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CHANGES IN COMPOSITION OF NEOGENE BENTHIC FORAMINIFERAL FAUNAS IN EQUATORIAL PACIFIC AND NORTH ATLANTIC

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ABSTRACT

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Deep sea benthic foraminiferal faunas were studied from three DSDP sites in the equatorial Pacific (Leg 85, depth about 4.5 km), and two DSDP sites in the North Atlantic (Leg 94, depth 3.5 and 2.5 km), for the interval between 25 and 0 Ma. The number of first appearances (FA's) and last appearances (LA's) of taxa in the early to middle Miocene was similar at all sites, despite differences in location and depth. Specific events, however, were rarely coeval at several sites, even within the Pacific. Changes in faunal composition began earlier (at about 18 Ma) in the equatorial Pacific than in the North Atlantic (about 15.5 Ma); these changes affected between about 20 and 30% of the total fauna. There is no simple, globally valid correlation between the changes in composition of the benthic foraminiferal faunas and events in oxygen and carbon isotopic records. The FA of *Cibicidoides wuellerstorfi*, however, appears to be coeval with the increase in oxygen isotopic ratios in the early middle Miocene.

INTRODUCTION

In the early to middle Miocene major changes occurred in the ocean—atmosphere system. It is generally thought, that before the middle Miocene temperatures in the oceans were more equable than today (e.g. Berger, 1981; Berger et al., 1981; Kennett, 1983). In the early middle Miocene temperature gradients from pole to equator and from shallow to deep water at low latitudes increased, and the oceans cooled. Data for these paleoclimatic theories are mainly from oxygen isotopic studies of benthic and planktonic foraminifera (e.g. Shackleton and Kennett, 1975; Matthews and Poore, 1980; Savin et al., 1981; Loutit et al., 1983): there was a worldwide, relatively rapid increase in $\delta^{18}O$ values in deep-sea benthic foraminiferal tests at high and low

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latitudes, and in planktonic foraminiferal tests at high latitudes in the early middle Miocene. Oxygen isotopic values from planktonic foraminifera at low latitudes did not show a similarly large increase. The duration of the major part of the increase in oxygen isotopic ratios may have been less than 50,000 yr (Pisias et al., 1985).

Some authors suppose that the change in oxygen isotopic values was a result of the initiation of glaciation of Antarctica (Shackleton and Kennett, 1975), and that the world was essentially ice-free before the middle Miocene. Recently, however, evidence has been presented in favor of the existence of pre-Miocene ice caps on Antarctica (e.g. Keigwin and Keller, 1984; Miller and Fairbanks, 1983, 1985; Poore and Matthews, 1984; Miller and Thomas, 1985), as was originally postulated by Matthews and Poore (1980). As yet it is not evident how much of the increase in oxygen isotopic values was caused by cooling, and how much by an increase in ice volume. The deep waters of the oceans, however, probably cooled.

Recently much research has been done on the carbon isotopic records from benthic and planktonic foraminifera (see e.g. Haq et al., 1980; Vincent et al., 1980; Vincent et al., 1985; Vincent and Berger, 1985; Vincent and Killingley, 1985). A major, worldwise increase in carbon isotopic values in planktonic and benthic foraminiferal tests has been recognized at about 17 Ma (Vincent et al., 1985; Miller and Fairbanks, 1985; Vincent and Berger, 1985). This change has been interpreted as a result of worldwide changes in productivity in the oceans, which may have caused the removal of organic carbon in organic-rich deposits on the shelves (Vincent and Berger, 1985). Miller and Fairbanks (1985), however, argue that the change in carbon isotopic ratios is part of a large-scale cycle in ^{13}C ratios, which lasted from 24.5 to 16 Ma. They explain the increase in carbon isotopic ratios at about 17 Ma as a result of a change in the ratio of the amount of carbon buried as $CaCO_3$ to the amount buried as organic carbon or of a change in $\delta^{13}C$ in rivers (input). The change toward heavier values of carbon isotopic ratios (at about 17 Ma) predated the change to heavier oxygen isotopic values (at about 14.5 Ma), but the relation between oxygen and carbon isotopic fluctuations (if any) has not yet been fully explained.

