29. PALEOCEANOGRAPHIC SIGNIFICANCE OF LATE MIOCENE TO EARLY PLIOCENE PLANKTONIC FORAMINIFERS AT DEEP SEA DRILLING PROJECT SITE 609¹

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ABSTRACT

The planktonic foraminifers in 124 samples from Holes 609 and 609B have been analyzed quantitatively to see whether oceanographic events in the late Miocene and early Pliocene (6.5–4.0 Ma) are reflected in the distribution of individual species. Major changes in sea-surface temperature and bottom-water circulation are postulated, mainly on the basis of the coiling-direction ratios in *Neogloboquadrina pachyderma* (Ehrenberg) and a dissolution index. A cool interval peaking at around 6.2 Ma was followed by climatic fluctuations, possibly indicative of glacial cycles, before a general warming in the Pliocene. Intense dissolution of $CaCO_3$ at this site on both sides of the Miocene/Pliocene boundary is inferred to have resulted from the presence of Antarctic Bottom Water, and an influx of less aggressive North Atlantic Deep Water is indicated at the actual boundary. These climatic and oceanographic changes are tentatively linked to the Messinian salinity crisis in the Mediterranean.

INTRODUCTION

The late Miocene to early Pliocene was an important period in the evolution of the world ocean. At approximately 6.2 Ma a series of events, some local and some global, combined to cause widespread changes in seasurface conditions and bottom-water circulation. These have been discussed elsewhere (e.g., Adams et al., 1977; Haq, et al., 1980; Loutit and Keigwin, 1982; Kennett, 1983; Loutit et al., 1983; Woodruff and Savin, 1985); the changes most relevant to the present study are the following:

1. An isochronic decrease of δ^{13} C in the world ocean at 6.2 Ma (the so-called latest Miocene carbon isotopic shift).

2. Cooling of surface waters.

3. Increase in bottom-water circulation rates and fertility of the oceans.

- 4. Lowering of sea level.
- 5. The Messinian salinity crisis.

6. Intensification of the Gulf Stream as a result of shoaling of the Panama Isthmus.

The effect of these changes was felt to varying degrees in the North Atlantic (see, e.g., Cita and Ryan, 1979; Bender and Keigwin, 1979; Shor and Poore, 1979; Poore, 1981; Thunell and Belyea, 1982). The purpose of this study is to examine in detail the quantitative composition of the planktonic foraminiferal fauna from Site 609 (Holes 609 and 609B), to assess whether paleoceanographic trends (both surface-water and deep-water) can be deduced from the distribution of the more important species. We attempt to link the changes through time at Site 609 to the patterns of world climate and ocean history. Site 609 was chosen because of its high sedimentation rates, relatively complete sequence, and position to the east of the Mid-Atlantic Ridge. The results presented here form part of a larger research project in which results from Sites 606 to 611 (Leg 94) and Sites 548 and 550 (Leg 80) will be combined with earlier work on DSDP Hole 552A (Leg 81) (Hooper and Funnell, in press), in an attempt to clarify the late Miocene and early Pliocene oceanographic history of the northeast Atlantic. The locations of these sites are shown in Figure 1.

METHODS

A total of 124 10-cm³ samples were obtained from Holes 609 and 609B. The main suite of samples was chosen from Hole 609, since this section extended up from a level corresponding to approximately 6.5 Ma (calculated from the sedimentation rate curve based on paleomagnetic data in Clement and Robinson, this volume). Because of drilling disturbance, however, the upper portion of the section to be studied was



Figure 1. Selected DSDP Sites (Legs 80, 81, and 94) in the North Atlantic.

¹ Ruddiman, W. F., Kidd, R. B., Thomas, E., et al., *Init. Repts. DSDP*, 94: Washington (U.S. Govt. Printing Office).
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considered unsuitable, and for that interval a series of samples was chosen from Hole 609B. The two sections were spliced at 313 m subbottom depth, where they have the same depth/age, according to the sedimentation rate curves. The sedimentation rate curves for Holes 609 and 609B were calculated from the following paleomagnetic data points (reversal boundaries):

609: *C1*, top, 4.40 Ma (278.0 m sub-bottom); *C1*, bottom, 4.47 Ma (282.25 m); *Chron 5*, top, 5.35 Ma (332.0 m); *C5*, *N1*, bottom, 5.54 Ma (338.5 m); and *C5*, *N2*, top, 5.68 Ma (346.5 m).

