Equatorial Pacific deep-sea benthic foraminifera: Faunal changes before the middle Miocene polar cooling

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ABSTRACT

Data on the composition of benthic foraminiferal faunas at Deep Sea Drilling Project Site 575 in the eastern equatorial Pacific Ocean were combined with benthic and planktonic carbon- and oxygen-isotope records and $CaCO_3$ data. Changes in the composition of the benthic foraminiferal faunas at Site 575 predated the middle Miocene period of growth of the Antarctic ice cap and cooling of the deep ocean waters by about 2 m.y., and thus were not caused by this cooling (as has been proposed). The benthic faunal changes may have been caused by increased variability in corrosivity of the bottom waters, possibly resulting from enhanced productivity in the surface waters.

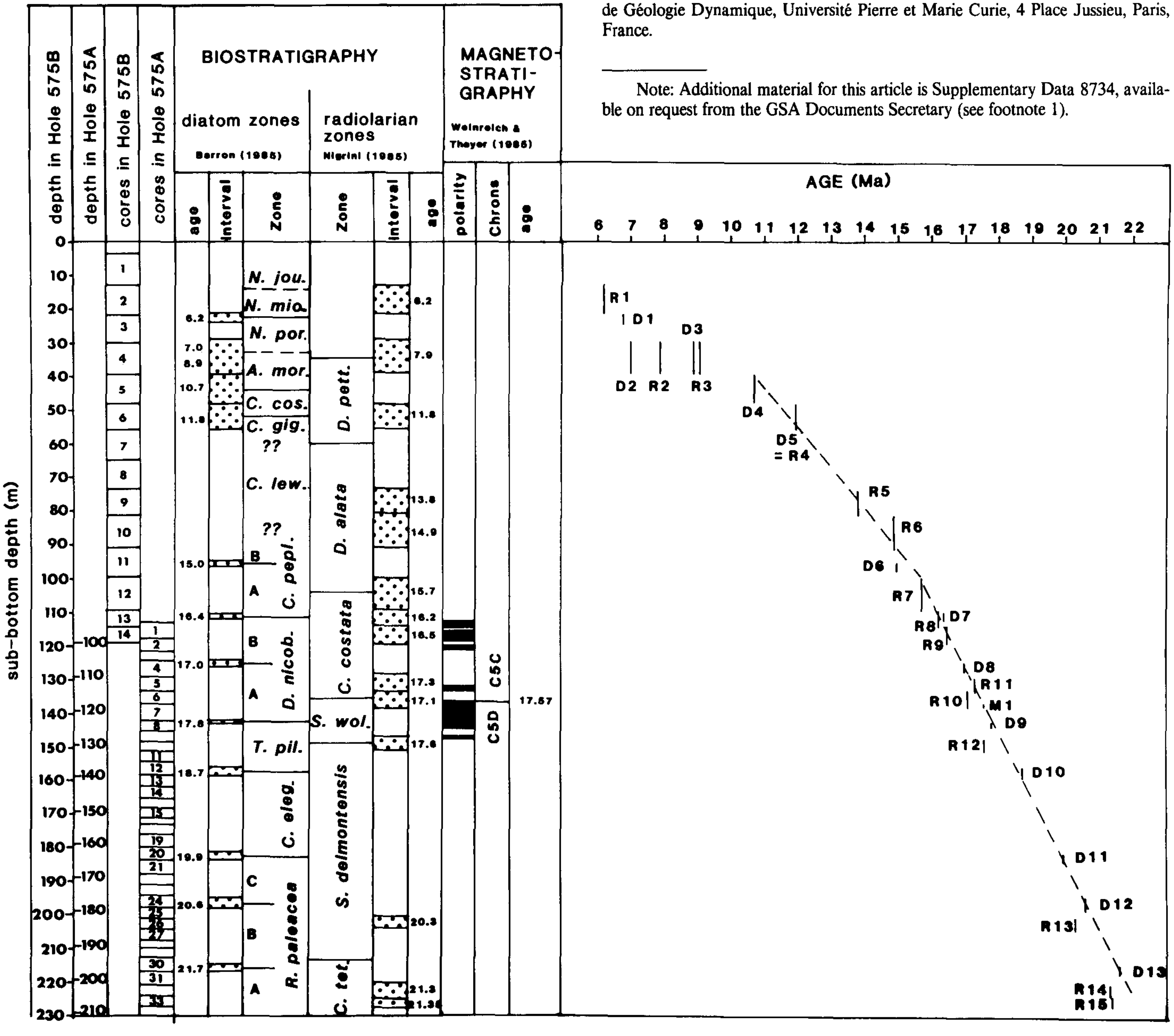

Figure 1. Depth of cores in Holes 575A and 575B, paleomagnetic polarity and zonation, radiolarian and diatom zones, ages of stratigraphic datum levels, and sedimentation rate curve. Numbered datum levels are listed in Table 1. R: radiolarian datum level; D: diatom datum level; M: paleomagnetic reversal. Stippled bands show depth intervals of datum levels and correspond to vertical lines in sedimentation rate diagram. Note offset in sub-bottom depth between levels of equivalent age in Holes 575A and 575B (see text). Numerical ages after Barron et al. (1985b).

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Note: Additional material for this article is Supplementary Data 8734, available on request from the GSA Documents Secretary (see footnote 1).

