28. MIDDLE PLIOCENE CHANGE IN PLANKTONIC FORAMINIFERAL FAUNA AT SITE 606[1]

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ABSTRACT

A "total fauna" curve (Ruddiman, 1971) shows that surface water overlying DSDP Site 606 (central North Atlantic Ocean) cooled suddenly at 3.1 Ma, within the Mammoth paleomagnetic reversed interval. At that time, *Globorotalia puncticulata, Neogloboquadrina pachyderma*, and *Globorotalia crassaformis* increased and *Globorotalia hirsuta, Globigerinoides sacculifer*, and *Sphaeroidinellopsis* decreased in abundance. Oxygen isotope results for *Globigerina bulloides* do not indicate a "stepwise" cooling, but probably reflect small changes in continental ice volume. It is hypothesized that as annual average temperatures decreased, *G. bulloides* delayed its bloom from spring to summer to follow a preferred temperature habitat.

INTRODUCTION

This report examines planktonic foraminiferal faunal changes which occurred in the central North Atlantic Ocean at about 3 Ma. Middle Pliocene oceanographic events have been the focus of considerable attention since the study of Shackleton and Opdyke (1977), which argued that Northern Hemisphere ice sheets became extensive beginning at about 3.0 to 3.2 Ma. That study showed evidence that glaciation occurred several hundred thousand years earlier than the previous stable-isotope estimate of its inception at ~2.5 Ma (Devereux et al., 1970; Shackleton and Kennett, 1975). Many subsequent studies revealed a significant enrichment in ^{18}O in foraminiferal carbonate at 3.1 Ma, clearly marking that time as an important threshold in Pliocene climatic evolution (Keigwin and Thunell, 1979; Keigwin, 1982b; Hodell et al., 1983; Weissert et al., 1984). This event has also been associated with the evolution of Mediterranean climate on land (Suc, 1984) and at sea (Thunell, 1979).

Not all workers agree that the event at 3.1 Ma was a permanent increase in continental ice volume. Backman (1979) first suggested that it might have been a cooling in the deep sea, since his revised biostratigraphy of North Atlantic DSDP sites suggested an initiation of ice-rafting at about 2.5 Ma. Similar views were also expressed by Prell (1982; 1984) and Thunell and Williams (1983). Finally, Shackleton et al. (1984) published a detailed record of climatic change for the last 3.5 Ma based on DSDP Hole 552A in the northeast North Atlantic Ocean. Oxygen isotope results from that hole revealed a minor enrichment in ^{18}O at ~3.1 Ma, of comparable magnitude to other events earlier and later. At that location there appears to have been neither a major $\delta^{18}O$ event nor a stepwise increase at 3.1 Ma.

Thus, considerable uncertainty exists about the deep-sea record of climatic change at 3.1 Ma. Is the $\delta^{18}O$ event at Hole 552A absent because of the core disturbance, which prevented recognition of the Mammoth paleomagnetic event (Shackleton et al., 1984)? Is it a step-like increase at other locations, but not at Hole 552A? Is it larger in the Pacific than in the Atlantic? How much of the $\delta^{18}O$ signal reflects temperature change and how much ice volume change? These are important and difficult questions to answer, and planktonic foraminiferal faunal results presented here, which suggest a step-like cooling, contribute to solution of only part of the puzzle.

DSDP Hole 606 was cored with the Advanced Piston Corer on the western flank of the Mid-Atlantic Ridge (37°20.32′N, 35°29.99′W; water depth 3007 m). Sediment from this site is well suited for the studying of middle Pliocene faunal events because of the excellent preservation of $CaCO_3$ microfossils (owing to relatively shallow water depth), the outstanding continuous recovery, the sedimentation rate of nearly 4 cm/10^3 yrs., and the lack of sediment disturbance. All geomagnetic reversals through the upper Gilbert are recognized, though at the time of this writing they are only constrained to within 1.5-m limits (Clement and Robinson, this volume). Furthermore, a detailed stable-isotope study of Site 606 benthic and planktonic foraminifers (Keigwin, this volume) affords precise correlation with the results obtained to the north (DSDP Hole 552A) by Shackleton et al. (1984).

