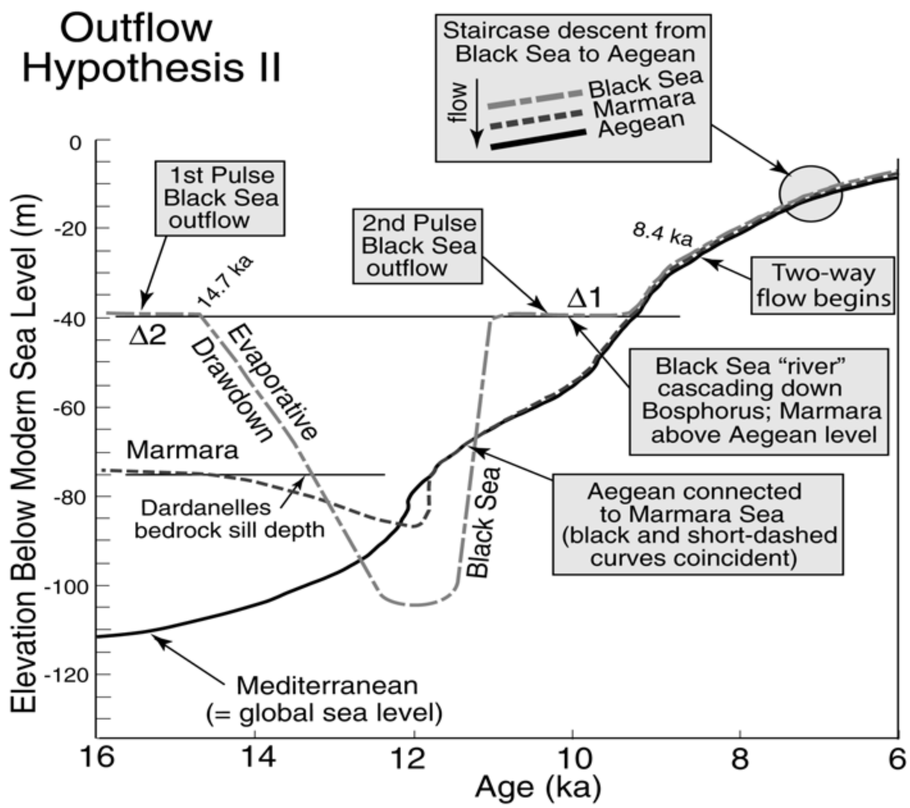

Figure 4. Modified *Outflow Hypothesis*, designated as version II. An ~16–14.7 ky BP episode of Black Sea outflow is incorporated, and the second pulse of Black Sea outflow is initiated somewhat earlier than in Figure 3B.

levels. Only since ~3 ky BP (not shown in the plot of Figure 3A), in what is known as the New Black Sea stage, do Ryan *et al.* (2003) believe that water exchange between the Black Sea and the Mediterranean has been like that of the present, with significant Black Sea outflow across the gateway.

In the Marmara Sea, the *Flood Hypothesis* predicts thorough mixing of the water column between ~10 and 8.4 ky BP, with a final turbulent stirring and flushing in of Mediterranean fauna and flora over a short period at 8.4 ky BP. According to the original *Outflow Hypothesis*, the Black Sea reached the –40 m bedrock sill depth in the Bosphorus Strait first, initiating a cascade downslope into the rising Marmara Sea from ~10–9 ky BP and building delta Δ1 (Figure 5). This hypothesis does not involve a catastrophic flood but instead predicts stratification and low oxygen conditions in the Marmara Sea since ~10 ky BP, similar to today (Figure 1C).

Is there any common ground between the *Flood Hypothesis* and our

Outflow Hypothesis? Yes, but only for the period before 10 ky BP. For example, we see considerable merit in the proposal of Ryan *et al.* (2003) that there were two outflow events at ~16–14.7 and ~11–10 ky BP, and we have incorporated these into a modified *Outflow Hypothesis* (version II, Figure 4). This modification does not violate any of the data presented by Aksu *et al.* (2002b) and Hiscott *et al.* (2002) and provides an explanation for the double unconformity present locally on the southwestern Black Sea shelf (α and α1 of Aksu *et al.* 2002b). Also, the ~16–14.7 ky BP outflow event provides an attractive explanation for the older delta 2 (Δ2) described by Hiscott *et al.* (2002) at the southern exit of the Bosphorus (Figure 5). With new cores, we have now established that the widespread mud drape on top of Δ2 and below the β3 unconformity was forming at 10,950 yr BP based upon radiocarbon dating from Core M02-111 (Table 1, Figures 6 and 7B). A comprehensive reanalysis of the development of Δ2 and the younger Δ1, and the constraints they place on Black Sea outflow, is presented in a later section.

In this paper, we marshal previously published and new evidence from the Marmara and Aegean Seas to evaluate the history of connection between the Black Sea and the open ocean. The critical debating points between Ryan and coworkers and our research team can be reduced to two fundamental issues:

(1) Is there any evidence in the Marmara Sea Gateway that the strong Black Sea outflow that began at ~11–10 ky BP was reduced to nothing (~10–8.4 ky BP) and then very little (8.4–3 ky BP) as Ryan *et al.* (2003) have proposed?

(2) Is there credible evidence that early Holocene climate throughout the region was sufficiently arid to promote net evaporation from the Black Sea surface from ~10–3 ky BP?

We first review the basis for the agreed early strong outflow (before ~10 ky BP). Then, we evaluate whether environmental and paleoceanographic proxy data from younger deposits are compatible with a continuation of this outflow to the present day, or instead suggest a predominant Mediterranean influence across the Marmara Sea Gateway from ~8.4–3 ky BP with significant net Black Sea outflow resuming only after that time.

2.1 The ~16–9 ky BP History of Connection and Black Sea Outflow

Until ~12 ky BP, global sea level was lower than the spill depth of the Marmara Sea at the Dardanelles Strait (e.g., Fairbanks 1989), effectively limiting water level in the Marmara Sea to a maximum height of ~ –70 m. Ryan *et al.* (2003) describe highstand deposits from the Black Sea dating to ~16–14.7 ky BP that indicate overspill into the Marmara Sea at that time. This influx of water into the small Marmara basin (with <1% of the volume of the Black Sea) would have

