Oligocene to Miocene benthic foraminiferal and abyssal circulation changes in the North Atlantic

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ABSTRACT: We reconstructed Oligocene-Miocene abyssal circulation changes in the North Atlantic using seismic, isotope, and sediment accumulation data, and evaluated the response of benthic foraminifera to these abyssal circulation changes. North Atlantic Oligocene-early Miocene abyssal benthic foraminiferal assemblages were relatively stable, showing few first or last occurrences. Late Oligocene subsidence at Sites 558 and 563 caused the local disappearance of a buliminid assemblage. *Nuttallides umbonifera* increased in abundance at the deepest locations (Sites 10, 119, 400; >3.5 km paleodepth) during the “middle” Oligocene in response to increased carbonate corrosivity and reduced bottom-water supply to the North Atlantic. A period of accelerated faunal change (disappearances) lasted from about 16 to 13.5 Ma (late early to early middle Miocene) at Sites 558 and 563; benthic foraminiferal relative abundance and flux changes began earlier, at 17 Ma and 19 Ma, respectively. These benthic foraminiferal changes correspond with a series of productivity and bottom-water changes. We speculate that increased primary productivity triggered these changes. The benthic foraminiferal taxonomic composition at Sites 558 and 563 have remained essentially unchanged from 13.5 Ma to the present.

INTRODUCTION

Studies of deep-sea benthic foraminifera were primarily of a taxonomic nature until the 1970’s. Streeter (1973) and Schnitker (1974) first established correlations between modern deep-water masses and deep-sea benthic foraminiferal distributions, raising expectations that these correlations would allow micropaleontologists to decipher Quaternary and Tertiary water-mass changes. Deep-sea water masses have small temperature-salinity variations on the order of tenths of a degree Celsius and less than a part per thousand salinity. Benthic foraminifera presumably are not sensitive to such small differences. Benthic foraminiferal-water mass correlations probably exist because water masses are associated with other physio-chemical properties (e.g. dissolved O2, total CO2, nutrients, corrosivity to carbonate). Since these properties may vary spatially along the path of a water mass and may vary through time, benthic foraminiferal-water mass correlations may not be unique. Although changes in bottom-water conditions affect benthic foraminifera, using benthic foraminiferal changes alone to reconstruct bottom-water changes potentially may result in equivocal results.

More recent studies have attempted to isolate controls on benthic foraminiferal distributions by examining a multitude of physio-chemical parameters. Correlations have been established with dissolved oxygen, sedimentary substrate and degree of carbonate availability (Lohmann 1978; Corliss 1979; Schnitker 1979; Bremer and Lohmann 1982; Miller and Lohmann 1983). Still, it is not clear whether these properties control distribution. This ambiguity has hindered attempts to characterize bottom-water changes using benthic foraminiferal assemblage changes. For example, *Uvigerina perigrina* Cushman expanded throughout the abyssal North Atlantic during the last glacial maximum. Because this taxon is associated with low oxygen in the water column in the South Atlantic (Lohmann 1978), it was suggested that glacial North Atlantic bottom waters were low in oxygen due to the complete shutdown of North Atlantic Deep Water (NADW) production (Streeter and Shackleton 1979). However, carbon isotopic and cadmium data suggest that there was a source of nutrient-depleted, oxygen-rich bottom water to the glacial North Atlantic, albeit at a reduced rate (Boyle and Keigwin 1982; Mix and Fairbanks 1985).

Initial studies of Tertiary deep-sea benthic foraminifera recovered by the Deep Sea Drilling Project pointed to three major periods of faunal change: near the end of the Paleocene, near the end of the Eocene, and in the middle Miocene (Berggren 1972; Schnitker 1979). Further studies have delineated the nature and timing of these foraminiferal changes.

1. The most dramatic Tertiary taxonomic turnover in the Atlantic and Pacific oceans occurred near the Paleocene/ Eocene boundary (Schnitker 1979; Tjalsma and Lohmann 1982; Miller et al. 1986). The cause of this change is unknown, but it may be related to climatic changes at the end of the Paleocene (Shackleton et al. 1984; Miller et al. 1986).

2. A faunal abundance change occurred throughout the deep sea just after the middle/late Eocene boundary; a series of last occurrences followed. The faunal changes were gradual and not so dramatic as the Paleocene/Eocene boundary event. The changes occurred in the Atlantic, Pacific, and Indian oceans and predated a large benthic oxygen isotopic increase (Tjalsma and Lohmann 1983; Miller 1983; Corliss et al. 1984; Miller et al. 1985b; Thomas 1985; Wood et al. 1985).

3. Woodruff (1985) and Schnitker (1986) noted a faunal turnover between about 16 and 13 Ma in the Pacific and Atlantic oceans, respectively, and suggested that this was related to a major 813O increase. Thomas (in press a, in press b) and Katz and Miller (1985) noted a similar overturn in the North Atlantic, but pointed out that the faunal changes began before the oxygen isotopic increase. Thomas (1985) noted that the changes in the Pacific began even earlier (ca 17 Ma).