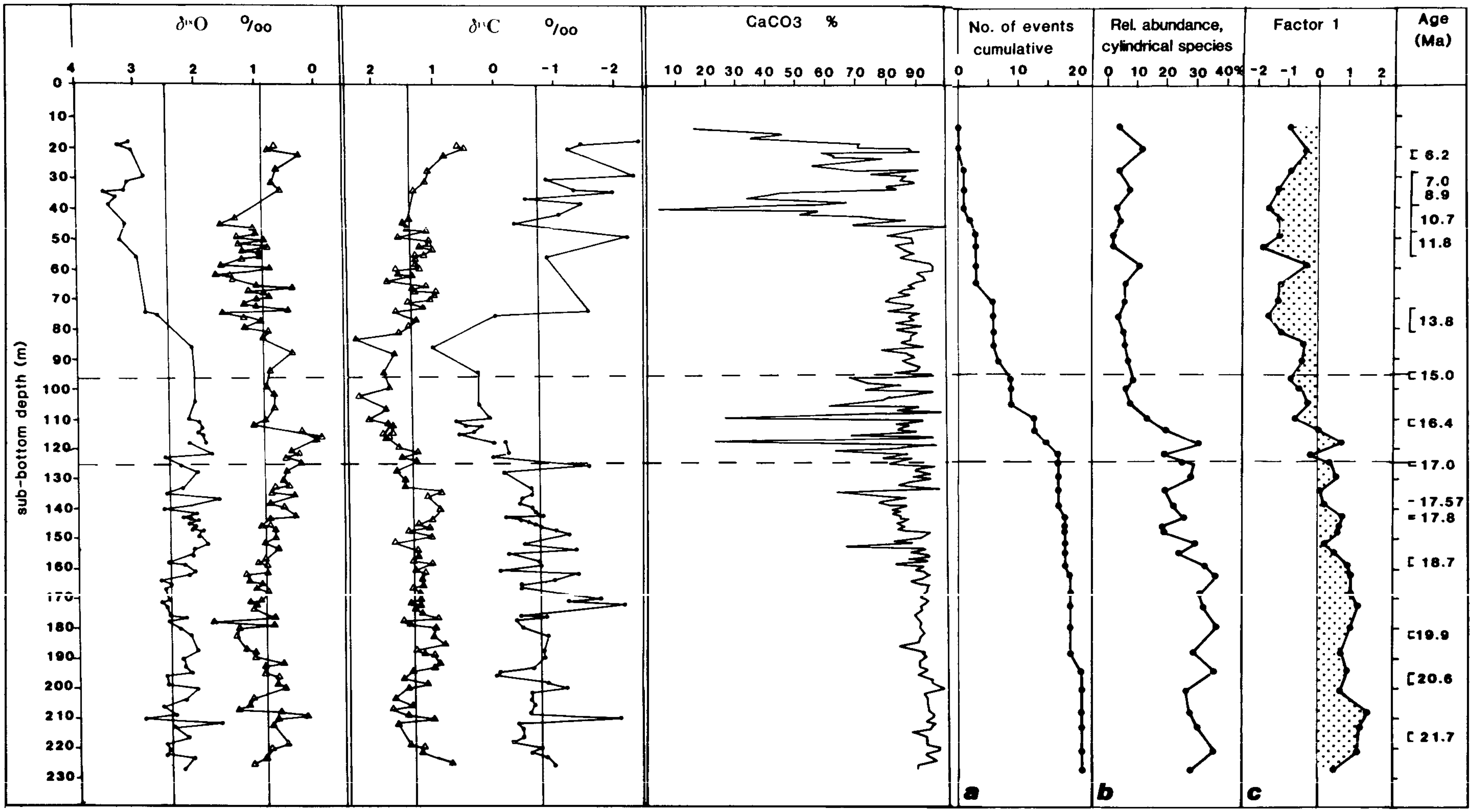

Figure 2. Carbon and oxygen isotopic stratigraphies for benthic (dot) and planktonic (triangle) foraminifera, weight percent $CaCO_3$, and benthic foraminiferal faunal events plotted versus sub-bottom depth. Ages as in Table 1. Vertical lines in isotopic plots are at average values. Curve *a* shows cumulative number of faunal events. Curve *b* shows relative abundance of cylindrical species (*Stilostomella* spp., *Pleurostomella* spp., and uniserial lagenids). Curve *c* shows values of first factor (explaining about 30% of total variance). Horizontal dashed lines are drawn at about 15 and 17 Ma.

INTRODUCTION

Earth has undergone considerable cooling during the late Mesozoic and Cenozoic and has changed from a warm and equable Cretaceous world without polar ice caps to the present colder planet with polar ice caps. The tropical regions have not undergone significant net cooling; thus, the latitudinal temperature gradients increased. The cooling of Earth and the increase in latitudinal temperature gradients did not proceed monotonically; periods of accelerated change alternated with stable periods (e.g., Shackleton and Kennett, 1975; Savin, 1977; Berger et al., 1981; Kennett, 1977).