The composition of Recent deep-sea benthic foraminiferal faunas is correlated with the watermass in which the faunas are living (see e.g. Douglas and Woodruff, 1981, for a review). Therefore changes in the deep-sea benthic foraminiferal faunas are expected to occur at the time of major reorganizations of the deep waters of the oceans, as for instance the early middle Miocene. Until recently, however, only one study of the correlation between faunal composition and isotopic record had been published (Woodruff and Douglas, 1981). The authors concluded that there was a major faunal turnover associated with the oxygen isotopic change at DSDP Site 289 on the Ontong-Java Plateau (West Pacific). Woodruff (1985) presents data on many more Pacific sites, and concluded that the major phase in benthic foraminiferal evolution occurred from 16 to 13 Ma and was correlated with the change in oxygen isotopic values. Berggren (1972) described an important faunal change in the deep sea benthic foraminiferal faunas in the Atlantic in the middle Miocene (DSDP Site 116) and the Bay of Biscay (DSDP Sites 118, 119). His data, however, did not show in detail the position of the first and last appearances of the various species, and the time control at these sites was not very precise; at that time no isotopic curves for the North Atlantic were available.

My studies are on benthic foraminiferal faunas from the equatorial Pacific (DSDP Sites 573, 574, and 575; Thomas, 1985) and the North Atlantic (DSDP Sites 608 and 610, Thomas, 1985) and I do not agree that there is a close correlation between the isotopic record and the faunal composition of deep sea benthic foraminifera. In this paper I compare faunal data from the equatorial Pacific and the North Atlantic, and evaluate the relation between the faunal changes and the isotopic changes. The time-control for the North Atlantic sites is given by paleomagnetic data (Clement and Robinson, in press). For the equatorial sites the paleomagnetic data are generally poor or non-existent, except for a short interval at Site 575 (Weinreich and Theyer, 1985); the biostratigraphic data, however, are good (Barron et al., 1985).

MATERIAL AND METHODS

Samples were obtained from three DSDP Sites drilled in the equatorial Pacific on Leg 85, Site 573 (present water depth 4301 m, 00° 29.91'N, 133° 18.57'W), Site 574 (4561 m, 04° 12.52'N, 133° 19.81'W), and Site 575 (4536 m, 05° 51.00'N, 135° 02.16'W). The three sites are on a N—S transect across the equatorial high-productivity zone. The samples used are core-catcher samples; the overall sample distance corresponds to about 0.5 Ma on average, but varies with the sedimentation rate. Time control by paleomagnetic data is lacking or not reliable in the Miocene part of the sections, with the exception of an interval corresponding to about 16—18 Ma at Site 575 (Weinreich and Theyer, 1985). The absolute timescale used is after Berggren et al. (in press), including the correlation of Anomaly 5 with Chron 11. Biostratigraphic control is generally good, and relies on data on planktonic foraminifers (Saito, 1985), calcareous nannofossils (Pujos, 1985), diatoms (Barron, 1985), and radiolarians (Nigrini, 1985; see Barron et al., 1985, for a synthesis of the biostratigraphic data of all Leg 85 sites). All sites were cored continuously, and the recovery was good. Preservation of benthic foraminifera is good at Site 573, but at Sites 574 and 575 severe dissolution of $CaCO_3$ makes study of foraminifera difficult to impossible in the uppermost part of the sections, corresponding to about 10.5 Ma at Site 574, about 12 Ma at Site 575.

From the North Atlantic I studied material from two sites drilled on DSDP Leg 94, Site 608 (present water depth 3534 m, 42° 50.21'N, 23° 05.25'W) and Site 610 (2427 m, 53° 13.30'N, 18° 53.21'W). The time control is provided by the paleomagnetic data (Clement and Robinson, in press), since the correlation between biostratigraphic zones and the absolute timescale is not well established at high latitudes. Biostratigraphic data are available for planktonic foraminifera (Weaver, in press; Jenkins, in press), calcareous nannofossils (Takayama and Sato, in press), and diatoms (Baldauf, in press). Site 608 was cored continuously, and the recovery was generally good for the Miocene and younger part of the section. The preservation of benthic foraminifera is good to fair. Site 610 was cored intermittently (1 core/50 m) in parts of the upper and middle Miocene. In the lower Miocene coring was continuous, but recovery and preservation of benthic foraminifera was not as good as at Site 608 (see site chapters in Kidd et al., in press).

From the Atlantic sites core catcher samples were used; the average sample distance corresponds to about 0.5 Ma at Site 608. In the interval between about 270 and 380 m sub bottom depth (corresponding to about 11.5—20.5 Ma) additional samples were used, so that the sample distance corresponds to 0.1—0.3 Ma.