These three intervals of benthic foraminiferal turnover did not coincide with the largest Tertiary 813O changes which occurred in the earliest Oligocene (36–35 Ma) and middle Miocene (14.8–13.5 Ma). Our goal is to determine what triggered these faunal changes. In this contribution, we concen-
trate on Oligocene-Miocene faunal changes in the North Atlantic.

We use comparisons of carbon isotopic records (Miller and Fairbanks 1985; Miller et al. 1986b), seismic stratigraphic studies (Miller and Tucholke 1983; Mountain and Tucholke 1985), and sediment accumulation data (this study) to reconstruct the history of Cenozoic North Atlantic abyssal circulation. We identify benthic foraminiferal changes and attempt to evaluate the response of Oligocene-Miocene benthic foraminifera to changes in abyssal circulation. Our approach will be threefold: 1) to examine relative abundance (percentage) changes of benthic foraminifera in the western North Atlantic in the most complete Oligocene-Miocene sections available; 2) to determine the significance of absolute accumulation rate (flux) changes (number/cm²/kyr) of taxa in these samples; and 3) to evaluate the stratigraphic turnover (appearances and disappearances) of taxa.

METHODS

Benthic foraminifera were studied from Oligocene to Miocene samples recovered from two Deep Sea Drilling Project Sites drilled in the western North Atlantic (text-fig. 1): Sites 558 (37°46’N, 37°21’W, 3754 m present water depth; 26 samples) and 563 (33°39’N, 43°46’W, 3796 m present water depth; 51 samples). These sites were chosen for their relatively continuous, well-preserved, deep-sea carbonate sequences (Bougault, Canè et al. 1985; Miller et al. 1985b). Prior to the drilling of these sites, there were no continuously cored, relatively complete Oligocene-Miocene sequences from the deep North Atlantic. In addition to the records from Sites 558 and 563, we used published data from Sites 119 (45°01.9’N, 7°58.49’W, 4447 m present water depth) and 400 (47°22.9’N, 09°11.9’E, 4399 m present water depth) in the Bay of Biscay (Miller 1983), and new data from Site 10 (32°37’N, 52°20’W, 4697 m present water depth; three samples) in the western North Atlantic to reconstruct the distribution of Nautallax umbonifera (Cushman) during the Oligocene (text-fig. 1).

Samples were soaked in a hydrogen peroxide solution (3%) and washed through a 63-μm sieve with a sodium hexametaphosphate solution. Aliquots from the greater than 149 μm size-fraction were picked for benthic foraminifera and mounted on reference slides. Approximately 300–500 specimens were picked whenever possible, but several samples contained 100–300 specimens (tables 1, 2).1

The benthic foraminifera were identified using the taxonomy outlined in the taxonomic notes (see “Systematic Paleontology”). The taxonomic base was derived from Miller (1983), Tjalsma and Lohmann (1983), and Tjalsma (1983). We made required taxonomic changes following examination of material at the U.S. National Museum (Miller and Berggren, unpublished) and various European collections (Berggren, pers. comm. 1984, 1985; see van Morkhoven et al. 1986, for discussions of museum collection comparisons).

1 All tables mentioned herein may be obtained from Micropaleontology Press or the authors.

We compared taxonomic ranges from our western North Atlantic sites with ranges reported elsewhere (text-figs. 8–10), including the eastern North Atlantic (Miller 1983; Miller et al. 1985a; Belanger and Berggren 1986; Thomas 1986a, b), Caribbean (Wood et al. 1985; Miller, unpublished), South Atlantic (Tjalsma 1983), and Pacific oceans (Douglas 1973; Douglas and Woodruff 1981; Thomas 1985; Woodruff 1985). Some of the more significant results are reported here; details of these comparisons are provided in van Morkhoven et al. (1986).

The census data are presented as a percentage of total benthic foraminifera counted (tables 1, 2). We used computer programs provided by Lohmann (1980 and pers. comm., 1982).

We conducted Q-mode Principal Components and Varimax Factor Analyses on relative abundance data. Our census data and multivariate analyses of Site 558 samples showed considerable scatter. We therefore report quantitative analyses primarily from Site 563. Loadings from two western North Atlantic trigger weight core tops (V17-165TW, 6–10 cm, 32°45’N, 41°54’W, 3924 m; V27-263TW, 4–8 cm, 35°00’N, 40°55’W, 3704 m) (text-fig. 1) were projected onto the Site 563 Q-mode vectors in order to determine when the present-day fauna developed. These loadings are components of sample vectors defined by the modern relative abundance data projected onto the coordinate system defined by the Site 563 vectors.

The comparison of relative abundance data with absolute abundance data is critical in evaluating the nature of faunal changes (Lohmann and Curry 1983). We calculated absolute accumulation rates (fluxes) of taxa at Site 563 using estimates of sedimentation rate, estimates of wet bulk density, and number of foraminifera per gram of sediment (table 3)2 in the form number/cm²/kyr. Our sedimentation rate estimates are based upon good magnetobiostratigraphic control, making them reliable compared with other Tertiary studies. However, these estimates are still coarse, relative to Quaternary piston-core studies.