609B: C2, top, 4.57 Ma (289.5 m); Chron 5, top, 5.35 Ma (330.5 m); C5, N2, top, 5.68 Ma (346.25 m).

The choice of sample levels was governed by two considerations: the need for an even distribution of samples between 397.68 and 269.20 m (upper Miocene through lower Pliocene) and the necessity of sampling lithological variations. Study of the shipboard sedimentological logs and black and white photographs of the cores revealed the presence of subtle lithological changes, from the dominant pure calcareous oozes to slightly more marly horizons, which made it difficult to differentiate preferred levels. However, the lithological alternations sampled correspond to distinct changes in the microfauna, which indicate varying degrees of dissolution. Average sample spacing was one per 79 cm, corresponding to approximately 20,000 yrs.

Approximately 5 cm³ of each sample was processed, and the remainder was retained for particle size analysis (work in progress). Each sample was disaggregated in water or 10% calgon (sodium hexametaphosphate) using a sediment shaker, then washed through a 63- μ m mesh sieve and dried.

Each sample was then dry-sieved through a $125-\mu m$ mesh sieve and the larger size fraction was split with a microsplitter until about 300 to 400 planktonic foraminifers were obtained (unless dissolution was particularly severe); these were identified and counted and percentages were calculated. For the most important species, a cumulative frequency graph was plotted (Fig. 2). Total benthic specimens were also counted, and a plot of the planktonic/benthic ratio was used as an index of dissolution (Fig. 3).

RESULTS

The results of the species counts are presented in Table 1 and in Figures 2 to 4. Figure 2 presents cumulative percentage abundance data on the five most significant species in the fauna (in terms of numbers and ecological significance), recalculated to 100% and plotted versus depth. These species or species groups are Globigerina bulloides, Globorotalia puncticulata, Globorotalia conoidea s.l. (G. conoidea and G. conomiozea counted as one group because of their morphological similarity), Neogloboquadrina pachyderma s.l. (sinistrally and dextrally coiled forms; N. continuosa morphotypes included in the range of variation), and Neogloboquadrina atlantica (sinistrally coiled form only). The distribution of each species downcore is summarized in the paragraphs following. As a result of the high latitude, the planktonic foraminiferal zonation is difficult (Weaver, this volume), so only depth and age (and not zonal position) are given in this summary.

1. G. bulloides. This species is regarded as an indicator of temperate water masses (Imbrie and Kipp, 1971; Ingle, 1973; Kipp, 1976; Keller, 1978a, 1980b, Kennett and Srinivasan, 1983). Its distribution is fairly even through the studied interval, with two peaks of 10% below 390.00 m (upper Miocene) and very low abundances through the basal Pliocene, up to about 320.00 m subbottom, where two peaks again reach 10%. Above this level, the relative abundance fluctuates around 5% (2-10%) from 315.00 m to the top of the section studied (lower Pliocene). 2. G. puncticulata. This species, the immediate ancestor of G. inflata, makes its first appearance above 275.30 m (lower Pliocene). It is not preceded by its ancestral form G. sphericomiozea (one specimen recorded). Another study (Hooper and Funnell, in press) indicates that G. puncticulata occupied an ecological niche similar to that of G. inflata (see also Kennett and Vella, 1975; Keller, 1978a; Thunell, 1979) in the transitional water mass of Kipp (1976), between subpolar and subtropical water masses.

3. G. conoidea s.l. G. conoidea and G. conomiozea are similar at Site 609, and in the following discussion are treated as one group, G. conoidea s.l. (following Keller, 1978a). This group is a member of the Globorotalia (Globoconella) lineage and hence related to G. puncticulata (Bandy, 1975; Srinivasan and Kennett, 1981; Kennett and Srinivasan, 1983). G. conoidea s.l. is very abundant in the upper Miocene at about 390.00 m and 370.00 m, at which levels it approaches 100% of the fauna, and at 353.00 m, where it approaches 20% of the fauna. Between these levels it is either absent or rare. Above 345.00 m this group is very rare, and it becomes extinct at 327.00 m, just above the Miocene/Pliocene boundary. The virtually monospecific assemblages of G. conoidea show a fairly narrow size range (200-300 μ m), include many broken and damaged specimens, and coincide with intervals of strong dissolution. This suggests secondary concentration, by either dissolution of the rest of the assemblage, current winnowing, or a combination of these effects.