METHODS

Samples of about 10 cm^3 from Core 12 of Hole 606 were disaggregated in a hot solution of water and sodium metaphosphate and washed over a 63-μm sieve. The coarse fraction was dried in an oven at $<50°C$, further sieved, and the fraction >180 μm was split with a microsplitter, aiming for a subsample of 300 whole specimens. All planktonic specimens were counted, and at least 98% were identified.

RESULTS AND DISCUSSION

Percent abundance data for planktonic foraminiferal species are presented in Table 1. Dominant faunal changes within the studied interval are an increase in the abun-

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Table 1. Site 606 faunal data (species abundance in percent) and ecological interpretation.

			"Cool"					"Warm"										"Other"				
Sub-bottom depth (m)	Fragmented/ whole planktonic[a]	Benthic/ whole planktonic[a]	*Globigerina woodi*	*Globigerina bulloides*	*Globorotalia puncticulata*	*Neogloboquadrina acostaensis*	*Globorotalia scitula*	*Neogloboquadrina pachyderma*	*Globigerina falconensis*	*Globorotalia hirsuta*	*Globigerinoides* cf. *ruber*	*Globigerinoides obliquus*	*Globigerinoides sacculifer*	*Globorotalia menardii*	*Sphaeroidinellopsis*	*Globoquadrina altispira*	*Orbulina* sp.	*Globorotalia crassaformis*	*Globigerinella aequilateralis*	*Globigerinita glutinata*	Unidentified	Total number planktonics in split
102.25	0.22	0.003	7	22	14	3	1	1	12	2	8	4	1	—[b]	2	6	—	12	1	3	2	388
102.75	0.12	0.003	11	17	21	1	—	2	8	—	11	6	1	1	1	2	—	15	1	1	1	664
103.25	0.12	0.006	3	16	27	3	—	2	10	—	11	7	2	—	1	3	—	11	2	2	1	491
103.55	0.11	0.005	6	24	15	5	1	2	6	4	11	8	5	—	1	1	—	5	1	4	1	392
103.75	0.13	0.003	11	24	11	4	—	3	10	11	8	5	2	—	1	2	—	3	—	2	—	962
104.05	0.08	0.003	9	12	19	8	—	—	14	18	8	4	—	—	—	4	—	—	2	2	—	330
104.15	0.09	0.007	10	22	20	4	—	—	7	21	5	6	—	—	—	3	—	—	—	—	—	289
104.25	0.07	0.004	12	25	17	6	—	—	13	16	2	—	1	—	—	—	—	1	—	3	—	249
104.35	0.11	0.015	5	29	17	1	—	6	9	19	4	3	—	—	—	—	—	1	1	3	—	1031
104.55	0.10	0.009	11	30	10	9	—	—	11	16	4	1	—	—	—	4	—	—	1	2	—	219
104.75	0.09	0.014	10	23	1	7	1	1	10	19	8	7	4	—	1	1	—	2	3	1	1	490
104.95	0.16	0.015	11	17	2	8	—	—	9	29	7	4	7	—	2	—	—	—	2	2	—	271
105.25	0.01	0.012	6	24	—	4	—	1	7	29	8	6	5	1	2	—	2	2	—	2	1	562
105.45	0.13	0.010	9	16	15	3	—	1	9	24	8	7	3	1	4	1	—	1	1	1	—	197
105.75	0.24	0.017	5	27	3	5	1	—	12	9	12	6	5	—	—	2	—	7	2	1	2	241
106.25	0.13	0.000	13	19	1	6	—	—	12	12	11	7	2	1	2	12	—	—	1	1	1	178
106.35	0.11	0.010	13	19	1	7	—	—	14	14	10	5	—	—	1	13	1	—	1	1	—	278
106.75	0.12	0.014	13	18	1	10	—	—	9	19	12	5	2	2	5	1	1	—	2	1	1	353

[a] Good preservation of these samples is indicated by low ratios of fragmented to whole planktonic foraminifers and of benthic foraminifers to whole planktonic foraminifers.
[b] — indicates species not found in split.

dance of *Globorotalia puncticulata, Neogloboquadrina pachyderma*, and *Globorotalia crassaformis*, and a less-pronounced decrease in the abundance of *Globorotalia hirsuta, Globigerinoides sacculifer*, and *Sphaeroidinellopsis* spp. Rather than base our interpretation on just one or a few taxa, we use the "total fauna" approach of Ruddiman (1971), for which the excess percentage of cool-water over warm-water faunal elements is shown in Figure 1. Table 1 also summarizes our assumptions about the temperature preferences of the middle Pliocene fauna, which rely heavily on the core-top distribution of Holocene species (Kipp, 1976) and the plankton tow data summarized by Bé (1977). We assume, further, that extinct species had approximately the same ecological requirements as their modern descendants or nearest relatives, recognizing that this avoids the fundamental question of why they are extinct. Thus, we assume that *Neogloboquadrina acostaensis* and *G. puncticulata* were relatively cool-water species and that *Globigerinoides obliquus* and *Sphaeroidinellopsis* spp. indicate warmer water.