For a detailed discussion of sample preparation and picking techniques see Thomas (1985; in press, a, b). Benthic foraminifera were studied in splits of the >63 μm fraction. From each sample about 200 specimens were picked and counted. Samples which contained less than about 180 specimens were not used. Counts of all specimens, relative abundances of the more common species and species groups, ranges and a discussion of the taxonomy are given in Thomas (1985; in press, a, b). A detailed discussion of the early to middle Miocene North Atlantic faunas is given in Thomas (in press, a).

For the interval between 0 and 25 Ma the preservation of benthic foraminifera is good at Sites 608 and 573; most of the data used in this paper are from these two sites.

RESULTS AND DISCUSSION

The deep sea benthic foraminiferal faunas in the North Atlantic and equatorial Pacific have many species in common, especially the more abundant species. There are quite a few differences in the occurrences of the rare species. For most of the samples more than 90% of the total fauna belongs to the combination of the following taxa: *Oridorsalis* spp., *Gyroidinoides* spp., *Cibicidoides* spp., *Epistominella exigua*, *Nuttallides umbonifera*, *Pullenia* spp., *Globocassidulina subglobosa*, *Melonis* spp., unilocular forms, miliolids, agglutinated forms, *Pleurostomella* spp., *Stilostomella* spp., uniserial lagenids, *Uvigerina* spp., buliminids, and biserial group (*Bolivina* spp., *Fursenkoina* spp., *Francesita advena*, *Stainforthia complanata*). Exceptions are some samples from the Atlantic sites from the period of northern hemisphere glaciation. In the deep equatorial Pacific *E. exigua* and *N. umbonifera* are more important constituents of the fauna than at the Atlantic sites; these species are the least common at the shallowest site (Site 610). Miliolids and agglutinated forms generally constitute less than 15% of the fauna.

The diversity is usually high, between 50 and 60 species per 200 specimens. The number of species is similar in Pacific and Atlantic (Fig.1), except for a period of low diversity at Site 608 (between about 18.5 and 17 Ma). This low diversity is caused by the high relative abundance of *Bolivina* spp. (mainly *B. spathulata*, more than 90% in some samples). At Site 610 the relative abundance of *Bolivina* spp. is also high at this time, but less extreme (up to 45%). This interval is discussed in detail in Thomas (in press, a). Although this interval is of much interest from a paleoecologic point of view, there are few to no irreversible faunal changes associated with it; therefore a discussion is outside the scope of this paper.

The high diversity is a problem in the study of deep sea benthic foraminiferal faunas because of the presence of many rare species. The more common species are usually cosmopolitan and have long ranges in time. The rare

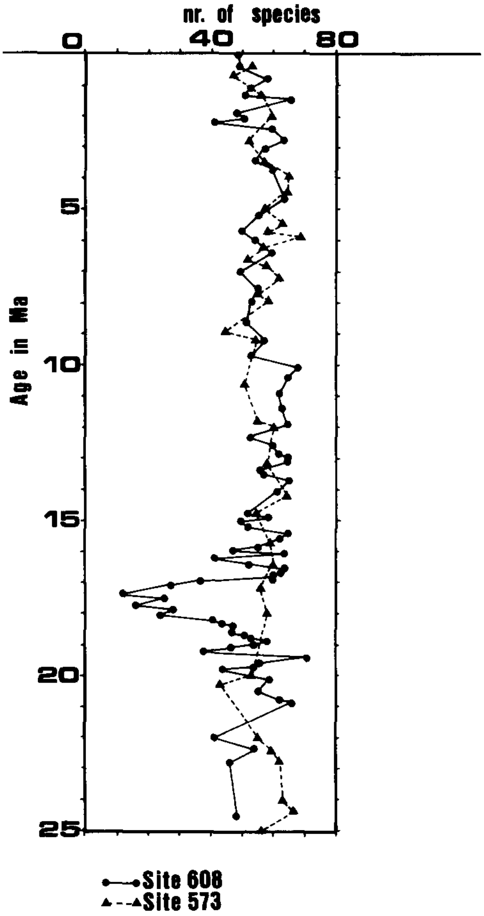

Fig.1. Diversity given as number of species per 200 specimens, plotted versus time for Site 573 (equatorial Pacific) and Site 608 (North Atlantic).

species show more variation as to occurrence in space and time, but first appearances (FA's) and last appearances (LA's) of rare taxa are difficult to date with precision. The exact position of FA's and LA's in reality may be quite different from a position found, because of the small probability of actually finding rare taxa in a sample. In addition, the taxonomy of deep sea benthic foraminifera is extremely confused. It is generally impossible to assess from the literature if a given range of a species is local or more widespread.

