Stable isotopic evidence from Holocene Sea of Marmara sediments for two-way watermass interchange between the Black Sea and the Mediterranean Sea

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Stable isotopic evidence from Holocene Sea of Marmara sediments for two-way watermass interchange between the Black Sea and the Mediterranean Sea

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The Sea of Marmara is a gateway between the Black Sea and the Mediterranean. It preserves within its sediments a history of palaeoceanographic interactions between the two seas. This record can be elucidated by investigations of changes in sediments, foraminiferal assemblages, and oxygen and carbon isotopic composition of foraminiferal tests. During the low stand of sea level of the last ice age, no marine connection existed between the Black Sea and the Mediterranean. This connection was reestablished during the sea-level rise of the last deglaciation. Although many investigations have been conducted on present-day oceanographic conditions of the Sea of Marmara, only one study[1] has been attempted to document a history of interaction between the Aegean and Black seas using the latest Quaternary sediment record. These workers used changes in sediment facies in cores from the deep eastern basin of the Sea of Marmara to reconstruct a history of oceanographic interchange between the Black Sea and the Mediterranean from the end of the Pleistocene to the present day. Based largely on the appearance of organic-rich anoxic sediments, they proposed that a two-way interchange was established across the Bosporus between 9.5 and 7.0 kyr ago, with changes since occurring in the relative strength of surface and bottom currents. Lane-Serff *et al.*[2] developed a model that predicts changing watermass exchange across the Bosporus sill related to the glacioeustatically-caused postglacial connection of the Black Sea to the Mediterranean. Our investigation is the first to examine the oxygen and carbon isotopic composition of planktonic and benthic foraminifera in a Sea of Marmara core to assist with understanding of the palaeoceanographic development of this gateway.

We have also examined benthic foraminiferal assemblages, since they assist with our interpretations based on the stable isotopic data. One previous study of late Holocene, deep-sea benthic foraminiferal assemblages has been conducted on the Sea of Marmara,[3] based on two short cores (0.9 m) taken from 1200 m water depth, which focussed on the use of foraminifera as indicators of changing depositional conditions in the basin.

Oceanographic setting

The Sea of Marmara, with a surface area of 11 500 km^2 and a maximum depth of 1238 m, is an almost totally enclosed depression lying between the Black Sea and the Aegean. These three seas are connected by two shallow straits. The Bosporus, which links the Black Sea with the Sea of Marmara, has two sills, the shallowest of which is at 35 m. The Dardanelles, which connects the Aegean with the Sea of Marmara, is slightly deeper (50–60 m; Fig. 1). The position of the Sea of Marmara establishes its importance as an oceanographic gateway between the neighbouring seas. The present vertical mass structure is dominated by two opposing currents operating at different water depths. Surface outflow from the Black Sea towards the Mediterranean takes place via the Bosporus. This surface current is underlain by a deeper underflow from the Aegean to the Black Sea.[4] The presence of these two currents in the Bosporus Narrows, an upper outflow from the Black Sea and a deeper counterflow from the Mediterranean, has long been known by maritime people of the region. The presence of a deep countercurrent in the Bosporus was proven by scientific experiment in 1680 by Luigi Ferdinando Marsigli (as documented in Ascherson[5]) and named Corrente Sottano. He also demonstrated that undercurrent waters are denser and more saline than surface waters in the Black Sea. This stratified flow is maintained with a persistent interface lying at water depths from 20–30 m. Salinities of the upper water are relatively low and exhibit a strong gradient, ranging from 26 ‰ at the Bosporus–Black Sea junction to 29.5 ‰ in the Dardanelles. Salinities of the deeper water are distinctly higher and more uniform, ranging from 39 ‰ at the Aegean–Dardanelles junction to 35 ‰ at the Bosporus–Black Sea junction,[6,7] Aegean water essentially exhibits the characteristics of the open-ocean high-salinity, warm water of the eastern Mediterranean Sea except that it is even more depleted in nutrients. Aegean water has experienced appreciable evaporation during flow through the Mediterranean from the Atlantic. The resulting high salinity and density of this water leads to enriched $\delta^{18}O$ values (+1.7 ‰). Nutrients are stripped from the surface water during transit through the Mediterranean and the especially low nutrient concentration of Aegean water imparts enriched $\delta^{13}C$ values (+1.2 to +1.5 ‰) to the total dissolved inorganic carbon, compared with Atlantic waters for the same depth and latitude.[8] By contrast, the Black Sea is brackish owing to extensive continental freshwater runoff. Salinities range from 14 ‰ (northwestern corner) to 19 ‰ (Bulgarian and Caucasian continental shelves) to 26 ‰ (near the Bosporus). As a result, $\delta^{18}O$ values are depleted (–2.5 ‰).[8] The Black Sea is also nutrient rich with the nutrients largely derived from the input of terrestrial organic carbon, which has depleted $\delta^{13}C$ values. This is reflected by the depleted $\delta^{13}C$ values of the total inorganic carbon of its water[9]. Despite nutrient enrichment of Black Sea water, planktonic foraminifera are absent and benthic foraminiferal assemblages are represented by low-diversity assemblages because of the low salinities.[10] Thus the waters flowing through the Sea of Marmara in opposite directions, from the Black Sea and the Mediterranean, have different salinities and nutrient concentrations. The markedly divergent isotopic compositions of the opposing water sources should be reflected in the $\delta^{18}O$ and $\delta^{13}C$ signatures of the calcareous foraminifera living in these waters.