4. Neogloboquadrina pachyderma (dextral). This morphotype of N. pachyderma is well established as an indicator of temperate areas (Kennett, 1968; Bandy, 1972; Ingle, 1973; Vella, 1974; Vella et al., 1975; Poore and Berggren, 1975; Kipp, 1976; Keller, 1978a, 1978b; Kennett and Srinivasan, 1980). Below 385.00 m (upper Miocene), the dextral form is an important faunal element. Through the uppermost Miocene and basal Pliocene (385.00-320.00 m), the dextral morphotype is effectively replaced by the sinistrally coiling morphotype, though there are four peaks of the right-coiling form between 345.00 and 310.00 m. Dextral N. pachyderma is the dominant planktonic foraminifer in the Pliocene of Site 609. Figure 4 shows the relative abundances of sinistral and dextral N. pachyderma.

5. Neogloboquadrina pachyderma (sinistral). This is not the same morphotype as the extensively documented Pleistocene form of sinistrally coiling N. pachyderma, which is compact, quadrate, and usually encrusted (e.g., Kennett, 1968; Kennett and Srinivasan, 1980; Huddlestun, 1984; Weaver, this volume). The late Miocene to early Pliocene form is essentially identical to the dextrally coiled variety (i.e., non-encrusted and lobate), and is here regarded as equivalent to Keller's (1978b) morphotype form 1. A few specimens of the encrusted form have been noted in samples from the upper Miocene (Keigwin, 1982b). The distribution of sinistral N. pachyderma, and its relationship to the rest of the fauna, suggests that it had a distribution in cooler water than the dextral form (see Discussion and references cited therein). As can be seen in Figure 4, the sinistrally coiled form was dominant largely in the late Miocene.

6. Neogloboquadrina atlantica (sinistral). Hooper and Funnell (in press) suggest that this species in high abundances may be a good indicator of cold (polar) water masses. Poore and Berggren (1975), however, regard this morphotype as a subpolar species. The only notable occurrence, comprising about 5% of the fauna, is between 320.00 and 327.00 m (basal Pliocene).

Planktonic/Benthic Ratio (Fig. 3)

A normal planktonic/benthic foraminiferal ratio in the deep sea is on the order of 100. Ratios markedly less than this are regarded as indicating increased dissolution (Berger, 1967, 1970). Benthic foraminifers dissolve less easily because of their more robust tests; they may also be protected from dissolution by overlying waters by dying below the sediment/water interface. Dissolution also affects the relative abundance of planktonic species; more resistant species (such as neogloboquadrinids) are selectively preserved (Berger, 1967, 1970). This should not affect the observed coiling ratio in N. pachyderma (see Discussion), which is here regarded as the main climatic indicator. Although the P/B ratio is not the most sensitive of dissolution indices, the results presented here indicate a fair degree of resolution. Keigwin (1976) has noted that, in the upper Miocene and Pliocene of the Caribbean, the P/B ratio and fragmentation index correlate very closely.

Lithological variations in the sediment seem to be reflected in the dissolution index, with marly intervals corresponding to levels of increased dissolution. Figure 3 shows the P/B ratios at Holes 609 and 609B. Below 390.00 m (upper Miocene) dissolution is moderate, but above this (390.00-355.00 m, upper Miocene) the ratio is exceptionally low for deep-sea deposits. Dissolution is moderate, though more intense in some intervals, from 355.00 m (upper Miocene) to 330.00 m (basal Pliocene). A decrease in dissolution is indicated by higher P/B ratios in the lower Pliocene (330.00-320.00 m). Dissolution is much more marked between 320.00 and 290.00 m (lower Pliocene), with pulses of strong dissolution that seem, however, to decrease in intensity upsection. The uppermost part of the section studied seems to be largely dissolution-free (290.00-270.00 m, lower Pliocene).

DISCUSSION

The preceding faunal evidence shows several trends.

Before 6.5 Ma, the dextral form of *Neogloboquadrina pachyderma* was abundant, indicating warm conditions, but a late Miocene to earliest Pliocene cool interval is indicated by the dominance of the sinistral form between 6.5 and 5.0 Ma, with short warm intervals between 5.6 and 5.0 Ma. *Globorotalia conoidea* s.l. was present in some abundance before 5.7 Ma, with two major pulses of abundance at 6.5 and 6.2 Ma. The gaps in its distribution may represent periods of especially intense dissolution or current activity, which may have removed the species from the record at this site. Alternatively, it may not have been present during these intervals. In the period from 6.0 to 5.0 Ma there were dramatic faunal changes. During this interval there were four major peaks in the abundance of dextral *N. pachyderma* (interpreted as warm intervals), in an assemblage otherwise dominated by the sinistral form. The four warm intervals (Fig. 4) have a periodicity of approximately 125,000 yrs., suggesting cyclicity. Each peak has several data points, and all discernible lithological fluctuations were sampled. Poore (1981) noted climatic oscillations with a period of 1 m.y. in the late Miocene, and higher-frequency oscillations, with a periodicity of one to several hundred thousand years, from about 7.5 to 6.5 Ma; he speculated that these oscillations may be related to orbital parameters.

