Periodic Freshwater Flooding and Stagnation of the Eastern Mediterranean Sea During the Late Quaternary

Abstract. *Major negative oxygen isotopic anomalies in planktonic foraminifera are associated with deep-sea anoxic mud layers (sapropels) deposited 9000 and 80,000 years ago in the eastern Mediterranean. The isotopic depletion in surface-dwelling foraminifera is significantly greater than in mesopelagic foraminifera. This difference in isotopic response suggests that surface-water salinities were drastically reduced during times of sapropel formation, possibly as the result of meltwater runoff from the Fennoscandian ice sheet into the eastern Mediterranean by way of the Black and Aegean seas.*

Cenozoic circulation and sedimentation processes in the Mediterranean Sea have been strongly influenced by a complex interplay of tectonic, oceanographic, and continental paleoclimatic events (*1*). The discovery of widespread Quaternary and late Tertiary sediments formed under anaerobic conditions in the eastern basin has prompted several workers to speculate on the periodic occurrence of "salinity events" in the Mediterranean (*2–4*). These anaerobic sediments (sapropels) are black, organic-rich mud layers, which are often marked by an abnormal planktonic foraminiferal fauna indicative of lowered surface-water salinities (*5–7*) and the complete absence of benthic faunas and bioturbation (*4, 8, 9*). Sapropel layers are prominent in each of the major sedimentary provinces of the eastern Mediterranean (*4, 10, 11*), although their areal distribution may not be continuous over the entire eastern basin (*9, 12*).

Several theories have been proposed to account for the periodic deposition of sapropelic muds in the eastern basin. Most investigators have invoked the production of a widespread and persistent low-salinity surface layer which would inhibit normal thermohaline vertical circulation, prevent the oxygenation of bottom water, and produce anoxic conditions in the deep basins (*2–4*). Other workers have related sapropel formation to density stratification produced by a warming of surface waters (*10*) or an association between freshwater input and current reversals in the Straits of Gibraltar (*13*). Olausson's model (*3*), presently the most widely accepted, relates sapropel deposition with deglaciation, enhanced meltwater runoff, and high sea stands. According to the theory, freshwater from the Black Sea flowed into the Aegean Sea and eastern basin as soon as sea level rose above the sill depth at the Bosphorus Straits (40 m). This freshwater outflow sufficiently reduced surface salinities and inhibited vertical circulation in much of the eastern basin to produce stagnation on the seafloor.

It is well known that the $^{18}O/^{16}O$ ratios of the calcite tests of planktonic foraminifera are useful indices of their average depth of growth in the water column (*14*). In this study, we have attempted to utilize the average depth habitat preferences and the resulting different $^{18}O/^{16}O$ ratios of several species of planktonic foraminifera to investigate the possible existence of a low-salinity surface layer during sapropel deposition. Oxygen isotopic determinations were made on five species of planktonic foraminifera from equivalent time horizons in two cores (*15, 16*). Samples were taken at 2000-year intervals before, directly within, and immediately after two different sapropel layers in each core. The sapropel layers selected for this detailed study were (i) sapropel A, deposited 9000 years before the present (B.P.), at the deglaciation transition between isotope stages 2 and 1 and (ii) sapropel B, deposited 80,000 years B.P. during interglacial isotope stage 5, prior to the glaciation transition into isotope stage 4 (*9*). The planktonic foraminiferal species chosen for isotopic analysis included two species dwelling near the surface (*Globigerinoides ruber* and *Globigerina bulloides*) and three mesopelagic-dwelling species (intermediate depth) (*Orbulina universa, Globigerinella aequilateralis*, and *Globorotalia inflata*) (*6*). During a large decrease in surface-water salinity, species inhabiting near-surficial waters should record a larger isotopic depletion than deeper-dwelling species.

Table 1. Oxygen isotopic changes across sapropel layer A (9000 years B.P.).