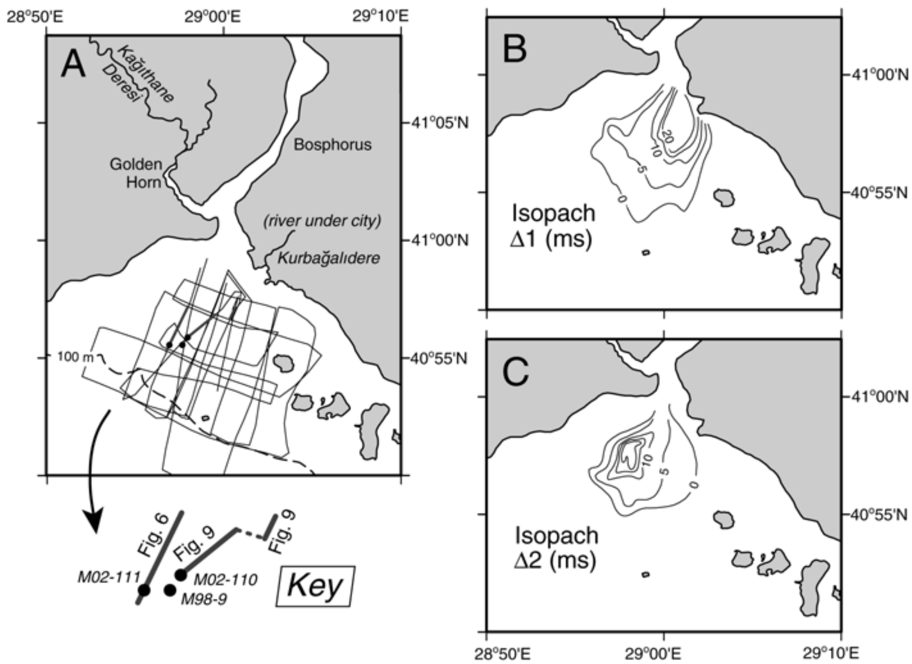

Figure 5. Maps of the area south of the Bosphorus Strait.
A. Boomer survey tracks (~280 line-km), core locations, and key to the locations of seismic profiles shown in other figures (see enlarged labels for cores and seismic profiles below the map). The Kağıthane Deresi and Kurbağalı Dere are small rivers described in the text and Table 1.
B. and **C.** Isopach maps of strait-mouth deltas, the younger Δ1 and the older Δ2, with sediment thicknesses in milliseconds of two-way travel time (10 ms ≈ 7.5 m).

maintained its water level at the Dardanelles spill depth until ~14.7 ky BP, creating a staircase descent from the Black Sea at ~ –40 m (Figure 4) or ~ –25 m (Figure 3A), to the Marmara Sea at ~ –70 m, to the gradually rising Aegean Sea.

The isolated mid-shelf delta (Δ2 of Hiscott *et al.* 2002) at the southern end of the Bosphorus Strait is here reinterpreted to have formed during the ~16–14.7 ky BP outflow event (Figures 5C and 6). The youngest topset-to-foreset transition of this delta is at a modern elevation of –69 m. Ideally, the topset elevation should be several meters below the contemporaneous sea level. Given potential uncertainty in the estimate of the depth of the Dardanelles sill, and possible uplift of Δ2 because of proximity to the North Anatolian Transform Fault (C. Yaltırak, personal communication 2004), the agreement between the topset-to-foreset elevation (–69 m) and the spill depth (~ –70 m) is remarkably good. When the first phase of Black Sea outflow ceased at ~14.7 ky BP (Ryan *et al.* 2003), Δ2 was abandoned and a marine drape filled depressions adjacent to the delta lobe (Figure 6 between β4 and β3). At this time, the Marmara Sea

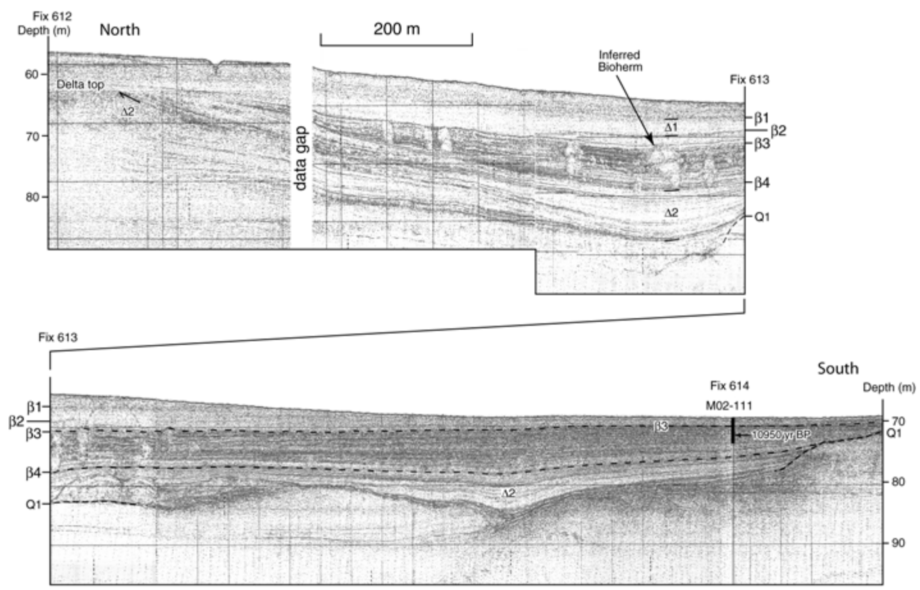

Figure 6. Huntec deep-tow boomer profile (location in Figure 5A) across Δ2, showing reflections β1–β4 and Q1 defined by Hiscott *et al.* (2002). Strata equivalent to Δ2 are confined between reflections β4 and Q1, whereas the younger Δ1 is represented in this profile only by its prodelta deposits between reflections β1 and β2. The mounds along the β3 surface are interpreted as algal-serpulid bioherms. Core M02-111 penetrates well below β3; facies, radiocarbon dates, and picks of reflectors are shown in Figure 7B.

was a landlocked lake, and evaporation from ~14.7–12 ky BP caused its surface to drop to ~ –100 m (Aksu *et al.* 1999) forming the β3 unconformity in the vicinity of Δ2. Our own observations on the shelf of the southwestern Black Sea confirm a lowstand of ~ –120 m during the same time period (Aksu *et al.* 2002b), so that there would have been no connection or water exchange between the Black Sea and the landlocked Marmara Sea. Proxy paleoclimate data are consistent with dry conditions at this time to account for the net evaporation (Mudie *et al.* 2002b).

During the ~16–14.7 ky BP outflow event, sands and gravels at the shallow western end of the Marmara Sea were reworked into west-directed bedforms (Aksu *et al.* 1999). We recently cored through the homogeneous mud drape that overlies these bedforms and recovered, from below the mud, a unit of gravelly sand of which 10–20% consisted of <2 cm pebbles (Figures 8 and 7A). Marine shells at the base of the mud provide a minimum age of 11,340 yr BP for this reworked gravel (Table 1), but the gravel itself was non-fossiliferous and potentially several thousand years older. It could have been formed contemporaneously with Δ2 during the ~16–14.7 ky BP outflow event when the Marmara Sea stood at –65 to –70 m. No erosional break was found within the