Evidence of similar climatic fluctuations, with a periodicity of several hundreds of thousands of years, has been noted in the upper Miocene of the North Pacific by Moore and Lombari (1981). The large-scale climatic fluctuations in the late Miocene were probably related to Antarctic glaciation (Arthur, 1979; Kennett, 1983). Increased ice volume may have resulted from the late Miocene cooling and may have caused sea-level fall; these factors are almost certainly related to the initiation of the Messinian salinity crisis at around 6.5 Ma (e.g., Keigwin, 1976; Keller, 1978a, 1980a, 1980b, 1981; Keller et al., 1982; Kennett, 1978; Moore and Lombari, 1981; Sancetta, 1978; Savin et al., 1981). But Keigwin, Aubry, and Kent (this volume), in a detailed isotopic study of highlatitude North Atlantic sites, have found no evidence of a major late Miocene cooling. They do note two apparent glacial episodes at 5.5 and 5.0 Ma, which approximately correlate with cool periods, as indicated by the N. pachyderma coiling ratio (Fig. 4), but additional cool events between 6.5 and 5.0 Ma at Site 609 (this study) do not seem to be matched in the oxygen isotope record of Keigwin et al. (this volume).

The dominance of *N. pachyderma* (sinistral) in the late Miocene probably indicates an overall cooling in the area (see, e.g., Poore and Berggren, 1975, who interpreted high percentages of sinistral *N. pachyderma* as indicating a cool event in the late Miocene/early Pliocene of the Hatton-Rockall Basin). Kennett and Vella (1975) and Keigwin (1976) postulated that the coiling ratio of *N. pachyderma* did not assume its present-day pattern until the early Pliocene and hence cannot be used in climatic interpretation of earlier periods. The evidence presented here, however, indicates that the coiling ratio is of value in indicating climatic trends in the late Miocene and early Pliocene, and this is supported by numerous studies in the Pacific, most notably those of Keller (1978a, 1979a, 1979b, 1980a, 1980b, 1981).

The dissolution index indicates marked fluctuations through the latest Miocene, but bears no constant relationship to the *N. pachyderma* coiling ratio. Selective dissolution of one of the coiling modes of *N. pachyderma* would not be expected, since they are essentially morphologically identical (Vella, 1974; Vella et al., 1975). The dissolution pattern through this interval indicates the presence of aggressive bottom waters in the latest Miocene and early Pliocene, but also indicates carbonate sedimentation (with two short interruptions) across

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Sample number (this study)	Core-Section, level (cm)	Sub-bottom depth (m)	Globigerina quinqueloba	Globizerina eamest	Globigerina bulloides	Globigerina falconensis	Globigerina woodi	Globigerina apertura	Globigerina nepenthes	Globigerina decoraperta	Globigerinoides obliquus	Globigerinoides triloba	Giobigerinoides quadrilobatus	Globigerinoides ruber	Orbulina universa	Orbulina suturalis	Gioborotalia conoidea (s.1.)	Globorotalia sphericomiozea	Globorotalia puncticulata	Globorotalia inflata	Gioborotalia scitula	Globorotalia cibaoensis	Gioborotalia margaritae	Gioborotalia hirsuta	Globorotalia crassula	Globorotalia crassaformis	Neogloboquadrina continuosa	Neogloboquadrina pachyderma (D)	Neogloboquadrina pachyderma (S)	Neogloboquadrina acostaensis (D)	Neogloboquadrina acostaensis (S)	Neogloboquadrina humerosa	Neogloboquadrina dutertrei	Neogloboquadrina atlantica (D)	Neogioboquadrina atlantica (S)	Sphaeroidinellopsis seminulina	Sphaeroidinellopsis sp. A	Sphaeroidinellopsis sp. B	Globigerinita glutinata	Globigerinita uvula	Globigerinella aequilateralis	Globigerinella calida	Benthic foraminifers	Silkcous microlosis trautoristrations and
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Table 1. Species counts for Site 609 (Holes 609 and 609B).