In my studies of benthic foraminifera I used the concept of faunal event. A faunal event is the first or last appearance of a taxon at a site, whether evolutionary (evolution—extinction) or migratory (immigration—emigration; vertical or lateral migration). In some instances I used a strong decrease in relative abundance as a faunal event. I used events that are distinguishable on faunal counting lists, i.e. only first and last appearances of species, that are present in a more or less continuous range of samples. The rarest species, i.e. species that are found in few samples, were not used.

Using this definition it is possible to study the number of events per time-unit (i.e. the event-rate), and to see if some periods are characterized by high event-rates, but not if the actual events are synchronous over large distances. Also, there is no distinction made between the FA or LA of an abundant and the FA or LA of a less common species. The events are plotted cumulatively versus time (Fig.2); a steep slope of the curves means a high event-rate, i.e. relatively many species had first or last appearances during that time interval.

At the Pacific sites the event-rate was relatively low before about 18 Ma, between 13 and 7 Ma, and between 6 and 3 Ma. The event-rate was high between 18 and 13 Ma, 6 and 7 Ma, and possibly between 3 and 2 Ma. No events were recognized from 0 to 2 Ma. The data for Site 575 are in close

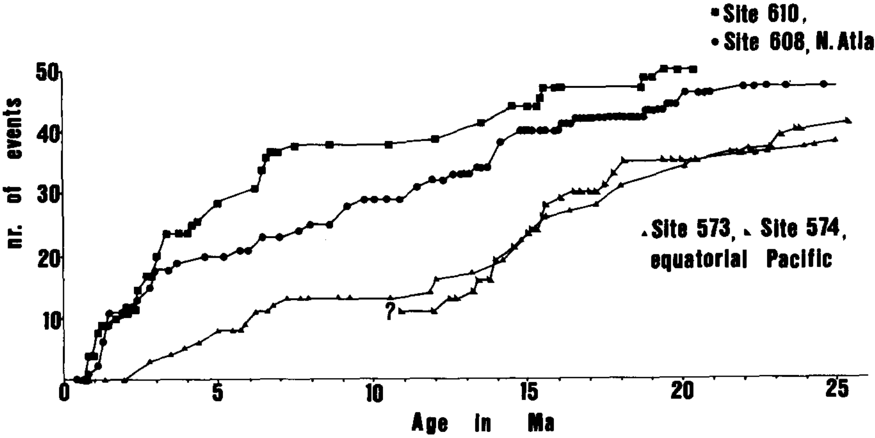

Fig.2. Faunal events plotted cumulatively versus time for two North Atlantic sites (608, 610) and two equatorial Pacific sites (573, 574). At Site 574 there are no data for the period younger than 10.5 Ma because of strong $CaCO_3$ dissolution. At Site 610 time control is poor for the period older than 4.5 Ma because of intermittent coring.

agreement with those for the other two sites (Thomas, 1985); there are few differences between the sites.

There are more differences between the Atlantic sites, where the difference in present water depth is about 1 km. The time-control at Site 610 is poor before about 4.5 Ma, because of intermittent coring. At both sites there were some events between 19 and 20 Ma, and an increase in the event-rate between about 15.5 and 14 Ma. At Site 608 the event-rate between 3 and 14 Ma was higher than the rate before 20 Ma; there probably was an additional increase in the event-rate between 6 and 7 Ma. After 3 Ma the event-rate increased dramatically. At Site 610 there were few events between 14 and 7 Ma, a strong increase in event-rate between 7 and 6 Ma, and a decreased event-rate between 6 and 3 Ma. After 3 Ma the event-rate increased dramatically, as at Site 608.

Overall there were more events from the early Miocene to today at Site 610 than at Site 608; the "extra" events at Site 610 occurred during the last 2—3 Ma. There are also more events from the early Miocene to today at Site 608 than at the Pacific sites; again the "extra" events occurred during the last 2—3 Ma. The events during the last 2—3 Ma in the North Atlantic are probably associated with the initiation of northern hemisphere glaciation, and will not be discussed in this paper (see Thomas, in press, b). At all sites there was an increase in the event-rate between 7 and 6 Ma. This increase was most pronounced at Site 610. This is the period during which the Mediterranean became isolated from the Atlantic Ocean (Messinian); there was a major, worldwide decrease in the carbon isotopic ratios in foraminiferal tests in this period (Haq et al., 1980; Vincent et al., 1980).