The most significant result of the total-fauna analysis is that at about 104.6 m sub-bottom there is an abrupt shift to increased abundance upsection of cool-water species over previously dominant warm-water species. Peak abundance of cool-water species occurs at 104.4 m sub-bottom, where cool-water species exceed warm-water species by 20 to 30%. Within the uncertainties of the limits of the Mammoth geomagnetic event, this faunal turnover occurred at 3.1 Ma.

If further work shows the faunal turnover at 3.1 Ma to have been a ubiquitous feature in the central North

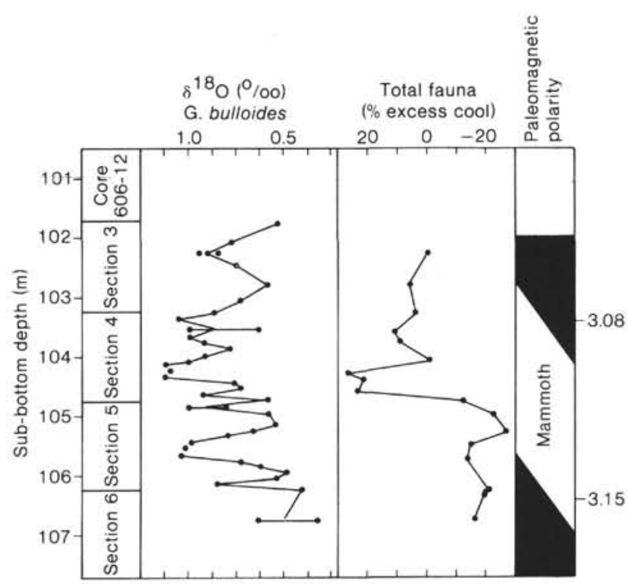

Figure 1. Faunal results of this study compared with oxygen isotope results (Keigwin, this volume) and paleomagnetic interpretation (Clement and Robinson, this volume). The "total fauna" curve suggests pronounced cooling of surface waters beginning at 3.1 Ma, whereas the oxygen isotope record of *G. bulloides* probably responds more to minor changes in continental glaciation.

Atlantic, then this event probably marks the establishment of modern biogeographic patterns. Site 606 underlies the boundary between the modern Transitional Surface Water mass, marked today by relatively abundant *Globorotalia inflata*, and the Subtropical Water mass, marked by warmer-water species (Bé and Tolderund, 1971;

Kipp, 1976). *G. inflata* s.s. evolved from *G. puncticulata* by about 3 Ma (Berggren, 1977), but it is not present in our samples. Most specimens of *G. puncticulata* below Section 606-12-2 are advanced forms but are mostly four-chambered rather than the typical three-chambered *G. inflata*. Thus, the available faunal evidence indicates that surface waters of the central North Atlantic cooled and the Transitional Faunal Province expanded before the evolution of the species (*G. inflata*) that distinquishes that province today.

Most workers would agree that cooling events during the Pliocene led to modern climatic patterns, but few studies have presented quantitative planktonic foraminiferal results in sufficient detail to determine the exact timing and extent of these changes. For example, cooling surface water in the middle Pliocene of the Panama Basin was inferred by Keigwin (1976), and a brief cool event elsewhere in the Pacific was identified at 3.0 to 3.2 Ma by Keller (1979). Studies in the Mediterranean region have also demonstrated quantitative foraminiferal evidence of middle Pliocene cooling (Thunell, 1979; Zachariasse and Spaak, 1983). Zachariasse and Spaak (1983) describe three Pliocene intervals marked by abundant *G. puncticulata* or *G. inflata*. The middle event probably began at about 3.1 or 3.2 Ma, since it was followed shortly by the extinction of *Sphaeroidinellopsis* (dated at 3.05 Ma in the Caribbean; Keigwin, 1982a), and therefore is probably correlative with our evidence of cooling. Abundance of the *G. inflata* group in Pliocene Mediterranean and nearby Atlantic sediments is associated by Zachariasse and Spaak (1983) with intensification of the cool eastern boundary current in the North Atlantic. Presumably this current system, at times when it was more intense, carried more of its *G. inflata* group fauna southward toward the Mediterranean.