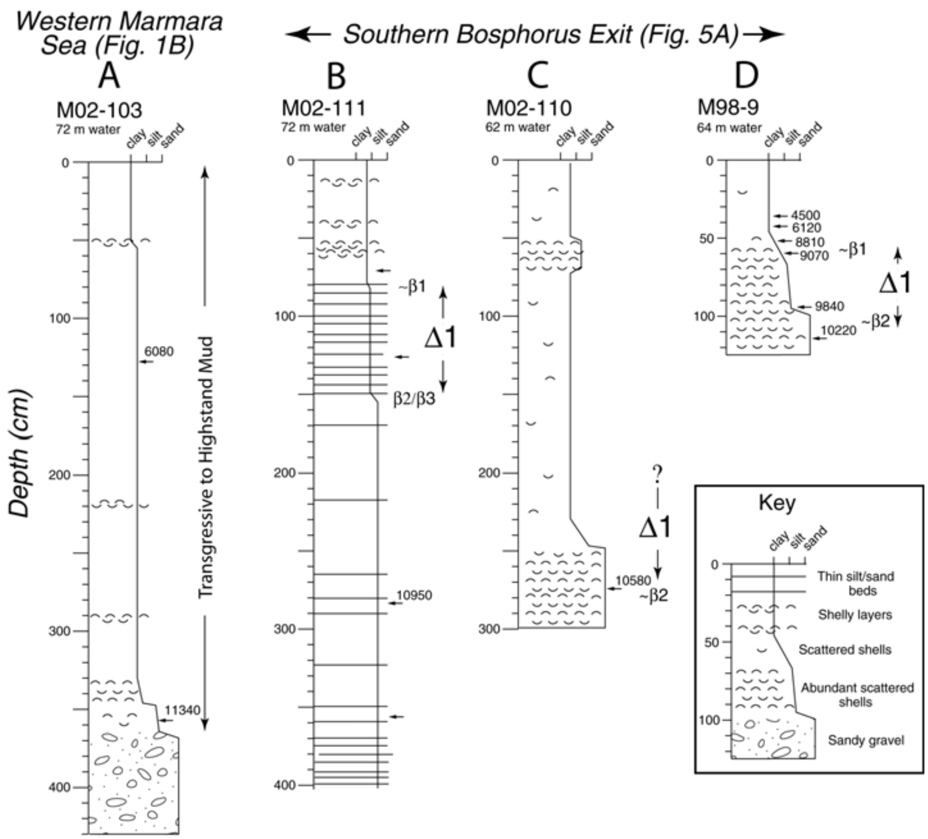

Figure 7. Graphic core logs for three new cores not described in earlier publications, and the previously described Core M98-9 (see also Figure 10). Radiocarbon dates are presented more fully in Table 1. Interpreted reflector depths are determined from seismic profiles at each core site and from changes in lithology.

mud drape, contrary to what would be expected if there had been a violent northward flow of Mediterranean water in the early Holocene as proposed by Ryan *et al.* (1997), Ryan and Pitman (1998) and Ryan *et al.* (2003).

At ~12 ky BP, the world ocean had risen to the depth of the Dardanelles sill, and Mediterranean waters rapidly refilled the small Marmara basin to its sill depth (–65 to –70 m). Because the Black Sea was still isolated from the world ocean at this time (Figure 3A) (Ryan *et al.* 2003), the Marmara Sea developed into an arm of the Aegean Sea and became fully saline. Its shelves were colonized by algal-serpulid bioherms, which are found on the crests of submerged barrier islands and bedforms in the western Marmara Sea, and on the β3 unconformity south of Bosphorus Strait (Figure 6) (Hiscott *et al.* 2002). The hiatus in Black Sea outflow during the interval ~14.7–10 ky BP provided a

Table 1. Radiocarbon ages reported as uncalibrated conventional ^{14}C dates in years BP (half-life of 5568 years; errors are 68.3% confidence limits). Data are for cores considered in this paper only; see Aksu *et al.* (2002b) for additional dates.

Core	Depth (cm)	Latitude	Longitude	Water Depth (m)	Dated Material	Radiocarbon years BP	Lab Number
M98-9	35	40°55.36'N	28°56.80'E	–64	*Anomia* spp.	4500±60	TO-7789
	42				*Nuclea nucleus*	6120±70	TO-8455
	52				*Varicorbula gibba*	8810±100	TO-8456
	60				*Turritella* spp.	9070±70	TO-7790
	94				*Turritella* spp.	9840±80	TO-7791
	113				*Mytilus* spp.	10,220±70	TO-7792
M98-12	50	40°50.54'N	27°47.68'E	–549	Bivalve fragment	4200±100	TO-8457
	130				*Nuculacea* spp.	10,660±130	TO-8458
M02-103	128	40°34.85'N	27°27.81'E	–72	*Turritella* spp.	6080±80	TO-11148
	358				*Parvicardium exiguum*	11,340±80	TO-11011
M02-110	275	40°55.61'N	28°57.10'E	–62	*Anadara* spp.	10,580±100	TO-11149
M02-111	284	40°55.31'N	28°36.13'E	–72	*Anadara* spp.	10,950±100	TO-11150
A91-20	120	38°26.00'N	24°58.00'E	–630	foraminifera	9830±70	TO-3742

unique environment for bioherm development that has not recurred since.

A second pulse of brackish-water outflow from the Black Sea began perhaps as early as ~11 ky BP (Ryan *et al.* 2003) but certainly by 10 ky BP (Aksu *et al.* 2002a). This outflow suppressed the growth of algal-serpulid bioherms and reactivated the deposition of a mud drape across Δ2 and the β3 unconformity. Soon, the outflow intensified and a second mid-shelf delta (Δ1 of Hiscott *et al.* 2002) began to develop on the shelf (Figures 5B and 9), precisely at the elevation of global sea level from 10–9 ky BP (Fairbanks 1989). At 10 ky BP, the Marmara Sea was still some 20 m below the depth of the Bosphorus sill, so the burgeoning Black Sea fed a brackish-water river that nourished Δ1. This delta is unusual because it grew upward into the rising sea level, so that the topset-to-foreset transition is shallowest in the youngest deposits (Figure 9). The radiocarbon age of the reflector that defines the top of Δ1 is 8810–9070 BP (Table 1, Figure 7D), whereas the base of the delta is younger than β3 and therefore younger than 10,950 BP (Figures 7B and 6). This base is dated at ~10,580 BP in core M02-110 (Table 1, Figures 7C and 9).

Core M02-110 sampled the bottomsets of Δ1 (Figure 9) and provides a much more reliable indication of the age of the delta than the extrapolated age previously published by us for core M98-9 (see criticism in Ryan *et al.* 2003). This second episode of Black Sea outflow, which created Δ1, was triggered by the swelling discharges of the Danube, Dniester, Southern Bug, Dnieper, and Don Rivers, augmented at times by Volga River discharge through the Manych

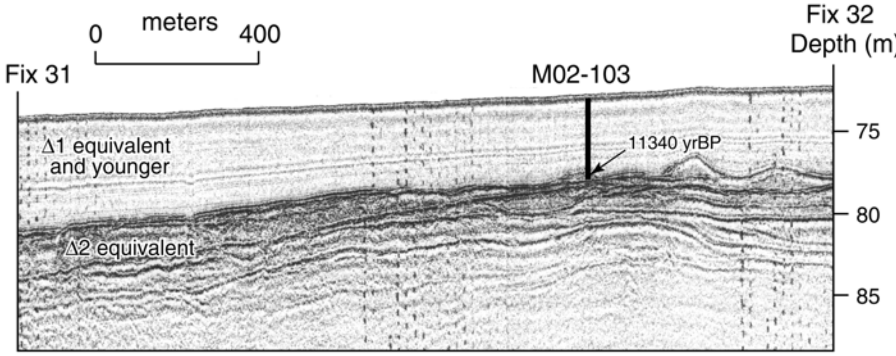

Figure 8. Huntec deep-tow boomer profile showing typical characteristics of the essentially homogeneous mud drape that overlies lowstand deposits around the Marmara Sea. The position of Core M02-103 on Figure 1B provides location. Core facies and ages are given in Figure 7B and Table 1. The highly reflective deposits below the cored interval are interpreted as fluviatile to shallow marine sands and gravels. Local crossbedding in this sediment indicates westward paleoflow (Aksu *et al.* 1999).