In the late early and early middle Miocene there were relatively high event-rates at all sites, but the timing was different in Atlantic and Pacific. This is shown more clearly in Fig.3, in which the event-rate curves for Site 573 and Site 608 are re-plotted. Those curves show the number of events between 2 Ma and the early Miocene, i.e. the events that occurred during the period of northern hemisphere glaciation are omitted. The difference between the two curves (the stippled area in Fig.3. a) is plotted in Fig.3. b. The numbers of faunal events between the early Miocene and about 2 Ma were abount the same in deep Atlantic and Pacific, but the faunal changes started earlier in the Pacific (at about 18 Ma, versus about 15.5 Ma in the North Atlantic). The number of events per time unit was low and about the same in Pacific and Atlantic between 25 and 18 Ma, but more events occurred at Site 573 after 18 Ma, i.e. the difference between the two curves increased. Between about 15 and 10 Ma the number of events per time unit was about equal at the two sites but higher than between 25 and 18 Ma. After about 10 Ma the event-rate increased at Site 608 and remained about equal at Site 573, so the difference between the curves decreased. The event-rates were essentially identical again after about 9 Ma, until the onset of northern hemisphere glaciation.

In conclusion, the number of first and last appearances of benthic fora-

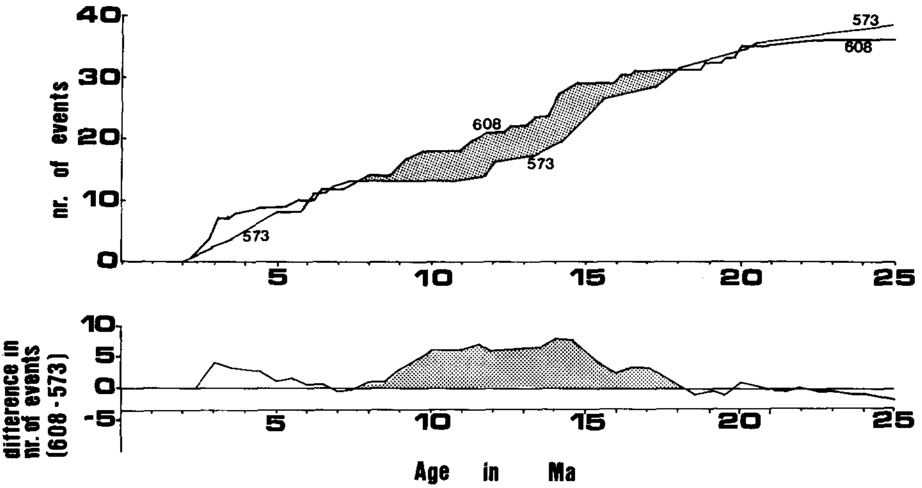

Fig.3. a. Faunal events plotted cumulatively versus time for Sites 573 and 608, for the period between 2 and 25 Ma. Events that are probably related to the initiation of northern hemisphere glaciation are omitted. The stippled area is the area between the two curves in the early to late Miocene. b. The difference in event-rates at Sites 573 and 608 plotted versus time. The stippled area corresponds to the stippled area in Fig.3. a.

miniferal taxa that occurred between the early Miocene and the onset of northern hemisphere glaciation is about the same at all sites. The late Miocene (6—7 Ma) period of faunal change is much more important at the shallower Atlantic site (2.5 km depth) than in the deep Atlantic and deep Pacific. The changes associated with the onset of northern hemisphere glaciation are more pronounced in the North Atlantic than in the equatorial Pacific.

Although the number of events between the early Miocene and about 2—3 Ma was about the same at all sites, the specific faunal events were usually different in timing from one site to another. There are substantial differences even between the three Pacific sites (see Thomas, 1985). All events recognized at the sites are shown in Table I, in time-order for Site 608. Overall, 87 events were recognized, 41 of which could be distinguished at one site only. Seven events were found at all five sites, ten events at four sites, ten at three sites, and 19 at two sites. Non-recognition of a faunal event at a site means that a species does not have a recognizable FA or LA at that site: the species may be too rare, or absent, or present throughout the site. Events recognized at more than one site were not coeval in most cases. Within the time-resolution applicable only two events were synchronous at all five sites: the FA of *Cibicidoides wuellerstorfi* (14.1—15.6 Ma) and the FA of *Ehrenbergina caribbea* (17.5—20.1 Ma). In addition, two events were coeval between Site 608 and all deep Pacific sites: the FA of the *Melonis barleeanus* group (18.2—20.1 Ma) and the FA of *Melonis pompilioides* (11.8—13.1 Ma). In the early to middle Miocene the only events synchronous at the two

Atlantic sites are the two events coeval at all five sites. Many faunal events occurred earlier in the Pacific than in the Atlantic.