CLIMAP (Climate/Long Range Investigation Mapping and Prediction) results showed that surface-water temperature anomalies and foraminiferal faunal changes were greater around the subtropical gyre margins than within the gyres (McIntyre et al., 1976). Temperatures at latitudes between the equator and 42°N were relatively stable. Assuming that oceanic circulation in the middle Pliocene was similar to that of today, it is seen that the faunal change at 3.1 Ma was particularly dramatic, and probably resulted from significant cooling.

It is suprising that such a large, stepwise faunal change is not reflected in the oxygen isotope record of near-surface-dwelling planktonic foraminifers (Fig. 1). $\delta^{18}O$ of *G. bulloides* is known to increase systematically with temperature decrease in upwelling regions. This has been shown regionally in core tops across a 4°C gradient (Prell and Curry, 1981) and in a high-resolution time series of the last several decades, where sea surface temperature has varied by 2°C (Dunbar, 1983).

Two hypotheses can account for our observation of faunal change in the absence of oxygen isotope change. The first is that there was simply no cooling at all and some unknown factor controlled the species abundance changes at 3.1 Ma. We reject this explanation because of independent evidence of cooling at this time from the terrestrial record (Suc, 1984), as well as nannofloral evidence from Site 606 and cores from other sites (Backman, this volume; Backman and Shackleton, 1983/84). Backman and Pestiaux (this volume) find a decrease in *Discoaster* abundance during the Mammoth Event at Site 606, which they interpret as indicating cooling of surface waters. A similar pattern was also found in an equatorial Pacific core (Backman and Shackleton, 1983/84).

The second hypothesis, which we favor, is that there was indeed a surface-water cooling at 3.1 Ma, but that the ecological requirements of *G. bulloides* render it unrecognizable using the oxygen isotope method. For example, this species may adjust its season of growth to maintain a preferred temperature. It is well known that at subtropical locations in the western North Atlantic, *G. bulloides* proliferates late in winter (Tolderlund and Bé, 1971; Deuser, et al., 1981). At higher latitudes in the North Atlantic, however, maximum test production occurs in late summer and fall (Tolderlund and Bé, 1971). Thus, as the surface water over Site 606 cooled at 3.1 Ma, *G. bulloides* could have shifted its bloom from the spring to the summer without recording a decrease in average annual temperature in its oxygen isotope ratio. This "seasonality" hypothesis is consistent with the benthic and planktonic $\delta^{18}O$ results for Site 606 (Keigwin, this volume). Near and during the Mammoth Event, virtually all of the $\delta^{18}O$ variability in *G. bulloides* can be accounted for by ice-volume changes, since the oxygen isotope ratios of *G. bulloides* and *Planulina wuellerstorfi* covary in this interval. In fact, the small increases in $\delta^{18}O$ of *G. bulloides* at about 102.3, 103.5, 104.3, and 105.6 m sub-bottom are matched by larger increases in the benthic record, suggesting that the deep sea cooled by 1 or 2°C during these minor glaciations.

CONCLUSIONS

Counts of middle Pliocene planktonic foraminiferal species reveal a pronounced cooling event in the central North Atlantic at 3.1 Ma. Evidence for this is increased abundance of *Globorotalia puncticulata* and *Neogloboquadrina pachyderma* and decreased abundance of *Globorotalia hirsuta, Globigerinoides sacculifer*, and *Sphaeroidinellopsis*. These faunal changes represent the replacement of a warm-water fauna by the Pliocene equivalent of the modern Transitional Fauna.

ACKNOWLEDGMENTS

We thank C. E. Franks and M. Poag for technical assistance in the laboratory and Harold Andrews and R. G. Fairbanks for helpful discussions. D. Lazarus and R. C. Thunell provided helpful criticism of the manuscript. This research was supported by NSF grant OCE 8308893. This is WHOI Contribution No. 5909.

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Date of Initial Receipt: 9 November 1984
Date of Acceptance: 6 March 1985