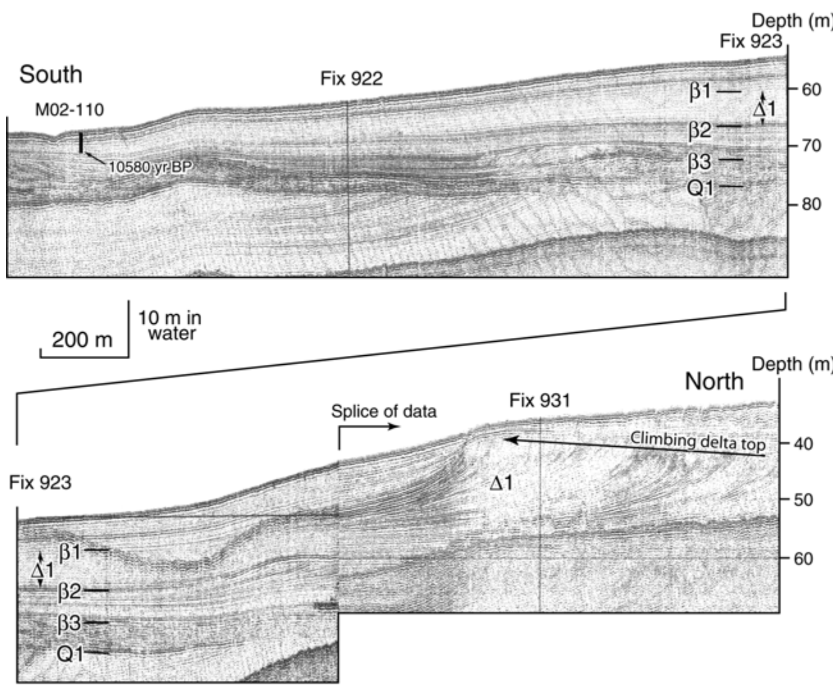

Figure 9. Huntec deep-tow boomer profile (location in Figure 5A) showing Δ1 delta front and prodelta, and the position of Core M02-110. The topset–foreset transition (offlap break) climbs consistently from right to left in the lower panel (north to south), indicating progradation during a relative sea-level rise. Foresets dip ~2°. Core M02-110 penetrates approximately to β2 at the base of the Δ1 succession; facies, radiocarbon dates, and picks of reflectors appear in Figure 7C.

outlet (Mamedov 1997; Chepalyga, this volume). The combined drainage area of these six rivers equals that of the Mississippi-Missouri system in America.

Ryan (2003) challenged our assertion that Δ1 and Δ2 were fed by Black Sea outflow through the Bosphorus Strait, suggesting instead that they are the deltas of either the Kağıthane Deresi or the Kurbağalı Dere, two small rivers that presently drain into the Marmara Sea near Istanbul (Figure 5A). This suggestion is untenable because the modern sediment discharge rates of these rivers are so small that it would take ~25,000–70,000 years to construct Δ1 (Table 2), a time span clearly at odds with the duration of delta progradation (~1000 years from ~10–9 ky BP). Hiscott *et al.* (2002) calculated Δ1sediment mass at 6.2×10^8 t.

Table 2. Comparison of water and sediment discharges of selected rivers with the modern Bosphorus (EIE 1999).

River or Strait	**Drainage Area (km^2)**	**Mean Discharge (m^3s^{-1})**	**Suspended Sediment Discharge ($t\ yr^{-1}$)**
Kocasu	21,611	151	1986×10^3
Kurbağalı Dere	41	1.6	9×10^3
Kağıthane Deresi	183	3.3	24×10^3
Modern Bosphorus	N/A	~10,000	surface outflow only

2.2 Evidence for Sustained Black Sea Outflow 10–3 ky BP

We have published several papers outlining why Black Sea outflow into the Aegean Sea through the Marmara Sea must have started ~10 ky BP and persisted to the present day. Black Sea outflow from ~10–6.4 ky BP is absolutely required to account for the intense water-column stratification and dysoxyia that accompanied deposition of contemporaneous sapropels S1 in the Aegean Sea (Aksu *et al.* 1995) and M1 in the Marmara Sea (Çağatay *et al.* 2000; Aksu *et al.* 2002a, c). This assertion has not been seriously challenged or rebutted by Ryan and coworkers, even though it is a fundamental inconsistency with their flood hypothesis. We remind the reader of the analogy of counting spectators as they leave a stadium in order to ascertain attendance. The large volumes of brackish water that entered the Marmara Sea from ~10–6.4 ky BP are an unambiguous indicator of persistent Black Sea outflow, because there is absolutely no other conceivable source for this low-salinity influx. Today, the volume of the semi-marine Black Sea outflow is ~50 times the combined volume of all rivers entering the Marmara Sea.

Benthic foramininfera allow estimation of bottom water oxygenation, using the benthic foraminiferal oxygen index (BFOI) of Kaiho (1994). Low values indicate dysoxic conditions at the seabed below a stratified water column (Kaminski *et al.* 2002). In the central Marmara Sea and northern Aegean Sea (Cores M98-12 and A91-20), low values confirm profound stratification through the ~10–6.5 ky BP interval (Figure 10). Dinoflagellate cysts *Brigantedinium simplex* and *Spiniferites cruciformis* (Figure 10) are sensitive indicators of low-salinity marine and fresh/brackish water conditions, respectively, and can be used to trace water masses. Mildly brackish water conditions prevailed in the Marmara Sea before its reconnection with the Aegean at ~12 ky BP (Core M98-12) and accompanied the development of sapropel in the Aegean Sea from ~10–6.5 ky BP (Core A91-20) (Figure 10). The only reasonable source of significant amounts of brackish water in the northern Aegean Sea is outflow from the Black Sea because small rivers in the region have insufficient catchments and discharges. This ouflow is confirmed in Core M98-12 by a broad peak in *Peridinium ponticum* (endemic to the Black Sea) from ~11–6 ky BP (Mudie *et al.* 2002a). Thus, Black Sea overflow began prior to 8.4 ky BP and continued into the Holocene.

Palynology indicates increased terrigenous supply of pollen from rivers beginning at ~11–10 ky BP and declining in the central Marmara and Aegean Seas by ~6 ky BP (Cores M98-12 and A91-20) (Mudie *et al.* 2002b). The persistent moderate pollen abundances at the southern exit from the Bosphorus Strait (Core M98-9) since ~9.5 ky BP are ascribed to pollen input into the Black Sea from major European rivers, and throughput of this pollen via outflow to the Marmara Sea (Figure 10).