Similarity of the faunas at Sites 573 and 608 to present-day faunas is shown in Fig.4; the similarity is defined as the relative abundance of specimens belonging to species that are present in a sample from the mudline at the same site. In this plot the importance of the abundant species is shown, whereas in Figs.2 and 3 the less common species are emphasized. Apparent is the high relative abundance of *Bolivina* spp. at Site 608 between 18.5 and 17 Ma. At Site 573 the faunal composition changed from 60—70% similarity to a mud-line sample to 85—95% similarity between about 18 and 15 Ma. The faunal changes at Site 608 started later than those at Site 573: at Site 608 the similarity changed from about 60– 70% to about 70—80% at 15—14 Ma, then changed gradually and with large fluctuations to about 90% similarity at about 6 Ma. At Site 573 the fauna reached 90% similarity at about 15 Ma, but it took until 6 Ma before the same similarity was reached at Site 608. Relative abundances of specimens, belonging to species that had a FA during the last 25 Ma are plotted on the left-hand side of Fig.4; these abundances were more similar for Pacific and Atlantic than the similarity plotted on the right-hand side of the figure. Therefore the larger similarity of faunas between 14 and 6 Ma to present day faunas in the Pacific can best be explained by an increase in relative abundance of long-lived species in the Pacific, not an increase in "new" species.

The faunal changes in the early to middle Miocene affected about 20—30% of the total fauna (Fig.4). It is a question of semantics whether such a change should be called a major faunal turnover or not: it was a time of relatively large changes in the deep-sea benthic foraminiferal faunas as compared with other periods. In my opinion, however, it cannot be said that the present day fauna originated in the middle Miocene, since many important changes occurred before and after that time, e.g. at the onset of northern hemisphere glaciation.

The change in oxygen isotopic values in the early middle Miocene is centered at about 14.6 Ma (Vincent and Killingley, 1985; Pisias et al., 1985; Barron et al., 1985). The change to heavier values of ^{13}C is centered at about 17 Ma (Vincent and Killingley, 1985; Vincent et al., 1985). Both these isotopics events occurred later and had a shorter duration than the faunal changes. The beginning of the faunal changes in the Pacific appears to be most closely related in time to a period of increased dissolution of $CaCO_3$ at about 18.5 Ma. The comparison between the timing of changes in faunal composition and isotopic change for the Pacific sites in given in Thomas (1985, a).

For Site 608 carbon and oxygen isotopic curves are presented by Miller et al., in press). The change in carbon isotopic values is not easily recognized in the Atlantic; the change to heavier values in oxygen isotopes occurs in cores 34—33 at Site 608, i.e. at the same level as the FA of *C. wuellerstorfi.* The faunal changes in the Atlantic appear to have a closer correlation with

TABLE I

Faunal events at two North Atlantic and three equatorial Pacific sites, in the interval from 0 to 25 Ma. FA: first appearance; LA: last appearance; DA: decrease in abundance. Note: to simplify the table the assigned age is given from the sample in which the faunal event occurs, not the range of uncertainty (distance between two samples). There are no data available from Site 574 for the interval 0—10.5 Ma, and from Site 575 for 0—12 Ma, as a result of severe dissolution of $CaCO_3$. At Site 575 drilling stopped at a level dated at about 22 Ma. The time control for samples from 610 is poor for all samples older than about 4.5 Ma. Bold face indicates faunal events that are coeval (within the time-resolution) at several sites.