High-frequency (10¹–10³ yr) changes in sedimentation rate and flux occurred in the Quaternary (Lohmann and Curry 1983). Even though similar changes may have occurred in the Oligocene and Miocene, our comparisons of flux and percentage data allow us to evaluate the importance of gross changes in sedimentation rate and absolute accumulations (#/cm²) on relative abundance data.

Q-mode Principal Components and Factor Analyses use a Cosine-theta matrix, standardizing each sample to unit length. Therefore, the Q-mode analysis translates data into relative abundances and is not appropriate for flux data. R-mode analysis is more appropriate, and can be performed upon three different expressions of the data by: 1) computing a cross-products matrix of raw flux data, taxa with highest absolute abundances being emphasized; 2) computing a covariance matrix of flux data with a zero mean, taxa with the highest variances being emphasized; 3) computing a correlation coefficient matrix of flux data with zero mean and unit variance, all species contributing equally to the analysis.

2 Table 3, containing absolute abundance parameters, may be obtained from Micropaleontology Press or the authors.
Each species vector of the absolute accumulation rate data from Site 563 was normalized to zero mean and unit variance, and an R-mode Principal Components Analysis was performed. This method was chosen because it emphasizes the patterns of change of all taxa, and is not controlled by the most abundant taxa.

Stratigraphic control for Sites 558 and 563 (text-fgs. 3a–c) is provided by magnetostratigraphy (Khan et al. 1985; Miller et al. 1985b) and biostratigraphy (planktonic foraminifera: Miller, Melillo, Berggren in Miller et al. 1985a; nannofossils: Aubry in Miller et al. 1985a). Stratigraphically useful planktonic foraminifera are illustrated (pls. 10–13) to document the taxonomic concepts used in developing the biostratigraphy. The nannofossil zonation follows Martini (1970). The planktonic foraminiferal scheme is a modification of Blow's (1969, 1979) and Bolli's (1957) zonations. Neither zonation is satisfactory in view of recent first-order magnetostratigraphic correlations (Poore et al. 1983; Miller et al. 1985a). However, we have found the following planktonic foraminiferal datum levels to be useful when compared with other magnetobiostatigraphic correlations (e.g. Poore et al. 1983; Berggren et al. 1985), and give approximate correlations to the zones of Blow and Bolli; a formal recodification of zonal schemes is in progress (Berggren and Miller, in prep.):

1. Last occurrence (LO) of Hantkenina spp. and LO Globorotalia cerroazulensis = top of the Eocene, base of Pseudohastigerina micra-Cassigerinella chipolensis Zone.

2. LO of Pseudohastigerina spp. = top of Pseudohastigerina micra-Cassigerinella chipolensis Zone. We observed that the first occurrence (FO) of Subbotina sellii (Borsetti) (= base P19 of Blow 1969) occurred at the same level as the LO of Pseudohastigerina (text-fig. 3a), indicating that P18 is equivalent to the P. micra-C. chipolensis Zone and that Zone P19 as defined (the interval from the FO S. sellii to the LO of Pseudohastigerina; Blow 1979) may not be a valid zone.

3. FO of Globigerina angulisuturalis Bolli = base of Zone P21a.

4. LO of Chilouquembelina spp. = base of Zone P21b.

5. LO Globorotalia opima opima Bolli = base of Zone P22 = base of Globigerina eiperoensis Zone.
6. FO Globorotalia kugleri Bolli = base of the Miocene = base of G. kugleri Zone (sensu Bolli, not sensu Stainforth et al. 1975).
7. LO Globorotalia kugleri = base of Zone N5 = base of Catapsydrax dissimilis Zone.
8. LO Catapsydrax dissimilis (Cushman and Bermudez) = base of Zone N7 = base of Globigerinatella insigna Zone.
9. FO Globigerinoides sancua de Stephani = base of Zone N8.
10. FO Praeorbulina glomerosa (Blow) = base of P. glomerosa Zone.
11. FO Orbulina suturalis Bronnimann = base Zone N9.
12. FO Globorotalia foehsi lobata Bermudez = base G. foehsi lobata Zone.
13. FO Globorotalia foehsi robusta Bolli = base G. foehsi robusta Zone.
14. LO Globorotalia foehsi spp. and FO Globigerina nepentes Todd = base Zone N14 and base Globorotalia mayeri Zone (coincident in our sites).
15. LO Globorotalia siakensis Lercy/mayeri Cushman and Ellisor = base of N15 and base of Globorotalia menardii Zone.
16. FO Neogloboquadrina acostaensis Blow = base Zone N16 and N. acostaensis Zone.

The LO Globorotalia siakensis/mayeri and the FO Neogloboquadrina acostaensis Blow are virtually coincident in our sites; therefore, Zone N15 as defined is missing or extremely condensed, although the section is apparently continuous through this interval (text-figs. 3a, c). In addition, we found that the FO of Orbulina coincided with the FO of Globorotalia peripherocuta Blow and Banner (Zone N9 is missing), and that the LO Globorotalia foehsi spp. coincided with the FO Globigerina nepentes Todd. Globigerinatella insigna Cushman and Stainforth is too rare to be biostratigraphically useful at our sites.