Paleo sea-surface salinity (SSS) was calculated (as explained in Aksu *et al.* 1995) using (1) a Mediterranean-based transfer function to determine sea-surface temperatures, (2) the paleotemperature equation of Shackleton (1974) to determine $\delta^{18}O$ of the ancient surface waters, and (3) empirical data to relate these latter values to salinity. In the Aegean and central Marmara Seas, SSS dropped dramatically during deposition of approximately time-equivalent sapropels S1 and M1 (Cores A91-20 and M98-12). SSS at the southern exit from the Bosphorus Strait was depressed from ~10–9 ky BP, consistent with high abundances of the fresh/brackish-water dinocyst *S. cruciformis*.

Elevated TOC (total organic carbon) in Aegean Sea sediments coincides with lowered SSS, increased terrigenous supply of pollen, and increased stratification of the water column (low BFOI). In the Marmara Sea, TOC has been persistently high since ~11–10 ky BP, with a moderate decrease since ~5–3 ky BP away from the Bosphorus exit (e.g., Core M98-12). Pollen abundance mimics these trends, confirming the terrestrial origin of the organic matter (Mudie *et al.* 2002b; Abrajano *et al.* 2002). The core data indicate development of a brackish-water surface layer in the Marmara Sea by ~11–10 ky BP, with the strongest water-column stratification from ~10–6.5 ky BP, when widespread sapropel developed in the gateway area. The ~11 ky BP onset of stratification is consistent with the timing of the second outflow event of Ryan *et al.* (2003), but its continuation well beyond ~10 ky BP is not (Figures 3A and 4). Instead, this continuation requires unabated Black Sea outflow as proposed by Aksu *et al.*

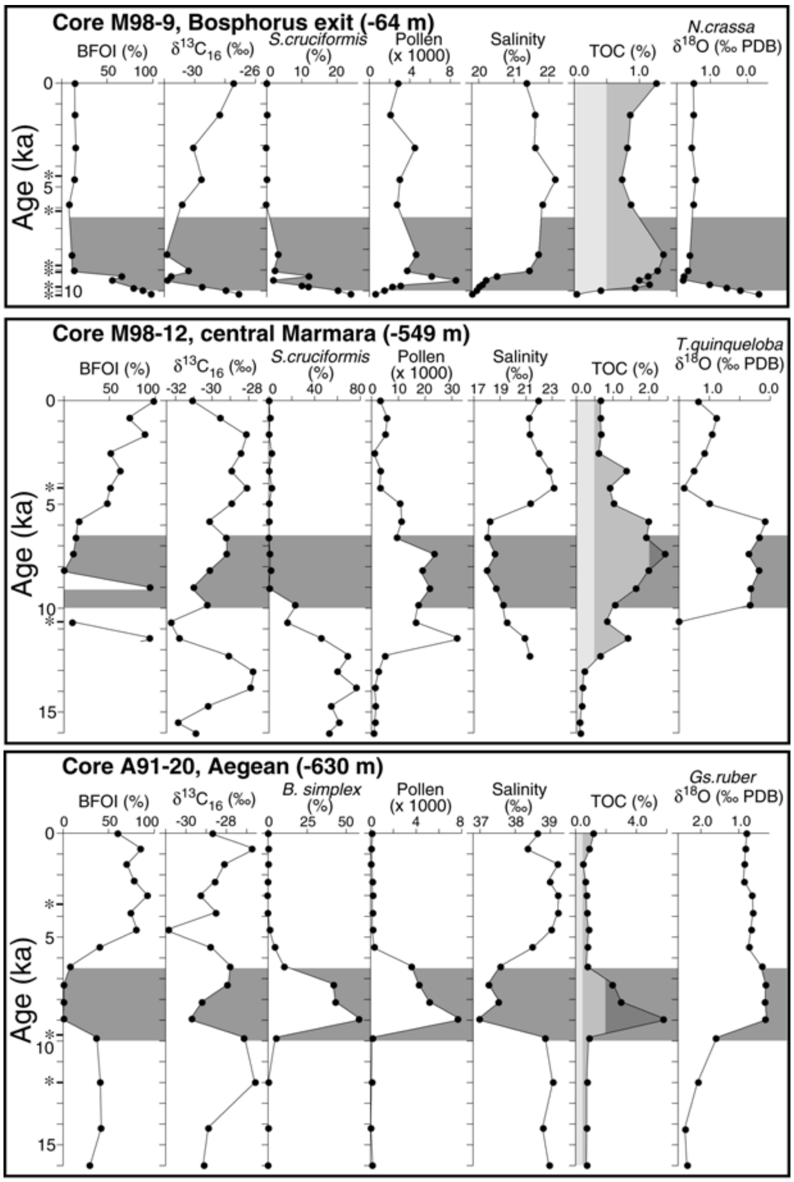

Figure 10. Downcore plots of key proxy variables; core locations in Figures 1B and 5A. Water depth at each site is indicated (e.g., -630 m). Samples were transposed into a time domain using radiocarbon dates tabulated in Aksu *et al.* (2002c), and the oxygen-isotope and ash record in Core A91-20. Control points are marked by asterisks (*) along the age scale. Where filled dots (sample positions) cluster, the accumulation rate was highest (e.g., deltaic strata at the base of Core M98-9). Where filled dots are missing for some variables, the species required for determinations were absent (e.g., *T. quinqueloba* before ~10 ky BP for Core M98-12). The gray band from ~10–6.5 ky BP coincides with sapropel deposition and significant changes in several proxy variables.

(2002a) and Hiscott *et al.* (2002).

Today, the semi-marine-water surface layer that is responsible for bottom-water dysoxyia originates entirely from Black Sea outflow. Local riverine input into the Marmara Sea is ~2% of the Black Sea outflow, and it is entirely inadequate to explain the profound water-column stratification that has prevailed in the Marmara Sea since ~10 ky BP. There was no interruption in the degree of stratification at ~8.4 ky BP, as would surely have accompanied a catastrophic flood. Similarly, the failure of open-marine foraminifera to colonize the Marmara Sea at ~8.4 ky BP is inconsistent with a major flood (Aksu *et al.* 2002c; Kaminski *et al.* 2002).

2.3 Evidence Against a Dry Early Holocene Climate

In their revised catastrophic flood model, Ryan *et al.* (2003) proposed that from ~10–8.4 ky BP, water level in the isolated Black Sea dropped by ~70 m from ~ –25 m to ~ –95 m (Figure 3A). They presumed that the drawdown of the sea surface occurred in a manner "akin to the Caspian Sea," where evaporation exceeded all inputs during warm periods of the Quaternary (Chepalyga 1984), although Mamedov (1997) reported that sea level in the Caspian was reduced by only about 15 m during the period of ~10–7.8 ky BP. Ryan and Pitman (1998) initially cited unpublished palynological data from cores collected along the Bulgarian coast as evidence for the persistence of cold**,** dry conditions similar to those of the Younger Dryas until 7.5 ky BP. They later presented a summary of Atanassova's pollen stratigraphy (1995) to bolster their argument for an early Holocene interval of cold, dry climate in the western Black Sea, characterized by herb-grass vegetation (Figure 11 of Ryan *et al.* 2003).