Event	Site 610	Site 608	Site 573	Site 574	Site 575
FA *Eponides tumidulus*	2.2	0.8	3.9	—	—
LA *Chrysalogonium tenuicostatum*	0.8	—	—	—	—
LA *Stilostomella consobrina*	0.8	—	5.3	**13.2**	**13.1**
FA *Eponides repandus*	—	**1.1**	—	—	—
LA *Pleurostomella acuminata*	1.1	—	—	—	—
FA *Bolivina subspinescens*	1.1	—	—	—	—
LA *Orthomorphina glandigena*	1.1	—	—	—	—
FA *Cibicidoides variabilis*	7.5	1.3	—	—	—
LA *Pleurostomella obtusa*	**1.7**	**1.3**	2.8	12.5	—
LA *Stilostomella annulifera*	**1.1**	**1.3**	—	—	—
LA *Stilostomella lepidula*	0.8	1.3	—	—	—
LA *Textularia agglutinans*	1.3	—	—	—	—
LA *Bolivina pseudoplicata*	—	1.5	—	—	—
FA *Ehrenbergina trigona*	6.6	1.5	—	—	—
LA *Pleurostomella acuta*	—	1.5	**15.6**	**16.5**	**15.8**
LA *Pleurostomella alternans*	—	1.5	5.0	—	—
LA *Pleurostomella bolivinoides*	0.8	1.5	—	—	—
FA *Stainforthia complanata*	5.0	**2.1**	**2.8**	—	—
FA *Quinqueloculina venusta*	—	2.4	—	—	—
FA *Hopkinsina pacifica*	2.4	—	—	—	—
FA *Hoeglundina elegans*	2.4	—	—	—	—
LA *Bulimina microcostata*	2.7	—	24.0	—	—
FA *Nonionella atlantica*	2.7	—	—	—	—
FA *Globocassidulina decorata*	—	—	2.8	—	—
FA *Pyrgo elongata*	**2.2**	**2.8**	—	—	—
FA *Pyrgo lucernula*	5.0	2.8	—	—	—
LA *Ehrenbergina caribbea*	4.1	3.0	—	—	—
FA *Sigmoilopsis schlumbergeri*	14.5	3.0	—	—	—
FA *Cassidulina teretis*	3.0	—	—	—	—
DA *Cibicidoides kullenbergi*	3.0	—	—	—	—
LA *Uvigerina graciliformis*	3.0	—	6.8	—	—
LA *Ehrenbergina trigona*	3.3	—	—	—	—
LA *Melonis affinis*	3.3	—	—	—	—
LA *Uvigerina bononiensis*	3.3	—	—	—	—
FA *Quinqueloculina pygmea*	—	3.7	—	—	—
LA *Stilostomella subspinosa*	—	4.6	6.2	—	—
DA *Cibicidoides mundulus*	5.0	—	—	—	—
LA *Bigenerina nodosaria*	19.5	5.7	13.2	**15.0**	**15.0**
FA *Eponides pusillus*	—	—	5.9	—	—

TABLE I (continued)

Event	Site 610	Site 608	Site 573	Site 574	Site 575
LA *Cibicidoides wuellerstorfi* var. C	—	—	6.2	—	—
LA *Cibicidoides trinitatensis*	6.2	—	—	—	—
LA *Fursenkoina cylindrica*	6.2	—	—	—	—
FA *Pyrgo murrhyna*	**6.4**	**6.4**	—	—	—
LA *Stilostomella abyssorum*	—	6.4	**14.2**	**13.2**	—
LA *Cibicidoides* cf. *kullenbergi*	6.4	—	—	—	—
FA *Bolivina translucens*	15.5	7.6	7.2	—	—
LA *Nonion havanense*	6.6	8.0	18.0	**14.0**	**15.0**
LA *Bolivina striatula*	—	9.2	**15.6**	**15.5**	**16.4**
LA *Bulimina alazanensis*	—	9.2	—	—	—
FA *Pyrulina cylindroides*	—	9.2	—	—	—
DA *Anomalina spissiformis*	13.5	9.7	**22.0**	**21.6**	—
LA *Bolivinopsis cubensis*	**14.5**	11.4	**14.8**	**15.0**	**15.1**
FA *Sigmoilina tenuis*	—	11.4	—	—	—
LA *Cibicidoides laurisae*	—	11.9	**17.2**	**17.8**	**17.7**
FA *Uvigerina bononiensis*	12.0	—	—	—	—
FA *Cibicidoides wuellerstorfi* var. C	—	—	12.0	—	—
FA *Melonis pompilioides*	4.3	**12.6**	**11.8**	**12.5**	**13.1**
LA *Vulvulina spinulosa*	—	—	17.2	**13.4**	**13.1**
FA *Quinqueloculina compta*	—	13.4	—	—	—
FA *Francesita advena*	**13.5**	—	**14.8**	**14.0**	**14.0**
LA *Amphicoryna hirsuta*	—	—	20.1	15.5	13.8
LA *Cibicidoides grimsdalei*	—	—	**14.2**	**14.0**	**15.0**
LA *Cibicidoides havanense*	—	14.1	—	—	—
FA *Cibicidoides wuellerstorfi*	**14.5**	**14.1**	**15.6**	**15.6**	**15.0**
FA *Eilohedra weddellensis*	6.4	14.1	—	—	—
FA *Ophthalmidium pusillum*	—	14.1	—	—	—
FA *Heronallenia lingulata*	—	—	15.6	14.5	16.6
LA *Cibicidoides perlucidus*	—	**14.8**	12.0	**15.0**	**15.0**
LA *Gyroidinoides girardanus*	—	**14.6**	5.0	**15.6**	**13.8**
LA *Fursenkoina mexicana*	15.4	—	—	—	—
FA *Bulimina elongata*	15.5	—	—	—	—
LA *Cassidulina havanensis*	—	—	**14.8**	**14.5**	16.4
LA *Bolivina spathulata*	2.0	16.1	—	—	—
LA *Cibicidoides mexicanus*	—	—	**18.0**	**17.8**	—
FA *Cibicidoides cicatricosus*	6.7	16.6	4.4	—	—
FA *Ehrenbergina caribbea*	**18.8**	**18.9**	**20.1**	**17.5**	**19.7**
FA *Stilostomella annulifera*	18.8	—	—	—	—
FA *Bolivina spathulata*	—	19.6	—	—	—
FA *Melonis barleeanus* group	3.0	**20.1**	**20.1**	**18.2**	**19.7**
FA *Uvigerina peregrina*	—	20.1	—	—	—
LA *Buliminella carteri*	—	—	20.3	—	—
FA *Bolivina striatula*	—	22.0	**18.0**	**18.2**	**18.6**
LA *Cibicidoides* aff. *mundulus*	—	—	—	22.2	—
FA *Sphaeroidina bulloides*	—	—	—	23.2	—
FA *Uvigerina graciliformis*	—	—	26.2	23.2	—
LA *Cibicidoides pseudoungerianus*	—	—	23.7	—	—
FA *Laticarinina pauperata*	—	—	25.0	31.2	—