The early to middle Miocene was a period of major changes in the ocean-atmosphere system; the East Antarctic ice cap probably originated or grew considerably, leading to a decrease in oceanic bottom-water temperatures. Increase in ice volume and decrease in temperature are reflected in a worldwide increase in $\delta^{18}O$ in tests of deep-sea benthic foraminifera, starting at about 14.5 Ma (e.g., Shackleton and Kennett, 1975; Kennett, 1977; Woodruff and Douglas, 1981; Savin and Yeh, 1981; Savin et al., 1981). At about 17.5 Ma, $\delta^{13}C$ in benthic and planktonic foraminiferal tests increased worldwide, probably as a result of deposition of extensive organic-rich sediment on the shelves (Vincent and Berger, 1985; Vincent et al., 1985; Miller and Fairbanks, 1985).

Deep-sea benthic foraminiferal faunas reflect changes in the deep-water masses of the oceans; thus, we can use data on faunal changes of deep-sea benthic foraminifera to trace changes in the deep-water masses. According to several authors, these organisms underwent a faunal turnover in the middle Miocene as a result of the cooling of the deep waters (Woodruff and Douglas, 1981; Woodruff, 1985; Berggren, 1972; Berggren and Schnitker, 1983; Schnitker, 1986). At Site 575, however, the benthic faunas started to change several millions of years before the cooling. The benthic faunal changes may be correlated with changes in planktonic productivity or with an increase in variability in the chemistry of the deep waters (possibly the result of fluctuations in productivity).