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106 107 108 109 110	41-4, 37 41-4, 70 41-4, 120 41-5, 70 41-5, 130	385.07 385.40 385.90 386.90 387.50				1 1 1		1					1	1 2 3	13 13 449	2 2 3 5 9							3 12 5 10 15 14 2 2 43			6	2	1	19	9		8 24 13 9	15 2 16 2 15 2 95 4 60	4 23 25 45 3
111 112 113 114 115	41-6, 30 41-6, 75 41-6, 130 42-1, 38 42-1, 110	388.00 388.45 389.00 390.18 390.90	1	3		2 2 2					7		2 2	7 1 2	300 239 329 10	0 9 2 5 0							I 3 1 3 3 21 8 34 33 156			1	1	1		1 8 3 7		9 5 13 5 16	11 1 56 1 34 1 56 67 4	10 18 18 5 46
116 117 118 119 120	42-2, 38 42-2, 110 42-3, 38 42-3, 110 42-4, 38	391.68 392.40 393.18 393.90 394.68	1 1 9 14	10 42 15 5	1 1 1	8 1 7	1	1 1 1				1	2 1 6 1 1	5 5 3	13 13 11	3 6 7 5 1	1	1 1 1				111	20 33 89 186 137 152 1 224 110 1 1 48 80 1		2	9	8 1	1 4	50 83 133 49	9 6 5 5 9	2 4 6 2		18 1 18 1 71 1 55 46	14 16 12 7 3
121 122 123 124	42-4, 110 42-5, 38 42-5, 110 42-6, 38	395.40 396.18 396.90 397.68	2 3 2	9 6 11 11	ä	9 1 6		1	3	2	2 1		2 2 1 5	6 1 5	51	3	1					1000	7 21 2 123 197 1 245 95 217 166 2		3 4 6	5	6 1	I	120 8 17:	2 0 1 5	1	3	2 68 1 61 7 47	1 10 79 9



Figure 2. Cumulative percent frequency plots for paleoclimatically important species at Site 609. G. conoidea plot is the sum of G. conoidea and G. conomiozea. C2, a reversal within the Gilbert magnetic epoch, and N1 and N2, reversals within Epoch 5, were used in the calculation of sedimentation rates for Leg 94 holes (see text). Uneven lines at the bases of C2 and N2 mark missing paleomagnetic data, and these two boundaries are inferred. Holes 609 and 609B (above 313 m sub-bottom) are spliced at 313 m, where they have the same age/depth relationship.

the actual Miocene/Pliocene boundary (5.4-5.2 Ma). The boundary is taken at 5.3 Ma (Berggren, 1981; Berggren et al., in press). The Pliocene pulses of dissolution started at 5.2 Ma and became less intense after 4.5 Ma; many samples from the upper part of the section show very little evidence of dissolution. N. pachyderma (dextral) became the dominant neogloboquadrinid at around 5.0 Ma, indicating an early Pliocene warming (Berggren and Schnitker, 1983; Keller, 1978a, 1979a, 1979b, 1981). That G. bulloides is present only in low numbers in the section deposited from 5.0 to 4.3 Ma probably reflects the effects of dissolution, because the species is fairly fragile (Berger, 1967). The next event was a peak in sinistral N. pachyderma at approximately 4.3 Ma, immediately followed by the first appearance of Globorotalia puncticulata.

These changes in bottom-water mass distribution (as indicated by dissolution) can be compared to presentday water masses. Thunell (1982) has shown that, for the western North Atlantic, there is a first-order correlation between the lysocline, benthic thermocline (the boundary between North Atlantic Deep Water [NADW] and Antarctic Bottom Water [AABW]), and the transition from carbonate-saturated waters to undersaturated waters. Thunell suggests that this relationship is not so clear in the present-day eastern North Atlantic, but it seems likely that calcite-corrosive bottom water in the late Miocene and early Pliocene was similar to presentday AABW, whereas noncorrosive bottom water may have resembled present-day NADW. The bottom-water changes also fit in well with work done by Murray (this volume) on bottom-water masses at Site 609, where, he



Figure 3. Planktonic/benthic (P/B) ratio at Site 609. Ratios markedly less than 100 indicate dissolution. See caption to Figure 2 regarding C2, N1, N2, and composite section for Site 609.

reports, AABW-like bottom water covered the site in the late Miocene and early Pliocene, but NADW-like bottom water was present in the earliest Pliocene. Keller (1978a, 1979a, 1979b, 1980a, 1980b, 1981), Keller et al. (1982), and Barron and Keller (1982) report surface-water cooling and increased bottom-water corrosiveness for calcite through several intervals in the late Miocene and earliest Pliocene in the Pacific Ocean. Hiatuses of similar ages have also been noted in the Caribbean region (Kaneps, 1979; Brunner and Keigwin, 1981; Keigwin, 1982a) and in the Panama Basin (Keigwin, 1976).