Species	Absolute depletion (per mil)	Average depletion* (per mil)	Difference† (per mil)	Isotopic depletion‡
Core TR171-27; 13,000 to 9000 years B.P.				
Globigerinoides ruber	−2.8	−2.1	−0.8	
Globigerina bulloides	−1.4			
Orbulina universa	−1.3	−1.3		
Core TR172-22; 13,000 to 9000 years B.P.				−0.1
Globigerinoides ruber	−2.1	−2.0	−0.7	
Globigerina bulloides	−1.9			
Globorotalia inflata	−1.3	−1.3		
Core TR171-27; 11,000 to 9000 years B.P.				
Globigerinoides ruber	−1.34	−1.23	−1.0	
Globigerina bulloides	−1.13			
Globigerinella aequilateralis	−0.21	−0.21		
Core TR172-22; 11,000 to 9000 years B.P.				−0.8
Globigerinoides ruber	−1.46	−1.73	−0.2	
Globigerina bulloides	−2.0			
Globorotalia inflata	−1.53	−1.53		

*Average $\delta^{18}O$ of *G. ruber* + *G. bulloides* = surficial species group; average $\delta^{18}O$ of *G. inflata* + *G. aequilateralis* + *O. universa* (when available) = mesopelagic species group. †Difference in $\delta^{18}O$ between surficial and mesopelagic species. ‡Isotopic depletion of surficial versus mesopelagic species in core TR171-27 relative to the $\delta^{18}O$ of surficial and mesopelagic species in core TR172-22.

Unfortunately, the uneven occurrences of the mesopelagic species in the cores make direct comparisons with each surficial species impossible. For example, $\delta^{18}O$ data are not available for *G. inflata* across sapropel A in core TR171-27 and for *O. universa* below sapropel A in core TR172-22. For this reason, we have averaged the isotopic depletions experienced by each of the two depth groups to quantify possible differences in isotopic response due to differences in depth habitats (*17*).

We have assumed that the individual species have not undergone large adjustments in their average depth of growth with time and that possible species-specific, nonequilibrium fractionation effects, if any, have changed very little or have remained constant over the two 8000-year time intervals that we studied (84,000 to 76,000 years B.P. and 13,000 to 5000 years B.P.) (*18, 19*).

Significant isotopic anomalies are recorded by the foraminiferal species within sapropels A and B in both cores, with the magnitude of a specific response varying according to the average depth habitat of each species (Fig. 1). The species dwelling near the surface record larger $\delta^{18}O$ depletions than the mesopelagic species. From 13,000 to 9000 years B.P. (sapropel A), the $\delta^{18}O$ depletions of the surficial species *G. ruber* and *G. bulloides* become more negative (depleted) by −2.1 and −1.9 per mil in TR172-22 and −2.8 and −1.4 per mil in TR171-27 (Fig. 1 and Table 1). Over the same time interval, the isotopic depletions in the mesopelagic species *O. universa* and *G. inflata* are both only −1.3 per mil (Table 1). From 84,000 to 80,000 B.P. (sapropel B), the $\delta^{18}O$ depletions of *G. ruber* and *G. bulloides* are −1.1 and −0.9 per mil in TR172-22 and −2.1 and −1.6 per mil in TR171-27 (Fig. 1 and Table 2). Over the same time interval, the $\delta^{18}O$ depletions in the mesopelagic species are much less (Table 2). In general, the isotopic values for each of the species return to characteristic oceanic values by 5000 and 76,000 years B.P., approximately 4000 years after the end of the sapropel-producing conditions.

On the basis of the different response of the mesopelagic and surficial species, we interpret the negative isotopic anomalies associated with sapropel layers A and B as representing the establishment of a low-salinity surface layer in the eastern Mediterranean. The isotopic anomalies are much too large to have been caused by temperature increases alone (a temperature increase of about 9° to 10°C is needed to explain the isotopic depletion of *G. ruber*). Furthermore, foraminiferal faunal changes associated with the sapropel layers suggest control primarily by salinity rather than by temperature (*20*). If the isotopic anomalies over the sapropel layers are ignored, we estimate that the average isotopic signals in the Mediterranean cores during the time intervals analyzed are comparable to the isotopic signals attributable to changes in Northern Hemispheric ice volume during the same time periods (*21-25*). We therefore feel that the ice volume component contributing directly to the isotopic anomalies of the sapropel layers is minimal (approximately 0.2 to 0.5 per mil) and that the isotopic anomalies were largely caused by massive inflows of low-salinity water into the eastern Mediterranean.

If the inflowing freshwater has an isotopic composition of approximately −30 per mil (*26*), the differences in isotopic response between the mesopelagic and surficial species suggest that surface-water salinities were diluted by at least 10 percent relative to the salinities at a depth of about 100 m. Such a dilution would reduce surface salinities by 2 to 3 per mil and would decrease surface densities enough to effectively prevent vertical mixing in the upper water column.