Ages are assigned using the geomagnetic polarity time scale (GPTS) of Berggren et al. (1985) by interpolating between magnetostratigraphic and biostratigraphic levels. The age model used for Site 563 is given by Miller et al. (1986b, model 1); that for Site 558 is given by Miller and Fairbanks (1985). Although stratigraphic control is good in general, uncertainties in correlations remain. For example:
1) Coring gaps, drilling disturbance, and possible magnetic overprinting complicate magnetostratigraphic interpretations (Khan et al. 1985). Gaps are prevalent in the Miocene at Site 558 and the “middle” Oligocene of Site 563.
2) The middle Miocene section at Site 563 contains a predominately normal interval (205–242 m subbottom); yet the middle Miocene of the GPTS contains a number of reversed intervals. Either the time correlative with these reversed intervals is missing at Site 563, or the section is disturbed.
3) Comparison of oxygen isotopic records from the middle Miocene of Sites 563 and 608 (eastern North Atlantic) suggests that there are a number of short (less than 1 m.y.) hiatuses at Site 563 (Miller et al. 1986b).

Isotopic analyses at Sites 558 and 563 were performed on samples of the benthic foraminiferal taxon Cibicidoides spp.—including Planulina wuellerstorfi (Schwager). Comparisons of isotopic data from these sites with Pacific Sites 77, 289, and 574 and with eastern North Atlantic Sites 608 and 119 are discussed by Miller and Fairbanks (1983, 1985), Miller and Thomas (1985), and Miller et al. (1986b).

Paleodepth estimates were calculated by backtracking (Sclater et al. 1971, 1977; Berger and Winterer 1974; Parsons and Sclater 1977) assuming simple thermal subsidence:

\[
Pd = Id + kt^a - S
\]

where \(Pd\) = paleodepth, \(Id\) = initial depth, \(t\) = (age base\(-ment - age of level considered), \(S\) = sediment correction of 0.66 \times \text{(basement depth subbottom - depth subbottom of level considered)}, \text{and} k = a constant derived from empirical age versus subsidence curves. Knowing \(k\) and present depth (\(Pr\), initial depth for a site can be computed:

\[
Id = Pr - kt^b + S
\]

For the western North Atlantic, \(k\) has a value of 300 (computed from data of Tucholke and Vogt 1979, solving equation 1 for \(k\), assuming \(Id = 2650\) m). These equations are valid for crustal ages less than about 80 Ma (Parsons and Sclater 1977), which includes Sites 563 and 558. The assumption of simple thermal subsidence at Site 558 and 563 appears to be valid, for these sites lie upon normal oceanic crust (Bougault, Cande et al. 1985). They subsided from approximately 2200–2400 m in the earliest Oligocene (35 Ma) to 3200 m in the latest Oligocene (24 Ma) to and 3600 m in the late middle Miocene (11 Ma) (text-fig. 2).

Carbonate flux rates for Sites 563, 558, and 608 were estimated roughly using widely spaced shipboard carbonate bomb data (Bougault, Cande et al. 1985; Ruddiman, Kidd et al. 1986), shipboard wet bulk density, and estimates of sedimentation rate. Uncertainties in sedimentation rates are the same as for benthic foraminiferal flux estimates (see above); however, the coarseness of the carbonate bomb data allows determination of only the broadest trends in carbonate flux.

RESULTS
Preservation
In general, benthic foraminifera at Sites 558 and 563 are well preserved, but dissolution, diagenesis, and stratigraphic mixing occur in some intervals, limiting resolution. Boersma (1985), for example, suggested that the Oligocene fauna at Site 563 was not representative of benthic production. To evaluate the state of preservation at Sites 558 and 563 we computed two dissolution indices: 1) \#fragments of planktonic foraminifera/(\#fragments + \#whole planktonics); 2) \#benthic foraminifera/(\#benthics + \#planktonics).

Increased dissolution causes increased fragmentation and increased percentages of benthics as the more fragile planktonics are preferentially dissolved (see Peterson and Prell 1985 for discussion of dissolution indices).

Background levels of dissolution indices at Site 563 are approximately 20–30% fragments and less than 2% benthics (text-fig. 4). Dissolution intervals (>50% fragments, >5% benthics) occur at the base of the Oligocene, within the lower Miocene (below an unconformity), and below the middle/upper Miocene boundary (text-fig. 4). A sharp increase in
fragmentation and percent benthics is associated with the foraminiferal lysoclinc in the modern ocean (e.g. Berger 1970; Peterson and Prell 1985). The relatively low background values for fragments and benthics (cf. text-fig. 4 and fig. 4 in Peterson and Prell 1985) indicate that Site 563 lay at or above the lysoclinc except during periods of increased dissolution in the early Miocene and late middle Miocene (text-fig. 2).

We ascribe the basal Oligocene dissolution interval to interaction with basaltic basement. At both Sites 558 and 563 the lowermost cores overlying basement show signs of alteration and poorer preservation; large overgrowths of calcite are especially pronounced in the lowermost sedimentary section at Site 558. Poorer preservation of the lowermost Oligocene at Site 563 is exemplified by the high percentage of planktonic fragments (text-fig. 4) and rare crystalline overgrowths (pl. 10, fig. 5b).