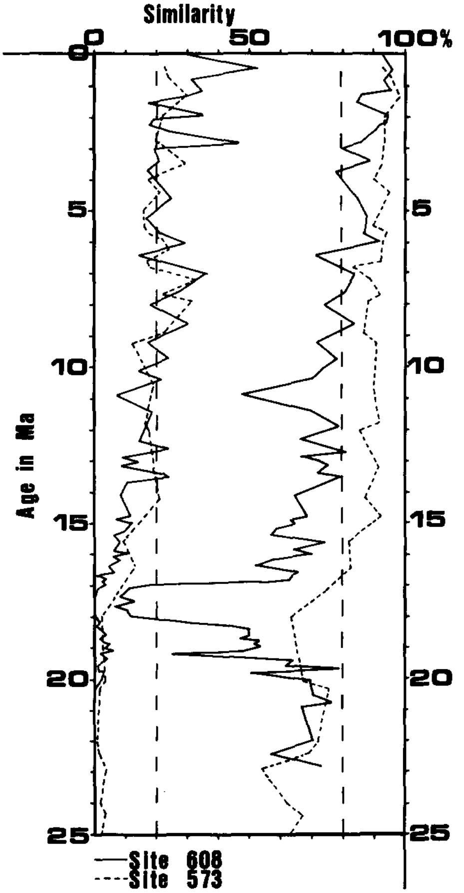

Fig.4. Similarity of the benthic foraminiferal faunas at Sites 573 and 608 to mud-line samples from the same sites. The right-hand curves give the relative abundance of specimens belonging to species that are present in a mud-line sample. The left-hand curves show the relative abundance of specimens that belong to species that have a First Appearance (FA) during the last 25 Ma. The area between the curves gives the relative abundance of long-lived species. At (time = 0) the right-hand curves do not intersect at 100%, because the range of rare species cannot be ascertained.

the isotopic events than the events in the Pacific, but even in the Atlantic several important faunal events predated the isotopic event; e.g. the FA of the *Melonis barleeanus* group (20.1 Ma) and the FA of *Ehrenbergina caribbea*. Some faunal events postdated the isotopic events, e.g. the FA of *Melonis pompilioides* (12.6 Ma at Site 608). The FA of *Cibicidoides wuellerstorfi* is the only faunal event that appears to be synchronous with the increase in oxygen isotopic values in both Pacific and Atlantic.

CONCLUSIONS

(1) Major faunal changes occurred in the deep-sea benthic foraminiferal faunas in Atlantic and Pacific in the early to middle Miocene, but the changes affected only 20—30% of the total fauna.

(2) The patterns of faunal change (the number of First Appearances and Last Appearances) were similar at all sites, but specific FA's and LA's were rarely synchronous at sites.

(3) The faunal changes started earlier in the Pacific (about 18 Ma) than in the Atlantic (about 15.5 Ma).

(4) There is no simple, globally valid correlation between changes in composition of benthic foraminiferal faunas and isotopic events. Commonly faunal changes predated isotopic changes. The FA of *Cibicidoides wuellerstorfi* seems to be related to the major increase in oxygen isotopic values in the early middle Miocene.

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