The source of the low-salinity water at 9000 years B.P. is almost certainly glacial runoff produced by the melting of the Fennoscandian ice sheet which partly drained into the Black Sea and thence into the Aegean Sea and eastern Mediterranean (*27*). Inflow of low-salinity water at 80,000 years B.P. may reflect initial instabilities in the Fennoscandian ice sheet as it increased in volume and areal extent from interglacial stage 5 into glacial stage

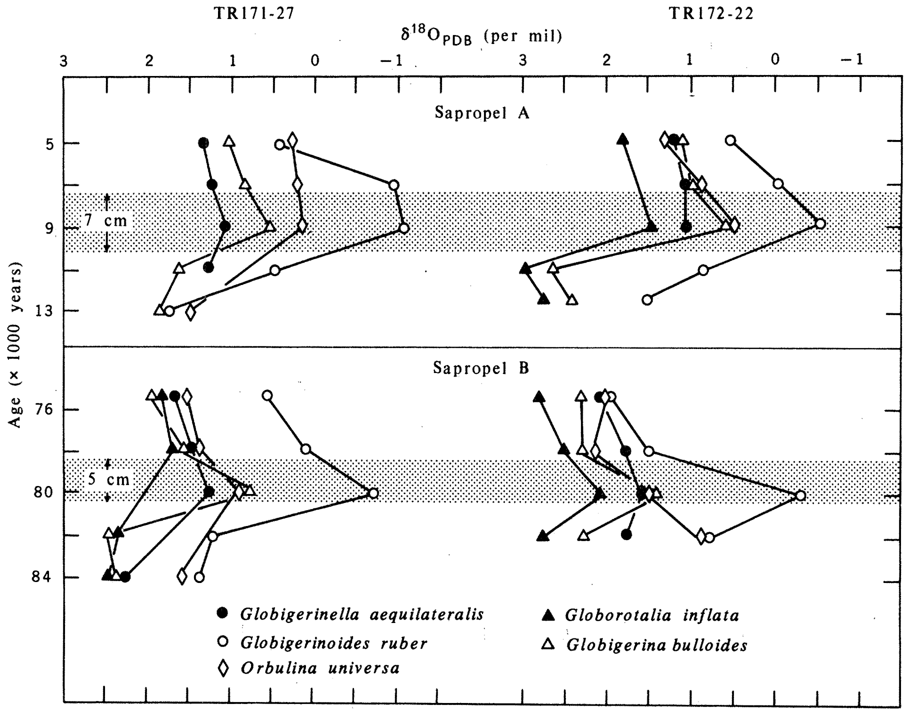

Fig. 1. Oxygen isotopic data for five species of planktonic foraminifera at 2000-year intervals across sapropel layers A and B in cores TR171-27 and TR172-22 from the eastern Mediterranean (*16*). The stratigraphic positions of the sapropel layers are shown by the stippling; $\delta^{18}O$ PDB is the deviation with respect to the PDB standard (*15*).

Table 2. Oxygen isotopic changes across sapropel layer B (80,000 years B.P.).

Species	Absolute depletion (per mil)	Average depletion* (per mil)	Difference† (per mil)	Isotopic depletion‡
Core TR171-27; 84,000 to 80,000 years B.P.				
Globigerinoides ruber	−2.1	−1.85	−1.25	
Globigerina bulloides	−1.6			
Globigerinella aequilateralis	−1.0	−0.6		
Orbulina universa	−0.2			
Core TR172-22; 84,000 to 80,000 years B.P.				−0.75
Globigerinoides ruber	−1.1	−1.0		
Globigerina bulloides	−0.9			
Globigerinella aequilateralis	−0.26		−0.5	
Orbulina universa	−0.58	−0.5		
Globorotalia inflata	−0.65			
Core TR171-27; 82,000 to 80,000 years B.P.				
Globigerinoides ruber	−2.0	−1.85	−1.0	
Globigerina bulloides	−1.7			
Globorotalia inflata§	−0.85	−0.85		
Core TR172-22; 82,000 to 80,000 years B.P.				−0.1
Globigerinoides ruber	−1.1	−1.0		
Globigerina bulloides	−0.9			
Globigerinella aequilateralis	−0.3		−0.9	
Orbulina universa	+0.6	−0.1		
Globorotalia inflata	−0.6			

*Average $\delta^{18}O$ of *G. ruber* + *G. bulloides* = surficial species group; average $\delta^{18}O$ of *G. inflata* + *G. aequilateralis* + *O. universa* (when available) = mesopelagic species group. †Difference in $\delta^{18}O$ between surficial and mesopelagic species. ‡Isotopic depletion of surficial versus mesopelagic species in core TR171-27 relative to the $\delta^{18}O$ of surficial and mesopelagic species in core TR172-22. §Estimated depletion based on the difference in isotopic composition between *G. inflata* and *G. aequilateralis*.