In contrast, Mudie *et al.* (2002b, their Table 2) summarized palynological data from lakes in a wide area west and south of the Black Sea and showed that oak-pistacio (*Quercus-Pistacia*) forests were present over most of the region by 10 ky BP, although local desert-steppe vegetation persisted until ~7 ky BP in the southeast, from Lake Van to the Caspian Sea. These forests indicate the early establishment of mesic climatic conditions characterized by >600 mm/year of precipitation (P) in excess of evapotranspiration (E), as is presently found in most of central and western Europe. Pollen diagrams for lakes in Bulgaria (Bozilova and Beug 1994) and for a long core from the Bay of Sozopol (Filipova-Marinova and Bozilova 2002) also show the presence of mesic deciduous oak forest before 8.4 ky BP, which accords with the establishment of a mixed coniferous-deciduous forest in Romania by about 9.5 ky BP (10,750 calBP; Björkman *et al.* 2003). Velichko *et al.* (1997) also report that broadleafed oak, lime, and elm trees were established in parts of the central Russian plains by 9.6 ky BP, following an interval between 9.9 and 9.5 ky BP during which winters were about 2° C colder.

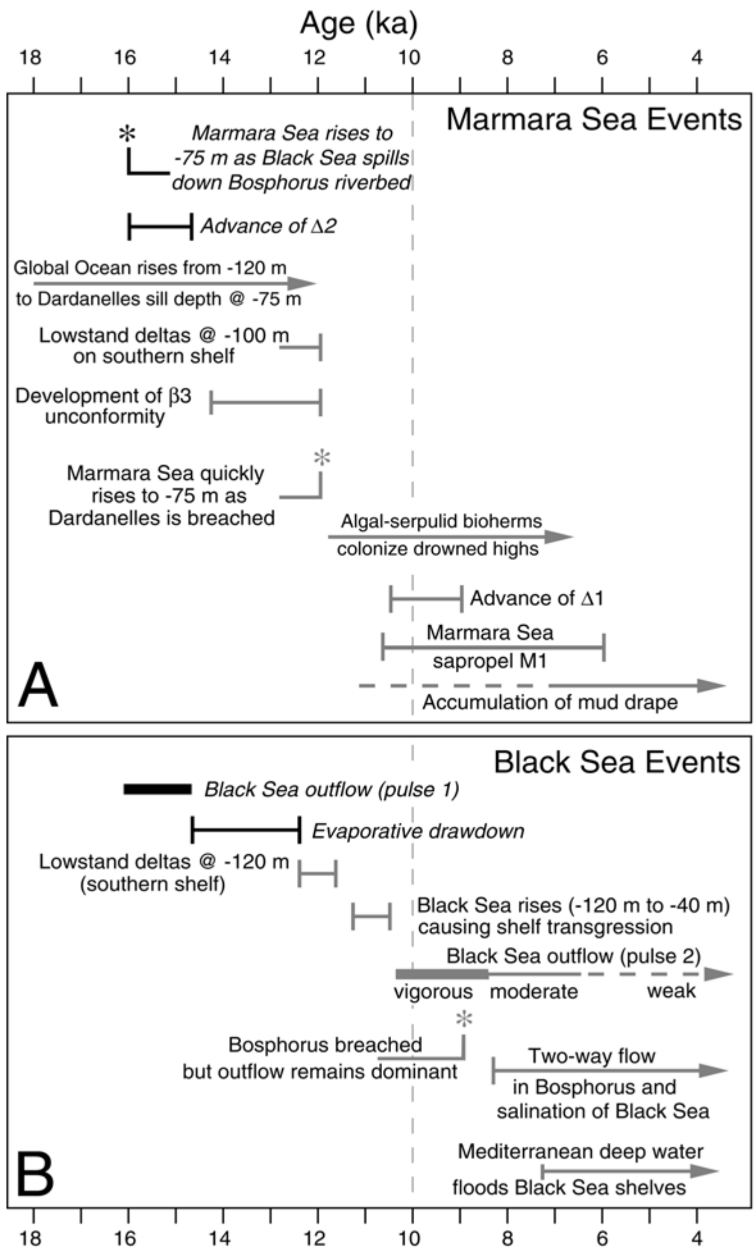

Figure 11. Summary of the paleoceanographic history of the Marmara Sea (A) and Black Sea (B). Timing and duration of some of the events colored gray are slightly modified from Hiscott *et al.* (2002, their figure 15) in order to conform with the *Outflow Hypothesis II* (Figure 4). Events in black with italics labels are additions to our earlier work. Asterisks (*) indicate events which occurred very rapidly, in tens of years to ~100 years. The Dardanelles sill depth is specified as –75 m rather than the modern value of –70 m to account for ongoing uplift of the area around the strait (Yaltırak *et al.* 2002).

Mudie *et al.* (2002b) studied marine pollen data from a deep-water core in the south-central Black Sea and from three cores in the Marmara Sea. They found an interval of ameliorating climatic conditions from 10–9 ky BP when a broadleafed oak forest tolerant of colder (–2° C) winters but requiring >600 mm per year excess moisture replaced a pre-existing, drought tolerant steppe-forest and herb-grass-shrub vegetation. They also documented increased warmth and humidity supporting a mesic, temperate, deciduous, oak-pistacio forest from 9 ky BP to the present, which was interrupted from ~8–3.2 ky BP by a climatic optimum with warmer and wetter conditions than today. Their reconstruction of the Black Sea area is consistent with precipitation and evaporation levels that Dolukhanov (1997) outlines for eastern Europe since ~11 ky BP, and it also matches the quantitative temperature and precipitation reconstructions of Velichko *et al.* (1997) for the central Russian plains from 50°–60° N.

Since the early Holocene, the Pontic Basin has apparently supported a range of vegetation types broadly similar to those found today (see Mudie *et al.* 2002b). The modern vegetation zones include the western subregion of Mediterranean woodland with a Csb climate (mesothermal, summer dry), the southern subregion of mesic Euxinian-type forest with a Cfa climate (humid subtropical conditions with year-round precipitation), and aridic steppe or savannah grassland subregions in the north and east with a semi-arid BSk climate (see Finch *et al.* 1957, for details). The eastern side of the Caspian Sea is a mid-latitude desert with a BSw climate. The Cs and Ca climate zones have an excess of precipitation over potential evaporation; the dry climate BS zones have a deficiency of rainfall (Finch *et al.* 1957).