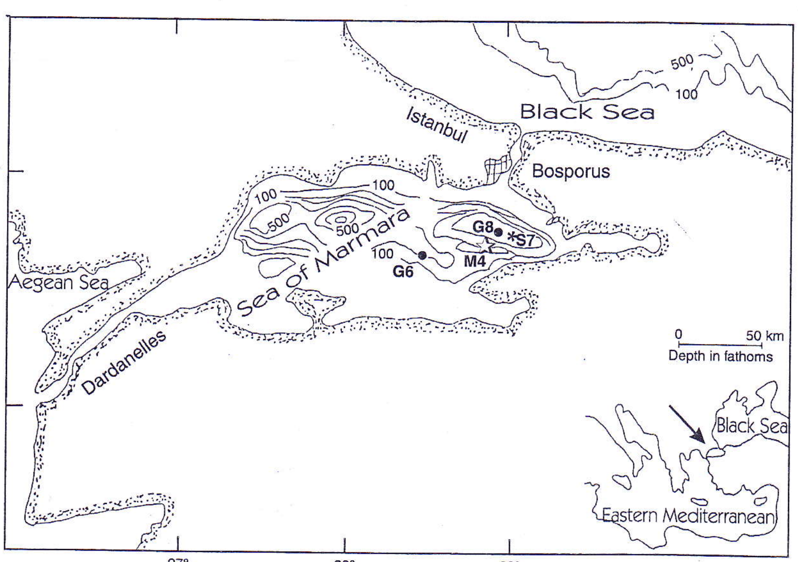

Fig. 1. Location map of the Sea of Marmara, showing the position of sediment cores mentioned in the text. Cores G6 and G8 are shown by solid circles, core M4 by a star, and core S7 of the present study by an asterisk.

Methods

Gravity core S7 (1.6 m in length) used in this investigation was collected from the eastern deep basin of the Sea of Marmara (40°01′08″, 29°09′31″) during a cruise of the R/V *Knorr* (7 May 1988) from a depth of 1225 m. The core was recovered in close proximity to a shorter core (G8-RV Pillsbury; 1.2 m length; with an apparent basal age of 5.4 kyr) studied by Stanley and Blanpied[1] (Fig. 1). Core S7 was subdivided into 10-cm-long sections and stored at Dokuz Eylul University, Turkey. The uppermost 2 cm was sampled from each 10-cm interval for foraminiferal, isotopic and sedimentological analyses. Foraminiferal assemblages were documented using the taxonomy employed by Yanko and Troitskaja[11] and Yanko *et al.*[12] Oxygen and carbon isotopic analyses were conducted on the benthic foraminiferal species *Brizalina spathulata* and the planktonic foraminiferal species *Globigerina quinqueloba*. Approximately 15 benthic and 30 planktonic foraminiferal specimens were selected from the >150 micron fraction for each stable isotopic analysis. Only specimens lacking authigenic pyrite were analysed. Specimens selected for isotopic analysis were cleaned ultrasonically in reagent-grade methanol, dried and roasted under vacuum at 375 °C for 1 h to remove organic contaminants. The samples were reacted in orthophosphoric acid at 90 °C with an on-line automated carbonate device. The evolved CO_2 was analysed using a Finnigan/MAT 251 light-stable isotope mass spectrometer at the Department of Geological Sciences, University of California, Santa Barbara. Instrumental precision is 0.1 per mil or better for both $\delta^{18}O$ and $\delta^{13}C$. All isotopic

Table 1. $\delta^{18}O$ and $\delta^{13}C$ values in tests of the planktonic foraminifer *Globigerina quinqueloba* and the benthic foraminifer *Brizalina spathulata* in core S7, Sea of Marmara.