4 (*28*). The magnitude of the isotopic anomalies in the sapropel layers argue against increased precipitation as the sole source of the low-salinity water (*27*). In the Gulf of Mexico, surface-dwelling species (*Globigerinoides sacculifer* and *G. ruber*) record similar isotopic anomalies due to meltwater inflow by way of the Mississippi River from the disintegration of the Laurentide ice sheet (*7*, *29*). This Laurentide meltwater pulse reached a maximum at about 11,600 years B.P. (*29*). If the chronologies are correct, the apparent age differences of meltwater events in the Gulf of Mexico (11,600 years B.P.) and in the eastern Mediterranean (9000 years B.P.) most probably result from differences in the drainage patterns of both regions and in eustatic control over the exchange between the Black and Mediterranean seas.

Despite the different positions of sapropels A and B in the paleoclimatic record, the oxygen isotopic anomalies at 9000 and 80,000 years B.P. are nearly identical in magnitude; this similarity suggests a common causal mechanism. Sapropel stratigraphy in the eastern Mediterranean may provide a record of instability and melting in continental Eurasian ice sheets (*30*). This in turn suggests that the previous interglacial episode (stage 5, 75,000 to 125,000 years B.P.), which contains three distinct sapropel layers (B, C, and D) (*4*, *9*), was paleoclimatically different from the present interglacial, which has only one sapropel layer (A) associated with the termination of the last glaciation. If sapropels C and D record advances and subsequent melting of the former Fennoscandian ice sheet during brief climatic coolings during stage 5, perhaps some of the isotopic substages of stage 5 seen in open-ocean isotopic records (*24*) are related to these advances.

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5. The planktonic foraminiferal faunas associated with sapropel layers are marked by extremely high frequencies (up to 70 percent) of *Neogloboquadrina dutertrei*. In the Atlantic, this species is most abundant in the low-salinity gyre margin regic → [W. F. Ruddiman, *Geol. Soc. Am. Bull.* **82**, 283 (1971); N. Kipp, *Geol. Soc. Am. Mem.* **145** (1976), p. 3; (*6*)]. *Neogloboquadrina dutertrei* also increases in abundance during the period of low-salinity runoff from the Laurentide ice sheet into the Gulf of Mexico [(*7*); R. C. Thunell, *Quat. Res. (N.Y.)* **6**, 281 (1976)].
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12. The complete lack of sapropels in core TR171-20 and the absence of particular sapropels in other cores from the western Ionian basin suggest that the areal distribution of individual sapropel layers is not continuous over the entire eastern basin.
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15. We made isotopic determinations with an on-line VG model Micromass 602-C instrument after in vacuo reaction in phosphoric acid at 50°C. Isotopic values are reported as per mil deviations from the Pee Dee belemnite (PDB) standard:

$$\delta^{18}\mathrm{O} = \left[\frac{(^{18}\mathrm{O}/^{16}\mathrm{O})_{\mathrm{sample}}}{(^{18}\mathrm{O}/^{16}\mathrm{O})_{\mathrm{PDB}}} - 1 \right] \times 10^3$$

16. The cores were taken on R.V. *Trident* cruises 171 and 172 in the Levantine Basin during August and September 1975 and contain complete paleoclimatic records for the last 140,000 to 250,000 years. The exact core locations are as follows: TR171-27, 33°50′N, 25°59′E, 3150 m; TR172-22, 35°19′N, 29°01′E, 2680 m.
17. The consistent occurrence of the surficial species *G. ruber* and *G. bulloides* across sapropel layers may provide important paleoecological information (these species seem to be especially tolerant of environmental stress and water mass changes). The abundance of *G. bulloides* undergoes distinct increases in some sapropel layers, decreases in others, or exhibits no change at all. It is difficult to determine if this variability is a response to temperature or to salinity. Thunell *et al.* (*9*) have shown that sapropel deposition is associated with both warming and cooling trends, and that variability in the abundance of *G. bulloides* may be primarily a response to different temperature regimes.