TABLE 1. BIOSTRATIGRAPHIC AND PALEOMAGNETIC DATUM LEVELS

Datum level	Depth (m)	Age (Ma)
R 1 *Stichocorys delmontensis->S. peregrina*	12.9- 21.5	6.2
D 1 B *Nitzschia miocenica*	21.5- 24.2	6.8
D 2 T *Thalassiosira burckliana*	29.7- 39.1	7.0
R 2 B *Didymocyrtis penultima*	29.7- 39.1	7.9
D 3 T *Actinocyclus moronensis*	29.7- 39.1	8.9
R 3 T *Cyrtocapsella japonica*	29.7- 39.1	9.1
D 4 T *Craspedodiscus coscinodiscus*	39.1- 48.3	10.7
D 5 B *Coscinodiscus temperei* var. *delicata*	48.3- 55.9	11.8
R 4 B *Cyrtocapsella japonica*	48.3- 55.9	11.8
R 5 B *Didymocyrtis laticonus*	73.7- 81.3	13.8
R 6 T *Calocycletta costata*	81.3- 91.0	14.9
D 6 T *Anellus californicus*	95.0- 96.5	15.0
R 7 B *Dorcadospyris alata*	99.5-109.2	15.7
R 8 T *Didymocyrtis prismatica*	109.2-114.0	16.2
D 7 B *Cestodiscus peplum*	110.3-111.8	16.4
R 9 B *Gyraffospyris toxaria*	114.9-118.1	16.5
D 8 T *Thalassiosira bukryi*	124.8-126.3	17.0
R10 B *Dorcadospyris dentata*	133.2-138.4	17.1
R11 B *Calocycletta costata*	129.1-133.2	17.3
M 1 boundary Chrons C5C/C5D	132.3	17.57
R12 B *Stichocorys wolffii*	147.3-151.2	17.6
D 9 B *Denticulopsis nicobarica*	142.5-142.7	17.8
D10 T *Craspedodiscus elegans*	156.2-158.8	18.7
D11 T *Bogorovia veniamini*	181.9-183.9	19.9
R13 B *Stichocorys delmontensis*	201.2-204.0	20.3
D12 T *Coscinodiscus oligocenicus*	195.3-198.4	20.6
R14 T *Theocyrtis annosa*	221.0-224.3	21.3
R15 B *Calocycletta virginis*	224.3-227.5	21.4
D13 T *Thalassiosira primalabiata*	215.2-217.1	21.7

Note: Depths are after Nigrini (1985), Barron (1985), and Weinreich and Theyer (1985); ages are after Barron et al. (1985a). T: top: B: bottom. D: diatom events: R: radiolarian events: M: paleomagnetic events. Data from above 112m are from Hole 575B; data below 112m from Hole 575A.

MATERIAL

We studied samples from Miocene biogenic oozes from hydraulic piston cores from Deep Sea Drilling Project (DSDP) Site 575 in the central equatorial Pacific (lat 05°51.00′N, long 135°02.16′W, water depth 4536 m). In the Miocene the water depth at the site (as estimated from backtracking) was probably similar to the present depth, but the site was located below the equatorial high-productivity belt (Weinreich and Theyer, 1985). Time control is by biostratigraphy (Pujos, 1985 [calcareous nannofossils]; Saito, 1985 [planktonic foraminifera]; Barron, 1985 [diatoms]; Nigrini, 1985 [radiolarians]; Barron et al., 1985a [synthesis]) and limited magnetostratigraphic data (Weinreich and Theyer, 1985). Benthic foraminifers were picked from the >63 μm fraction. Counts in larger size fractions were inconsistent because rectilinear species passed the sieve dependent upon details of the sieving process (Thomas, 1985). Oxygen- and carbon-isotope ratios of benthic and planktonic foraminifera and $CaCO_3$ content of the bulk sediment were measured (see Vincent and Killingley, 1985, for methodology). Data are plotted in terms of sub-bottom depth. Age-equivalent levels in Hole 575A are offset in depth compared with Hole 575B; a value of 19.2 m must be added to the nominal depth of samples in Hole 575A (Fig. 1). The correlation was made on a foraminiferal turbidite horizon at a color change in the sediments, and it is in excellent agreement with biostratigraphic, isotopic, $CaCO_3$, and sand-content data (Vincent and Killingley, 1985). Numerical ages were derived from diatom and radiolarian events (Barron et al., 1985a, 1985b; see Table 1). The sedimentation rate curve is shown in Figure 1; the time scale is after Barron et al. (1985b); note that Anomaly 5 is correlated to Chron 11 (Berggren et al., 1985).

RESULTS

Data on the faunal composition of the benthic foraminifera were plotted vs. sub-bottom depth together with the oxygen isotopic curves for benthic and planktonic foraminifera (*Oridorsalis umbonatus* and *Globoquadrina venezuelana*) and the $CaCO_3$-content curve (Fig. 2[1]). Benthic foraminiferal $\delta^{18}O$ values increase strongly between 85 and 75 m sub-bottom; planktonic values increase little (Vincent and Killingley, 1985). Benthic and planktonic $\delta^{13}C$ values are high between 125 and 75 m sub-bottom. $CaCO_3$ percentages fluctuate strongly above 45 m sub-bottom and between 125 and 95 m sub-bottom.