The relatively complete Miocene section at Site 563 provides a good record of faunal changes; the coherent, smoothly varying fluctuations appear to be unrelated to dissolution indices (text-fig. 4). The Oligocene stratigraphic section at Site 558 is more complete than that at Site 563; however, the dissolution indices (text-fig. 5) and relative abundance data at this site show considerable scatter. Similarly, we have noted that stable isotopic data from Site 558 showed greater scatter and evidence of diagenesis than the record at Site 563 (Miller and Fairbanks 1985). We attribute this scatter to greater stratigraphic mixing and the presence of more lithified intervals at Site 558. We emphasize the record at Site 563 in our faunal analyses, and use the record at Site 558 in a supporting role.

Stratigraphic ranges

Many of the taxa identified at both Sites 558 and 563 are long ranging, occurring throughout the Oligocene-Miocene section. Approximately 34 out of 88 taxa identified range throughout the section at Site 563. This estimate may overemphasize long-ranging taxa because we did not split genera with numerous species but low abundances (e.g. Lagena, Fissurina, Dentalina) or with uncertain taxonomy (e.g. Operculina, Gyroidinoides, Lenticulina). Still, many species show continuous ranges. Therefore, there was no catastrophic taxonomic turnover in the Miocene at Sites 558 and 563, in agreement with Boltovskoy (1980) and Thomas (1985).

Stratigraphic ranges at both sites show no interval of increased number of FO (text-figs. 6, 7); however, ranges at both sites show two distinct patterns:

1) a series of gradual LO in the Oligocene, resulting from the loss of various taxa characteristic of the upper abyssal zone (e.g. buliminids, Osangularia spp., Hanzawaia ammophila...
TEXT-Figure 3a

(Guesmbel), and Gavelinella micra (Bermudez; Tjalsma 1983; Miller et al. 1985a). We attribute this to Oligocene subsidence of Sites 558 and 563 from the upper to lower abyssal zones (text-fig. 2).

2) a locus of LO within the middle Miocene (text-figs. 6, 7), beginning at about 16 Ma (base of Chron C5br; Zone N8; near Zone NN4/NN5 boundary) near the early/middle Miocene boundary. This faunal "turnover" lasted until about 13 Ma (Chron C5AA; Zone N12; Zone NN7).

Many of the LO between 16 and 13 Ma (middle Miocene) at Sites 558 and 563 may be local, not true, extinctions. A similar pattern of an increased number of LO in the middle
Miocene has been noted in the Pacific (Thomas 1985; Woodruff 1985) and eastern North Atlantic oceans (Thomas 1986a, b; Schnitker 1986), although many of the taxa with LO differ from site to site. Nevertheless, comparison of ranges among various Atlantic, Pacific, and Caribbean deep-sea locations suggests that many taxa characteristic of the Paleogene became extinct in this interval: Cassidulina havanensis Cushman and Bermudez, Anomaloides semimembratus (Beckman), Cibicidoides havanensis (Cushman and Bermudez), Buliminella grata Parker and Bermudez, Bulimina jarvisi Cushman and Parker, and Anomaloides pseudogrosserosus (Colom) (text-figs. 6–10). Bolivina huneri Howe last occurred at Site 563 at ca. 13.8 Ma (Globorotalia fohsi fohsi Zone); this is the youngest reported occurrence of this taxon and may also be a true extinction. *Vulvulina spinosa* Cushman became extinct slightly later (about 11.5 Ma; see taxonomy section). This taxonomic turnover represents one of the three major intervals of increased benthic foraminiferal changes in the Cenozoic, although the change was not precipitous. The faunal change apparently began at Site 563 at least 1 m.y. before the sharp increase in oxygen isotopes (text-fig. 6). Thomas (1986) reported that the disappearances in the Pacific began earlier than those in the Atlantic, and therefore pre-dated the δ18O increase by several m.y. Almost all species found in modern core tops V17-165TW and V27-263TW had appeared by the middle Miocene at Site 563; thus, late middle Miocene assemblages are taxonomically similar to modern assemblages.
Comparison of ranges

Comparison of benthic foraminiferal stratigraphic ranges from Atlantic and Pacific bathyal to abyssal DSDP sites and outcrop sections shows that some taxa exhibit first and last occurrences which are markedly diachronous (text-figs. 9–10). For example, the LO of *Cibicidoides grimsdalei* (Nuttall) varies from Zone P18 (earliest Oligocene) to Zone P22 (latest Oligocene) as a function of increasing paleodepth (text-fig. 9). *Melonis sphaeroides* Voloshinova appeared in the Oligocene at upper-middle bathyal locations. In lower bathyal-abyssal locations this taxon first appeared in the middle Miocene, except for sporadic, earlier occurrences (text-fig. 9). *Laticarinina pauperata* (Parker and Jones) varies in FO from Zone P21 to N11, probably as a function of sampling of this rare species (text-fig. 9).