Sample number	Core depth (m)	$\delta^{18}O$ (PDB)		$\delta^{13}C$ (PDB)	
		Planktonic foraminifer *G. quinqueloba*	Benthic foraminifer *B. spathulata*	Planktonic foraminifer *G. quinqueloba*	Benthic foraminifer *B. spathulata*
1	0.0–0.02	Insufficient specimens			
2	0.1–0.12	0.46	1.36	−2.48	−0.89
3	0.2–0.22	0.40	1.42	−2.48	−0.89
4	0.3–0.32	0.54	1.40	−2.46	−0.88
5	0.4–0.42	0.37	1.71	−2.39	−0.48
6	0.5–0.52	0.26	1.56	−2.49	−0.91
7	0.6–0.62	0.61	1.57	−2.18	−0.95
8	0.7–0.72	0.52	1.38	−2.51	−0.89
9	0.8–0.82	0.38	1.29	−2.30	−1.29
10	0.9–0.92	Insufficient specimens			
11	1.0–1.02	—	1.50	—	−1.00
12	1.1–1.12	—	1.54	—	−0.87
13	1.2–1.22	0.17	1.30	−2.65	−1.03
14	1.3–1.32	0.61	1.32	−2.65	−1.35
15	1.4–1.42	0.24	1.28	−2.47	−1.16
16	1.5–1.52	0.39	1.41	−2.40	−1.13
17	1.6–1.62	0.38	1.48	−2.57	−1.17

data are expressed using standard delta notation in per mil relative to the Peedee Belemnite (PDB) carbonate standard. It is unknown whether the taxa used for the isotopic analyses produce calcite in isotopic disequilibrium, and hence no corrections were made. The base of the core (bulk sediment sample; 1.58–1.60 m) was radiocarbon dated at the CSIR, Pretoria, South Africa. Since the analysis was conducted on bulk sediment that may contain reworked older carbon, the reported age may be considered a maximum. Therefore, two AMS radiocarbon ages were run (at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, California) on hand-picked cleaned benthic foraminifera from core depths of 1.0 m and 1.1 m.

Results

Core S7 is predominantly a uniform grey mud, containing approximately 5 % sand in most samples. Two samples (5 and 11) contain almost 15 % sand. No graded sand layers or evidence of breaks in deposition were detected. The base of the core (1.58–1.60 m) has an uncorrected ^{14}C age of 8440 ± 300 years (Pta-6556; $\delta^{13}C$ value of −2.6 ‰ PDB) for the bulk sediment. This yields an average rate of sedimentation of 18 cm/1000 yr, which is similar to that of nearby Core G8 (20 cm/1000 yr) taken from a similar water depth.[1] However, the AMS dating yielded a considerably higher rate of sedimentation, confirming the suspicion that the carbon in the sedimentary matrix contained an older allogenic carbon component. The sample from the 1 m depth (CAMS 48877) yielded a radiocarbon age of 1960 ± 60 years. The sample from 1.1 m in the core (CAMS 46039) yielded an age of 1800 ± 70 years. At the 2-sigma level of statistical confidence the ages are interchangeable, giving an average rate of sedimentation of 56 cm/1000 yr. Thus the age of the base of core S7 is determined instead to be approximately 3 kyr. It is suspected that the radiocarbon ages previously reported from nearby deep cores,[1] determined using bulk sediment, are much younger by an equally large factor.