Ryan *et al.* (2003) advocated using the water-level excursions of the Caspian Sea as a guide for interpreting the Late Quaternary changes in climate and sea level in the Black Sea basin. At the simplest level, the extreme aridity east of the Caspian Sea makes it a questionable model for their proposed 10–8.4 ky BP drawdown in the Black Sea. Nevertheless, the underlying principles that control the behavior of the Caspian Sea (Chepalyga 1984) can easily be applied to the Black Sea basin, even if the boundary conditions differ. The Black Sea basin presently has a large excess of river inflow, R, over net evaporation, P – E. (P and E are annual precipitation and evaporation over the surface of the water body, respectively. If P – E = a positive quantity, the difference is called net precipitation; if negative, we use net evaporation). This large fresh-water supply from the Danube, Dniester, Dnieper, Southern Bug, and Don Rivers drives a net outflow of ~300 km^3/year through the Bosphorus Strait (Özsoy *et al.* 1995; Polat and Tuğrul 1996). To evaluate the climatic implications of the proposal of Ryan *et al.* (2003) for a rapid early Holocene sea-level fall in the Black Sea, let us assume a closure of the Bosphorus at 10 ky BP and try to account for a subsequent drop in water level of ~70 m in the brief cold, dry interval from 10–9 ky BP. After 9 ky BP, our data indicate a climate much like today, and we see no reason to expect a negative water balance in the Black Sea at that time. If the Black Sea was indeed low at ~9 ky BP, then we would predict no further net evaporation; instead, water level might have been static or slowly rising.

We used the Black Sea bathymetric map to calculate that a water loss of ~25,600 km^3 is required to depress the sea surface from –25 m to –95 m. The average annual loss rate over a 1000-year interval would therefore have been ~25 km^3 if the Ryan *et al.* (2003) proposal of evaporative drawdown is valid. In a closed basin, a water-volume loss must be explained by an annual excess of output (evaporation, E) over inputs (precipitation, P, and river inflow, R):

$$\Delta V = R + P - E$$

If we set ΔV to -25 km^3/year, and assume that river input at ~10 ky BP was two-thirds of the modern ~350 km^3/year (to account for drier conditions), then a P – E value of ~ –258 km^3/year will satisfy the mass-balance equation for ΔV.

P – E for the modern Black Sea has been estimated by many researchers. The average of nine estimates published between 1970 and 1992 is –117 km^3/year (Jaoshvili 2002, his Table 5.1 and references therein). A parameter that can be compared among the modern Black Sea, the ~10 ky BP Black Sea, and other Eurasian marginal seas and lakes, is the *net potential evaporation* (NPE), which is obtained by normalizing P – E to the surface area of the water body: NPE = (P – E)/area. For the modern Black Sea (area = 441,000 km^2), NPE = –0.27 m/year. For the ~10–8.4 ky BP Black Sea described above (average area during fall from –25 m to –90 m elevation ~368,000 km^2), NPE = –0.70 m/year. For comparison, Table 3 lists NPE values for selected marginal seas and enclosed water bodies of central Eurasia. The Red Sea and Persian Gulf are at the most evaporative end of the spectrum, with NPE of ~ –2 m/year.

For the Black Sea to have dropped to a lowstand of ~ –95 m in 1000 years with ~66% of its modern fluvial input, the evaporative conditions over the sea surface had to be intermediate between those of the modern Caspian and Aegean seas (Table 3), leading to a net potential evaporation more than double the modern value. The Caspian region has a much drier, continental climate than the Black Sea, and the Aegean region is much warmer year-round, explaining the significantly higher rates of evaporation in both these areas relative to the Black Sea basin. Other researchers (e.g., Chepalyga 1984) assume changes in P – E of perhaps 20–30% during transitions from forest to steppe conditions, much less than the factor of two required to explain a 10–9 ky BP rapid evaporative lowering of the Black Sea. As a result, we conclude that the evaporative drawdown proposed by Ryan *et al.* (2003) cannot be explained by reasonable boundary conditions. The only alternative scenario that might permit such a rapid drawdown without recourse to unrealistic aridity would be a reduction in river flow to far less than 66% of modern discharges. However, neither the pollen data nor lake-status studies for the early Holocene (Harrison *et al.* 1996) support such a profound reduction in river flow throughout central and eastern Europe at that time.

Table 3. Estimates of net potential evaporation (NPE) for marginal and inland seas

Name	Age	P – E (km^3/yr)	Area (km^2)	NPE (m/year)	Source
Black Sea	modern	–117	441,000	–0.27	9 estimates (Jaoshvili 2002)
Aegean Sea	modern	–104	174,000	–0.60	Josey (2003)
Black Sea	~10 ky BP	–258	368,000	–0.70	This paper, to evaluate proposed drawdown of Ryan *et al.* (2003)
Caspian Sea	1900-1985	–296	371,000	–0.80	Golubev (1998), Kosarev and Makarova (1988)
Aral Sea	1926-1960	–56	65,780	–0.85	Micklin (1988)
Persian Gulf	modern	–482	241,000	~ –2.00	Johns *et al.* (2003)
Red Sea	modern	–924	440,000	–2.10	Sofianos *et al.* (2002)

As a final cautionary note regarding paleoclimate models, it is now evident that the interpretation of early Holocene herb-grassland vegetation requires careful re-evaluation in light of quantitative studies of the Younger Dryas *Artemisia*:chenopod pollen signal, formerly interpreted as indicating cold, dry conditions (Prentice *et al.* 1992). The ratio of these herbs was formerly used as a drought index, but it is now clear that the same pollen ratios can result from an increase (not decrease) in surface winter runoff. This finding has especially important implications when trying to track the switch from steppe to steppe-forest vegetation based on pollen signals.

3. NON-CATASTROPHIC EXPLANATION OF THE 8.4 KY BP AND 7.15 KY BP PALEOCEANOGRAPHIC SHIFTS

There is encouraging convergence between the Flood Hypothesis (Ryan *et al.* 1997; Ryan and Pitman, 1998; Ryan *et al.* 2003) and our Outflow Hypothesis II (Figure 4). The suggestion of a significant time lag between the first marine connection at the Bosphorus and colonization of the Black Sea shelves by euryhaline fauna (Aksu *et al.* 1999 and 2002a, based on arguments in Lane-Serff *et al.* 1997) was incorporated by Ryan *et al.* (2003) into their modified flood hypothesis (Figure 3A), so it is no longer an issue for debate. We have incorporated the two periods of Black Sea spillover identified by Ryan *et al.* (2003) into our modified outflow hypothesis (Figure 4). Where we continue to disagree is on the post-10 ky BP history of the Marmara Sea Gateway. Ryan *et al.* (2003) and Major (2002) base their requirement for a catastrophic inundation of the Black Sea at 8.4 ky BP entirely on a dramatic shift in the Sr-isotopic composition of mollusc shells to open-marine values. We see no need for such an interpretation because the isotopic shift can also be the result of a time lag in the connection process.

Lane-Serff *et al.* (1997) described the way in which two-way flow becomes established in narrow and shallow straits, using the Bosphorus channel as their example. From ~10–9 ky BP, the Black Sea was significantly higher than the Marmara Sea and the Bosphorus acted like a river (Figure 4), so there was no possibility of open-ocean water reaching the Black Sea to change its Sr-isotopic signature. Once the Marmara Sea reached the Bosphorus sill depth at ~9 ky BP, the depth of water in the strait would have been too shallow to allow sustained two-way flow. The presence of small quantities of brackish-water dinoflagellate cysts in the southern Black Sea by ~9 ky BP (Mudie *et al.* 2004) may indicate that some Mediterranean water periodically succeeded in reaching the Black Sea by that time, transporting dinoflagellate cysts northward. However, this volume was so small that the chemical composition of Black Sea shelf waters did not change (Major 2002).