The FO and LO of many taxa are synchronous (within 1–2 m.y. resolution) from site to site, occurring within one to two planktonic foraminiferal zones. *Planulina wuellerstorfi* consistently appeared near the beginning of the middle Miocene (late Zone N8 to Zones N9–10; text-fig. 8). *Anomalinaoides pseudogrosserugosus* (LO Zones N9–10) and *Bulimina grata* (LO Zones N8–11) show last occurrences which are remarkably consistent. *Cassidulina havanensis* consistently disappeared near the early/middle Miocene boundary (Zones N7–8). *Gavelinella micra* last appeared in the early “middle” Oligocene (Zones P18–P21b). *Cibicidoides eocaenus* (Guembel) disappeared in the late Oligocene.

Even taxa which show local LO and FO may be biostratigraphically useful. For example, the presence of *Cassidulina havanensis*, *Cibicidoides havanensis*, *Bulimina impendsens* Parker and Bermudez, *B. jarvis* Cushman and Parker, *Hanzawaia ammophila* (Guembel) (text-fig. 10), and *Bulimina tuxpanensis* Cole (not shown) indicate middle Miocene or older strata; although these taxa may be locally absent in the Oligocene-lower Miocene, their absence is not age diagnostic.
TEXT-Figure 4
Percent planktonic fragments and percent benthic foraminifera, Site 563. (See Methods and table 4, which can be obtained from Micropaleontology Press or the authors.)

It is clear from comparisons made here that certain benthic foraminifera can provide relatively reliable biostratigraphic markers. Others may be only locally useful. During periods of accelerated turnover such as the middle Miocene, deep-sea benthic foraminifera can be used for developing fairly refined biozonations, with stratigraphic resolution of a stage or better. In periods of slower turnover (such as the Paleocene or late Neogene), biozones will be quite broad, encompassing entire series (Berggren and Miller, in prep.).

Relative abundances
Q-mode Factor Analysis of relative abundance (percentage) data from Site 563 yielded early Oligocene (Factor IV), late Oligocene-early middle Miocene (Factor I), and late middle-late Miocene (Factor II) assemblages (text-fig. 11). Factor III is dominated by *Oridorsalis* spp., and mainly reflects changes in other taxa (the “closed sum problem”; see below). The early Oligocene assemblage was dominated by buliminids (*Bulimina jarvisi*, *B. glomalarchlergeri* Tjalsma and Lohmann, and *B. alazanensis* Cushman) and *Gyroidinoides* spp. (text-fig. 12). This assemblage disappeared as a result of subsidence from upper abyssal to lower abyssal zones. *Pleurostomella* spp. was important throughout the Oligocene (text-fig. 12). The late Oligocene to middle Miocene was dominated by *Globocassidulina subglobosa* (Brady) and *Cibicidoides mundulus* (Brady, Parker and Jones), along with *Cibicidoides lamontdoheryi*, n. sp. (text-figs. 11, 13). An as-
TEXT-Figure 5
Percent planktonic fragments and percent benthic foraminifera, Site 558. (See Methods and table 4, which can be obtained from Micropaleontology Press or the authors.)
Semblage dominated by *Nuttallides umbonifera* and *Planulina wuellerstorfi* developed in the middle Miocene at about 14 Ma (text-figs. 11, 14).

Core-top assemblages at V17-165 and V27-263 have high projected loadings on the *Nuttallides umbonifera*-*Planulina wuellerstorfi* assemblage (Factor II, text-fig. 11). This comparison indicates that an assemblage quantitatively similar (i.e., an *N. umbonifera*-P. *wuellerstorfi* assemblage) to the modern fauna at Site 563 had developed by ca 14 Ma (middle Miocene). The "modern" *N. umbonifera*-P. *wuellerstorfi* assemblage at Site 563 apparently developed in the middle Miocene with sequential increases in abundances of *Pullenia bulloides* (d'Orbigny), *Epistominella exigua* (Brady), *Melonis barleanum* (Williamson), *Planulina wuellerstorfi*, and *Nuttallides umbonifera* (text-fig. 14) and decreased abundances of *Globocassidulina subglobosa* and *Cibicidoides mundulus* (text-fig. 13). The relative abundance changes leading toward the "modern" assemblage began about 17 Ma (text-figs. 11, 13, 14), culminating by about 14 Ma. These changes began before the $^8$O increase in benthic foraminifera (text-fig. 11).

Relative abundance data from Site 558 shows a similar increase in *P. wuellerstorfi*, *E. exigua*, and *M. barleanum* between about 15.5 and 14 Ma (text-fig. 15). However, the high abundances of *N. umbonifera* noted in the upper Miocene at Site 563 were not as pronounced as at Site 558.