THE MESSINIAN CRISIS

The isolation and evaporation of the Mediterranean in the latest Miocene has been well documented (e.g., papers in Drooger, 1973; Ryan et al., 1974; Cita, 1975; Berggren and Haq, 1976; Van Couvering et al., 1976; Adams et al., 1977; Arthur, 1979; Keigwin and Shackleton, 1980; Loutit and Keigwin, 1982; Kennett, 1983; Cita, 1984). Events of particular interest to the present study have been listed earlier in this chapter (see Introduction). All have been related to an increase in ice volume in the late Miocene, in both the Southern Hemisphere (Shackleton and Kennett, 1975) and the Northern Hemisphere (Mercer and Sutter, 1982).

The late Miocene cooling event (peaking at 6.2 Ma) postulated in this study correlates well with the events we have listed. This does not agree with Cita and Ryan's (1979) interpretation of the late Miocene; they detected a cooling event after the onset of the Messinian salinity crisis and from that inferred that glaciation and a sealevel fall were caused by the isolation of the Mediterranean, rather than the reverse. The *Neogloboquadrina pachyderma* distribution in this study may reflect glacial cycles, in that it indicates four warm/cold alternations between 5.6 and 5.0 Ma. But no "special" event reflecting the end of the Messinian salinity crisis can be inferred from the data.

The intensification of bottom-water circulation, coincident with the possible influx of "AABW" into the area, seems to have occurred before 6.2 Ma but within the age limits (7.0-6.2 Ma) set by Ciesielski et al. (1982). Sediment transport may have taken place if the distribution of *Globorotalia conoidea* does actually represent current winnowing, though there is no evidence of a real hiatus at Site 609. Several authors (Ryan et al., 1974; Schnitker, 1980; Blanc and Duplessy, 1982) have sug-



Figure 4. Coiling ratio in *N. pachyderma* at Site 609. Dashed line at 360 m indicates where sample 73 has been omitted (no *N. pachyderma*). See caption to Figure 2 regarding C2, N1, N2, and composite section for Site 609.

gested that isolation of the Mediterranean would cause a global salt deficiency, leading to a temporary cessation in the formation of all Northern Hemisphere deep water.

CONCLUSIONS

The inferred paleoceanographic history of Site 609 through the late Miocene and early Pliocene is as follows:

1. Just before 6.5 Ma (corresponding to 395.00 m sub-bottom), there was a decrease in sea-surface temperature (indicated by an increase in sinistral *Neogloboquadrina pachyderma*) associated with an influx of AABWlike bottom water into the area, which caused extensive dissolution. There was an increase in bottom-water circulation rates; these events may have been linked to increased ice volume at the poles. Selective dissolution and possibly current-winnowing by intensified bottom circulation led to the formation of almost monospecific foraminiferal sands, dominated by *Globorotalia conoidea* s.1.

2. Apparently the isolation of the Mediterranean was preceded by glaciation and presumed glacio-eustatic sealevel depression. 3. Sea-surface temperatures reached a minimum at around 6.2 Ma (370.00 m sub-bottom). The ensuing cool period was followed by cyclical alternations of warmer and colder intervals between 5.6 and 5.0 Ma, with a periodicity of roughly 125,000 yrs.

4. From 5.3 to 5.2 Ma, bottom waters at Site 609 became much less corrosive for calcite, possibly reflecting the displacement of AABW-like bottom water by NADWlike bottom waters. This displacement occurred at about the same time as the reestablishment of the connection between the Atlantic and the Mediterranean, but it is unclear whether the events were related.

5. After 5.2 Ma (320.00 m depth), bottom waters become more corrosive for calcite, indicating the return of AABW-like bottom water to the area. Dissolution became gradually less marked over the next million years before effectively ceasing, indicating the return of NADWlike bottom water as the dominant water mass in the area (Murray this volume).

6. The early Pliocene was much warmer than the late Miocene, though minor temperature fluctuations did occur.

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