Benthic foraminiferal assemblages are dominated (average 70 %) by infaunal species, indicative of suboxic conditions. Pervasive pyritization of benthic foraminifera and stunting of benthic foraminiferal tests are due to the low dissolved oxygen concentrations in the bottom water and sediments. Only calcareous benthic forms are represented in the assemblages. A total of 50 benthic foraminiferal species were identified. However, only three species dominate: *Brizalina spathulata, Bulimina striata* and *Cassidulina minuta.* By far the most dominant form is *B. spathulata,* a species considered to be well adapted to the low oxygen concentrations in the bottom water of the Sea of Marmara. A detailed description of the changes in the benthic foraminiferal assemblages will be presented elsewhere. There is only a single species represented in the planktonic foraminiferal assemblage, *Globigerina quinqueloba,* present in the core, because of the isolation of the Sea of Marmara and the relatively low salinity of the surface water.

Oxygen and carbon isotopic data are presented in Table 1. Oxygen isotopic values in both planktonic and benthic foraminifera show relatively little variation (<0.5 ‰) throughout the sequence. Carbon isotopic variations in planktonic forms are also relatively small (<0.5 ‰) but are larger in benthic forms (<0.9 ‰).

Discussion

Sea level during the last glacial maximum (121 m below present)[13] was well below present-day sill depths of both the Bosporus and Dardanelles. Both straits would have been represented by exposed valleys[1] and the Sea of Marmara by a basin isolated from the ocean. The Black Sea was then a large lake disconnected from marine influences of the Mediterranean.[2] The sea-level rise, following the last deglaciation, led to reconnection of the Black Sea with the ocean via the Sea of Marmara. At that time, marine faunas, including benthic foraminifera, recolonized the Sea of Marmara and the Black Sea.[10,14–16]

During the Holocene, the hydrographic regime of the Sea of Marmara was controlled by the interactions of the two adjacent water bodies: Black Sea low salinity outflow enriched with nutrients, and the Mediterranean underflow of near-normal ocean salinities and lower nutrients. These two water masses are separated by a sharp halocline. Strong vertical density stratification in the Sea of Marmara has reduced the oxygen concentrations of subhalocline waters.[4] Organic carbon composition of sediments is high (1.0–1.8 %)[3] and modern benthic foraminiferal assemblages are dominated by dysoxic taxa. The continuous presence of high organic carbon content of sediments and dysoxic foraminiferal assemblages throughout core S7, and lack of bioturbation suggests that dysoxic conditions were maintained in the Sea of Marmara at least since 3 kyr BP. This is considered to have resulted from interchange of waters between the Mediterranean and the Black Sea causing strong vertical stratification in the Sea of Marmara. However, oxygen concentrations were apparently never low enough to form sapropels. Many benthic foraminiferal species found in core S7 presently live in the Mediterranean within a salinity range of between 36 ‰ and 39 ‰.[12,17–19] This suggests that there were also no large changes in bottom water salinity during the last 3 kyr, a conclusion supported by the $\delta^{18}O$ values of the benthic foraminifera.

The oxygen and carbon isotopic data clearly indicate that a strong vertical water mass structure of the Sea of Marmara was maintained consistently during the last 3 kyr. The relatively depleted $\delta^{18}O$ values of the planktonic foraminifera reflect persistent outflow of relatively low-salinity waters from the Black Sea during this time. By contrast, the significantly enriched $\delta^{18}O$ values of the benthic foraminifera reflect the inflow of colder, more saline deeper water from the Mediterranean. This conclusion is supported by the foraminiferal $\delta^{13}C$ analyses. The planktonic foraminifera record significantly depleted $\delta^{13}C$ values (–2.18 to –2.65 ‰; Table 1) throughout the core, relative to the benthic foraminifera (–0.48 to –1.35 ‰). Surface outflow of nutrient-rich Black Sea water to the Sea of Marmara, marked by very depleted $\delta^{13}C$ values, took place throughout the last 3 kyr. By contrast, the less depleted $\delta^{13}C$ values exhibited by the benthic foraminifera reflect the influence of deeper water from the Mediterranean. The vertical carbon isotopic gradient in the Sea of Marmara during the last 3 kyr is the reverse of that of the open ocean. Open-ocean surface water is nutrient-depleted compared with deeper water; hence, it is marked by relatively enriched $\delta^{13}C$ values. Late Holocene planktonic and benthic foraminifera recorded in core S7 tapped two different reservoirs of dissolved inorganic carbon associated with the two-layered vertical water mass structure. The present study shows the great potential for studying the Holocene palaeoceanographic history of the Sea of Marmara using stable isotopic analysis of foraminiferal tests. It will take much longer sediment cores to study the history of the two-way flow since the early Holocene.

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