**Absolute abundances**

Absolute accumulation rates of benthic foraminifera must be evaluated in order to decipher benthic foraminiferal re-
Stratigraphic ranges of benthic foraminifera at Hole 558. Explanations as for text-figure 6.
**SYNCHRONOUS TAXA**

![Diagram of synchronous taxa](image)

**TEXT-FIGURE 8**
Comparisons of stratigraphic ranges calibrated through planktonic foraminiferal zones to the same time scale (Berggren et al. 1985). X = single, isolated specimen. Dashed line = uncertain or possible range. Horizontal line indicates top or base of range. If no top or base is indicated, taxon ranges to top/base of examined section. Arrow indicates range extends beyond time period illustrated here (i.e., into the Eocene or Pliocene). Data from: Site 116, Belanger and Berggren (1986); Site 119, Miller (1983); Sites 218 and 171, Douglas (1973); Site 515, Tjalsma (1983); Sites 548 and 549, Miller et al. (1985b); Sites 552–555, Schnitker (1986); Sites 558 and 563 (this study); Sites 573–575, Thomas (1985); Sites 608 and 610, Thomas (1986a, b); Trinidad (= Trin.), Cuba, and COST B-2 well, Miller (unpublished); Barbadlos (= Barb.), Wood et al. (1985); Pacific compilation (Pac.), Woodruff (1985). No zonations are available from Woodruff’s compilation, and correlations were made indirectly with time scale.

Response to bottom-water changes. Comparison of Quaternary relative (percent) and absolute accumulation rate (flux) data (Lohmann and Curry 1983) shows that the percentages of many taxa (e.g., *Nuttalildes umbonifera*) reflect their fluxes while the percentages of others (e.g., *Ordorosalis* spp., *Melonis* sp.) may vary independently. The relative abundances of these latter taxa fluctuate merely as a function of changes in the abundances of other taxa (i.e., due to the “closed sum” problem). We computed the flux of benthic foraminifera in order to determine whether the Oligocene-Miocene relative abundance changes noted are indicative of changes in absolute accumulation rates, and to evaluate the reliability of Oligocene-Miocene relative abundance changes for reconstructing faunal response to environmental changes.

R-mode Principal Components Analysis of the flux (absolute accumulation rate) data shows the loss of typical “Paleogene” taxa and the ascent of “modern” taxa in the late early to early middle Miocene (between 19.1 and 13.5 Ma; text-fig. 16). The R-mode analysis of zero mean and unit variance data was chosen because it emphasizes correlations between species, rather than the most abundant taxa (see methods).
The changes suggested by the R-mode analysis (text-fig. 16) are also apparent in the raw flux data. Between ca 19 and 16 Ma, the fluxes of Cibicidoides grimsdalei, Bulimina larvari, C. eocaenius, C. havanensis, Hanzawaia ammolithica (negative loadings, Principal Component I; text-fig. 16) and C. mundulus (negative loadings, Principal Component II; text-fig. 16) decreased while the fluxes of Cassidulinella crassa d’Orbigny, Bolivina antepressa Subbotina, and Anomaloides pseudogrosserugosus increased (positive loadings, Principal Component III). At about 13.5 Ma, the fluxes of Nuttalilides umberi, Uvigerina cf. havanensis Cushman and Bermudez, and Planulina wuellerstorfi increased (negative loadings, Principal Component III, text-fig. 16). Thus, both the absolute and relative abundance data indicate that a major faunal abundance change occurred in the late early to early middle Miocene. However, R-mode analysis of the absolute accumulation rate data shows that the faunal change began by 19 Ma (text-fig. 16); in contrast, Q-mode analysis of the relative abundances suggest a slightly later start (ca. 17 Ma) of faunal changes (text-fig. 11).

The slight discrepancy (17 vs. 19 Ma) in the initiation of the faunal change is in part due to the fact that Q-mode analyses emphasize the most abundant taxa and that the relative abundances of some taxa vary independently of their accumulations. The different methods of analysis (R-versus Q-mode; Principal Components versus Factor Analyses) cannot alone account for the discrepancy, since the raw percentage and flux data show different changes. An R-mode analysis of relative abundance data (not shown) indicates that a Planulina wuellerstorfi-Nuttalilides umbonifera-Meloliot barleeanum assemblage developed between about 17 and 14 Ma. Thus, R-mode Principal Components Analysis of percentage data at Site 563 yields results similar to the Q-mode analysis of percentage data, but different from the R-mode analysis of flux data.

Comparison of absolute and relative abundance data shows that the percentages of many Oligocene-Miocene taxa faithfully reflect their fluxes: Nuttalilides umbonifera, Planulina wuellerstorfi, Pullenata bulloides, Meloliot barleeanum, Epistomillina exigua (cf. text-figs. 14, 17) and Cibicidoides mundulus (cf. text-figs. 13, 18). The percentages of certain others do not as clearly mimic their fluxes (e.g. Globocassidulina subglobosa, cf. text-figs. 13, 18; Gyrotritidae spp., cf. text-figs. 19, 20), while others vary independently of their fluxes (e.g. Oridorsalis spp., Stilostomella spp., cf. text-figs. 19, 20). The relative percentage changes of Oridorsalis spp. strongly influence the Q-mode analysis because this taxon is abundant (text-fig. 11); however, the relative fluctuations of Oridorsalis spp. primarily reflect the "closed sum" problem, rather than changes in its absolute accumulation rate.

DISCUSSION

Deep-water oceanographic setting of the Oligocene-Miocene North Atlantic

We use sediment and foraminiferal accumulation rate data (text-figs. 21, 22), dissolution indices (text-fig. 22), carbon isotopic comparisons (text-figs. 21, 23, 24), and seismic stratigraphic evidence (text-fig. 24) to reconstruct abyssal circulation in the North Atlantic.