The first clear evidence of marine dinoflagellate cysts (*Spiniferites mirabilis*) in the Black Sea occurs at ~8.5 ky BP (Mudie *et al.* 2004). Kaminski *et al.* (2002) independently concluded from benthic foraminiferal data that effective and sustained two-way flow was not established until ~8.5 ky BP. This dating coincides almost exactly with the dramatic shift in the Sr-isotopic composition of Black Sea molluscs that Major (2002) and Ryan *et al.* (2003) ascribe to a catastrophic inundation of the Black Sea. Instead, we propose that the 8.4 ky BP event simply marks the onset of sustained two-way flow, permitting sufficient Mediterranean water into the Black Sea basin to induce a rapid change in the Sr-isotopic composition of its waters. Today, the Black Sea has a sharp chemocline that separates more saline (~22‰) and anoxic basinal waters from less saline (~18‰) and oxygenated surface waters. A comparable chemocline likely characterized the Black Sea as it began to receive saline inflow from the Marmara Sea. Disruption of this early stratification, perhaps by a major storm or set of storms, might have been enough to trigger an homogenization of Sr-isotopic values between the deep and surface water masses at ~8.4 ky

BP. There is, we believe, no need to advocate a catastrophic flood to affect such a change.

4. CONCLUSIONS

The Outflow Hypothesis II (Figure 4) represents a rethinking and consolidation of our interpretation of the evolution of the Marmara Sea Gateway since ~16 ky BP, incorporating two pulses of Black Sea outflow suggested by Ryan *et al.* (2003) and Major (2002) for the period 16–10 ky BP. For younger times, we reject the notion that the level of the Black Sea again fell to ~ –90 m, followed by a catastrophic incursion of marine water at ~8.4 ky BP. Instead, our previously published multiproxy data from cores in the Marmara Sea, and interpretation of seismic facies in high-resolution boomer profiles, point conclusively to unabated Black Sea outflow from ~10.5 ky BP to the present. This outflow formed a cascading river from ~10.5–9 ky BP until the level of the world ocean (and Marmara Sea) reached the elevation of the sill in the Bosphorus Strait. From 9–8.4 ky BP, the outflow was sufficiently strong to prevent any measurable amount of saline water from entering the Black Sea, and so during this time, there was only one-way (outward) flow through the strait. Beginning at ~8.5 ky BP, two-way flow was established leading quickly to (1) a sharp shift in the Sr-isotopic composition of the Black Sea (Major, 2002), and (2) arrival of the first Mediterranean immigrants (dinoflagellates and benthic foraminifera). Considerably later at ~7.15 ky BP, the salinity of shelf waters in the Black Sea became high enough to permit euryhaline molluscs to thrive.

Our perception of the history of the gateway is summarized in Figure 11, modified from an earlier version published by Hiscott *et al.* (2002, their Figure 15). Except for minor shifts in the timing of events needed to conform more closely to the Outflow Hypothesis II, the only substantive change is the incorporation of a ~16–14.7 ky BP pulse of outflow which nicely accounts for the development of the older Δ2 south of the Bosphorus Strait. Previously, we had interpreted Δ2 to be much older (marine isotopic stage 3), but new radiocarbon dates show that the β3 unconformity represents a very short hiatus. When β3 was flooded by the rising Mediterranean via the Dardanelles Strait at ~12 ky BP, marine conditions were established and algal-serpulid bioherms developed on the unconformity.

We have intimately linked the development of the younger Δ1 with the onset of water-column stratification and sapropel deposition in the Marmara and Aegean Seas (Aksu *et al.* 2002a; Hiscott *et al.* 2002). When Δ2 was actively prograding during pulse 1 (Figures 4 and 11), global sea level was still depressed and the Marmara Sea was a brackish to semi-fresh lake. As a result, the water column in the Marmara Sea remained unstratified, and no sapropel developed there. However, we predict that the contemporary Aegean Sea should have become stratified as a consequence of the low-salinity discharge through the gateway from ~16–14.7 ky BP. We intend to look for organic-rich deposits of that age in the Aegean to support the proposed early history of the gateway.

The evidence for persistent Holocene Black Sea outflow is, in our view, unambiguous. The main arguments are summarized below.

(1) Calculated sea-surface salinity in the Marmara Sea has been low since ~11 ky BP, and requires a large fresh- to brackish-water input like what is provided by the Black Sea today. Local rivers cannot account for the calculated dilution of surface waters.

(2) Poor oxygenation of bottom waters in the Marmara Sea, based on the characteristics of the benthic foraminiferal communities, points to a strong and persistent Holocene pycnocline. Such intense water-column stratification can result only from the presence of a low-salinity surface layer. As before, Black Sea outflow is implicated.

(3) A climbing mid-shelf delta is present on the Marmara Sea shelf directly south of the Bosphorus exit. Local rivers cannot possibly account for its development because of their small sediment discharges. Deltaic growth is securely dated in cores from ~10.5–9 ky BP, precisely when rising global sea level was ~5 m shallower than the elevation of the topset–foreset transition of the delta.

(4) The brackish-water outflow through the Bosphorus Strait was sufficiently strong (and initially sufficiently thin) to prevent the establishment of two-way flow in the strait until ~8.5 ky BP (cf. Lane-Serff *et al.* 1997), so that salinization of the Black Sea was delayed and Mediterranean fauna and flora were unable to migrate northward.

(5) Even after the onset of two-way flow, the quantity of saline water which was advected northward across the Bosphorus Strait did not have an immediate impact on salinity of the shelf water masses. Hence, euryhaline molluscs did not successfully colonize the Black Sea shelves until ~7.15 ky BP, well after the initial connection.

(6) The widespread and homogeneous mud drape which blankets lowstand deposits in the Marmara Sea began to accumulate at ~11.5 ky BP and is uninterrupted by facies or faunal changes that would surely have accompanied a northward-flowing marine flood. Because the volume of the Marmara Sea is tiny compared with the volume of water needed to raise the level of the Black Sea from ~ –90 m to ~ –25 m (Figure 3A), a flood of the magnitude proposed by Ryan *et al.* (2003) should have left an indelible record in the Holocene succession on the shelves of the Marmara Sea. No such record exists.

More work is needed to understand fully the evolution of the Marmara Sea Gateway and Black Sea. We believe that the Outflow Hypothesis II (Figure 4) is a major step toward resolving the incompatible models of Aksu *et al.* (2002a) and Ryan *et al.* (2003). It is encouraging that new research appears to have reduced the number of disputed events. The time interval 10–7 ky BP now holds the final challenge for advocates and detractors of a catastrophic flood. Concerted study of cores spanning this time interval will eventually unlock the final mysteries of the Holocene paleoceanography of this exciting area.

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