The number of faunal events (Fig. 2, curve *a*) is equal to the sum of first and last appearances, whether they are evolutionary or migratory. We do not know whether a specific first or last appearance is evolutionary or migratory, and therefore all events are added. This curve shows periods of changes in deep waters as reflected in the benthic faunas, whether they reacted by evolution or by migration. First and last appearances are not distributed homogeneously; periods of change alternate with stable periods. The changes affected only about 30% of the fauna because many species belong to long-lived species. Faunal events are concentrated between 125 and 105 m sub-bottom (17.0 to 15.5 Ma); e.g., the first appearance of *Cibicidoides wuellerstorfi* between 110 and 108 m sub-bottom (16.1 to 15.7 Ma).

"Faunal changes" plotted as number of faunal events tend to emphasize relatively rare species; trends in the more common species are emphasized by multivariate analysis of relative abundance data (Fig. 2, curves *b* and *c*). The first factor derived in a multivariate analysis of species counts (explaining about 30% of the variance) changes most in the interval

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[1] A table of $CaCO_3$, oxygen, and carbon isotope data as plotted in Figure 2, GSA Supplementary Data 8734, is available on request from Documents Secretary, Geological Society of America, P.O. Box 9140, Boulder, CO 80301.

where most faunal events occur. This factor is mainly made up of *Stilostomella* spp., *Pleurostomella* spp., and uniserial lagenids (all cylindrical species, positive score), and *Epistominella exigua, Laticarinina pauperata*, and the *Cibicidoides mundulus* group (trochospiral species, negative score). The curve of the first factor score strongly resembles a curve of the sum of the relative abundances of the cylindrical species (Fig. 2, curve *b*).

DISCUSSION

Changes in benthic foraminiferal faunal composition at Site 575 occur between about 125 and 105 m sub-bottom (17.0 to 15.5 Ma), whether we emphasize first and last appearances or changes in relative abundances. Similar faunal changes occurred at the same time at nearby Sites 573 and 574 (Thomas, 1985). The increase in $\delta^{18}O$ in benthic foraminiferal tests is at 85 to 75 m sub-bottom at Site 575 (about 14.5 Ma, Fig. 2). Thus, the benthic foraminiferal faunal changes in the deep eastern equatorial Pacific started about 2 m.y. *before* the cooling of the bottom waters. The faunal changes were coeval with an increase in $\delta^{13}C$ in benthic and planktonic foraminiferal tests. Such an increase in $\delta^{13}C$ has been observed worldwide (Miller and Fairbanks, 1985; Miller et al., 1987; Vincent and Berger, 1985; Vincent et al., 1985; Woodruff and Savin, 1985), and it has been interpreted as resulting from storage of organic material on the shelves (the "Monterey event"; Vincent and Berger, 1985). The $CaCO_3$ content of the sediments at Site 575 shows great variability and an overall decrease between 155 and 95 m sub-bottom (18 to 15 Ma) and extremely low values and high variability between 125 and 95 m sub-bottom (17 to 16 Ma, Fig. 2). Similar low values of $CaCO_3$ content occur in the same age interval in large areas of the Pacific (Barron et al., 1985b). The fluctuations in $CaCO_3$ content are cyclic, the frequency being on the order of 40 ka (Vincent and Thomas, unpub. data; Thomas, 1986c). Most benthic faunal changes occur in this interval of greatest variability in $CaCO_3$ content; species that have their last appearance in the interval with strong $CaCO_3$ dissolution do not reappear higher in the section where dissolution is again minimal ($CaCO_3$ values >90%).

The sedimentation rate did not decrease in the interval of overall lower $CaCO_3$ values (Theyer et al., 1985; Barron et al., 1985a; Fig. 1). The lower overall sedimentation rate of $CaCO_3$ was probably balanced by an increased sedimentation rate of the other component of the sediment, biogenic silica. The high sedimentation rate of biogenic silica resulted from an increase in productivity of siliceous microorganisms (possibly linked to increased availability of nutrients), thus providing the link between high $\delta^{13}C$ values (result of high productivity) and increased corrosivity of the bottom waters (compare $\delta^{13}C$ and $CaCO_3$ curves, Fig. 2). The increased dissolution of $CaCO_3$ may have been caused by deposition of more organic matter on the sea floor. The organic material oxidized to form CO_2, which caused increased dissolution. The changes in the benthic foraminiferal fauna are concentrated in the periods of highest variability in corrosivity of the bottom waters for $CaCO_3$.