→ N. J. Shackleton, J. D. H. Wiseman, H. A. Buckley, *Nature (London)* **242**, 177 (1973); C. Vergnaud Grazzini (*19*) has estimated the deviation from oxygen isotopic equilibrium for the following species: *G. bulloides*, −0.2 per mil; *G. ruber*, ~0.0 per mil; *G. inflata*, −0.8 per mil; *G. acquilateratis*, −1.5 per mil; and *O. universa*, −1.0 to 0.0 per mil. These estimates are based on analyses of specimens from Mediterranean plankton tows and surface sediments, with the apparent deviation from isotopic equilibrium conditions being lower in sedimented forms than in tow-collected specimens.

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20. Principal component and factor analyses of the planktonic foraminiferal faunal data across these sapropel layers, in addition to several others examined, produce paleoclimatic and paleotemperature curves which provide no evidence of unusually warm temperatures during sapropel formation (*9*).
21. Earlier oxygen isotopic analyses [C. Emiliani, *Quaternaria* **2**, 87 (1955); C. Vergnaud Grazzini, *Science* **190**, 272 (1975)] have shown that planktonic foraminifera from Mediterranean Quaternary sediments record larger isotopic changes as compared to isotopic records from the Caribbean. In both core TR171-27 and core TR172-22, the average δ^{18}O change of all the species combined from 13,000 to 5000 years B.P. is −1.1 per mil. The average isotopic change over the same time interval in four isotopic records characteristic of open-ocean areas is −0.9 per mil in the Caribbean: V12-122, −0.9 per mil (*22*) and P6304-8, −0.9 per mil (*23*); in the Pacific: V28-238, −0.7 per mil (*24*); and in the Indian: V19-188, −1.0 per mil (*25*). From 84,000 to 76,000 years B.P., the average isotopic signal is −0.5 per mil in core TR171-27 and +0.5 per mil in core TR172-22. Over the same time interval in the four isotopic records characteristic of the open ocean, the average isotopic signal is +0.65 per mil (*22–25*). The fact that most of the species in core TR171-27 do not seem to reflect the isotopic enrichment near the transition from stage 5 into stage 4 is most probably a function of sample interval and not a fundamental difference with the other records.

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27. The deposition of sapropel A occurred at approximately the same time that contact was established between the Aegean Sea and the Black Sea (approximately 9000 years ago). At this point, large amounts of fresh water from the Black Sea would have flowed into the eastern basin. This hypothesis does not negate the possibility of increased precipitation enhancing the low-salinity surface layer. We are, however, suggesting that the timing of sapropel deposition and freshwater input from the Black Sea are isochronous.
28. Both reversible and irreversible perturbations apparently are common along margins of the terrestrial ice she → [T. Hughes, G. H. Denton, M. G. Grosswald, *Nature (London)* **266**, 596 (1977)]. We cannot at this time pinpoint the exact source of the meltwater inflow, nor can we determine why large areas of the western Ionian basin do not have sapropel deposits in the Late Quaternary (*9*).
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30. Northern Hemisphere glaciation commenced $\sim 3.2 \times 10^6$ years ago, with the first major glacial-interglacial cycles beginning $\sim 2.5 \times 10^6$ years → [N. J. Shackleton and N. D. Opdyke, *Nature (London)* **270**, 216 (1977)]. A major cooling of the Mediterranean also occurred 3.2×10^6 years ago (R. C. Thunell, in preparation), and the oldest sapropel layers recovered in the Mediterranean (leg 13, site 125A, core 2-2) have been dated at $\sim 2.4 \times 10^6$ years B.P. [N. Ciaranfi and M. B. Cita, *Initial Rep. Deep-Sea Drill. Proj.* **13**, 1387 (1973); M. B. Cita and W. B. F. Ryan, *ibid.*, p. 1405]. Sapropel deposition during the Pliocene, therefore, may also be related to early fluctuations in the Northern Hemisphere ice sheet.

31. Isotope analyses were carried out in the Benedum Stable Isotope Laboratory at Brown University. D.F.W. gratefully acknowledges the support of R. K. Matthews. J.P.K. was supported under grant OCE 75-21262 from the National Science Foundation. We thank Captain Herbert Bennett and the crew of the R.V. *Trident* for their assistance during the piston-coring cruises. Contribution No. 210 of the Belle W. Baruch Institute for Marine Biology and Coastal Research.

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