Our conclusions differ from those of Woodruff and Douglas (1981) and Woodruff (1985) for Site 289 in the western Pacific and for various other sites in the Pacific. These authors concluded that there was a close correlation between the benthic foraminiferal faunal changes and the increase in benthic foraminiferal $\delta^{18}O$ values. Comparison of our data with Woodruff's data on Site 289 is difficult because of the difference in size fraction studied (this study: >63 μm; Woodruff: >150 μm). Woodruff (1985, Fig. 22) showed that at least some faunal changes predated the oxygen isotopic increase at Site 289; high negative loadings on factor 4 (indicating the presence of a fauna indicative of high surface productivity) are correlated with high values of carbon isotopic ratios at about 17 Ma. A plot of faunal events at Site 289 (using Woodruff's data, after recalculating ages to our time scale) shows that most faunal events occurred in two periods: 15.0 to 13.0 Ma and 10 to 9 Ma (first appearance of *C. wuellerstorfi* at 15.0–14.9 Ma). Cylindrical species decreased in relative abundance at about the same time as at Site 575, but the decrease is less pronounced (possibly a result of the difference in size fractions studied). Thus, at Site 289 most faunal events did not occur at the same time as the decrease in relative abundance of the cylindrical species.

Kurihara and Kennett (1986) concluded that there was a direct correlation between the increase in oxygen isotopic ratio and benthic faunal change at southwestern Pacific Sites 590, 591, and 206. Data from Site 590 are inconclusive because of the presence of a hiatus (17.7–15.5 Ma, as corrected to our time scale). Data from Site 206 (Figure 10 of Kurihara and Kennett, 1986) suggest that some benthic faunal changes occurred before the oxygen isotopic event; factor 5 has high values in the upper lower Miocene. *Bolivina pusilla* loads significantly on this factor, and *Bolivina* species are indicators of high surface productivity (e.g., Boltovskoy and Wright, 1976; Poag and Low, 1985). Thus, this benthic faunal change may have been caused by a change in surface productivity.

We do not suggest that the response of benthic foraminifera to Miocene environmental changes was the same in all oceans and at all depths. Our results from the Pacific differ from results in Berggren (1972), Schnitker (1986), Thomas (1986a, 1986b, 1987), Belanger and Berggren (1986), and Miller and Katz (1987) for the North Atlantic, indicating that Miocene faunal events of deep-sea benthic foraminifera in the Pacific and the North Atlantic were not coeval. The first appearance of *C. wuellerstorfi*, for example, occurred at 16.1–15.7 Ma in the eastern Pacific, 15.0–14.9 Ma in the western Pacific, 14.8–14.1 Ma in the eastern Atlantic, and 15.2–14.9 Ma in the western Atlantic (Miller and Katz, 1987; Thomas, 1987, and in prep.). Cylindrical species decreased in relative abundance in the northeast Atlantic at about 10 Ma (Thomas, 1986b, 1987) and in the equatorial Pacific at 17.0–15.5 Ma. Miller and Katz (1987) and Thomas (1987), however, indicated that benthic foraminiferal faunal events in the northwest and northeast Atlantic also at least partially predated the middle Miocene oxygen isotopic increase. We suggest that cooling of deep waters and changes in surface productivity influence the composition of benthic foraminiferal faunas; at different sites one or the other dominates, producing different faunal responses.

CONCLUSIONS

The early to middle Miocene faunal changes in deep-sea benthic foraminiferal faunas were not simply a result of the middle Miocene cooling of the deep waters of the oceans. The faunal changes did not occur at the same time all over the world, and they started several millions of years *before* the cooling in at least some locations and at some depths (e.g., Site 575, in the eastern equatorial Pacific, at about 4.5 km depth). The benthic faunas appear to react to an increase in surface productivity and increased variability in corrosivity of the bottom waters.

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Reviewer's comment

This paper is intriguing in that it shows that major changes in equatorial Pacific benthic foraminifers predated the major cooling event of the middle Miocene and may have been due to increased productivity. In contrast to most papers on Miocene isotopes, the age model presented is clear and convincing; therefore, the ages assigned to the various changes are well constrained.

John Barron