Seismic stratigraphic evidence and comparisons of Atlantic and Pacific δ18O records indicate a northern bottom-water source for the North Atlantic throughout much of the Oligocene and Miocene. Beginning in the earliest Oligocene, bottom water entered the North Atlantic across the Greenland-Scotland Ridge, eroding the prominent unconformities Horizon A' and reflector R4 (Tucholke and Mountain 1979; Miller and Tucholke 1983). Comparison of carbon isotopic records between the western North Atlantic and Pacific verifies that nutrient-depleted bottom water analogous to modern North Atlantic Deep Water entered the North Atlantic in the early Oligocene (Miller and Fairbanks 1983, 1985) (text-fig. 23, center panel). This comparison also shows a continued supply of North Atlantic deep water during the Miocene with peak supply at ca 19-18 Ma and 12 Ma (text-fig. 24, isotopic column). Seismic stratigraphic studies show that these North Atlantic deep water peaks are associated with erosional disconformities. Reflectors R2 and X in the northern and western North Atlantic, respectively, are associated with a hiatus between ca 20 and 17 Ma (text-fig. 24).
(Miller and Tucholke 1983; Mountain and Tucholke 1985). Reflector Merlin in the western North Atlantic correlates with the upper middle Miocene (ca 12–11 Ma) peak in deep water supply (text-fig. 24) (Mountain and Tucholke, 1985). The events in the North Atlantic apparently were expressed in the Pacific (text-fig. 24), for Pacific hiatus NH1 correlates with erosion associated with reflectors R2 and X (Keller and Barron 1983), and erosion associated with Merlin correlates with Pacific hiatuses NH3/4 (Keller and Barron 1983) and reflector Purple (Mayer et al. 1985).

Carbon isotopic differences between the eastern and western North Atlantic basins suggest that the eastern basins were relatively isolated and poorly oxygenated during the Oligocene-early Miocene. At about 15 Ma the differences between the eastern (Site 608) and western (Site 563) basins disappeared, indicating increased advection into the eastern basins (text-fig. 21) (Miller et al. 1986b). This change may be attributed to increased advection across the Iceland-Faeroe portion of the Greenland-Scotland Ridge (Miller et al. 1986), closing of Reykjaness Ridge fracture zones (Tucholke and
**TEXT-Figure 11**

Q-mode varimax factor analysis of benthic foraminiferal relative abundance data from Site 563 (table 1). Values greater than the mean are stippled. Species contributing to each factor and their factor scores are indicated under each column. Factor I explains 23% of the variance, Factor II explains 16% of the variance, Factor III explains 28% of the variance, Factor IV explains 15% of the variance. Projections of modern samples V17-165 TW and V27-263 on Factors I (11% variance explained) and II (38% variance explained) are indicated with squares; projections on Factors III and IV explained only 3% and 2% of the variance, respectively, and were not plotted.

**TEXT-Figure 12**

Relative abundances of taxa which are most abundant in the Oligocene at Site 563.
Mountain 1986), or changes in the configuration or hydrography at the Romanche Fracture Zone (e.g. Lohmann and Curry 1983).

Comparisons of carbonate flux, planktonic foraminiferal flux, benthic foraminiferal flux, and dissolution provide other means of evaluating changes in bottom-water conditions. Carbonate records from Sites 563, 558, and 608 were used to compute flux (text-fig. 21) (Site 608 is situated in the eastern North Atlantic: 42°50.21′N, 23°05.25′W, 3525 m present depth; Ruddiman, Kidd et al. 1986). We computed flux of total planktonic and total benthic foraminifera at Site 563 (text-fig. 22).

Intervals of intense dissolution occurred at Site 563 at ca 22-20 Ma and ca 11-10 Ma (text-fig. 22). These dissolution intervals apparently are associated with peak North Atlantic deep water formation inferred from carbon isotope comparisons and erosional disconformities noted in the seismic stratigraphic record (text-fig. 24).

Carbonate flux was low (<2 g/cm²/kyr) throughout the Oligocene to early Miocene in the North Atlantic (Sites 558, 563, 608) (text-figs. 21, 22). At about 19-18 Ma carbonate flux increased dramatically at Site 558 (text-fig. 21). At Site 563 planktonic foraminiferal and benthic foraminiferal fluxes increased at 19-18 Ma (text-fig. 22), although net carbonate flux apparently remained unchanged (text-fig. 21). The increased fluxes of carbonate at Site 558 and of foraminifera at Site 563 at ca 19-18 Ma are associated with decreased dissolution (text-figs. 21, 22). Therefore, the increased fluxes may be attributed either to increased supply (productivity), decreased dissolution, or both. We speculate that the increased fluxes at 19-18 Ma were due to a combination of decreased dissolution and increased productivity.

At about 15.5 Ma, carbonate flux increased at all three sites examined (text-fig. 21), while dissolution remained low at Site 563 (text-fig. 22). At about 10.5 Ma carbonate flux again increased (text-fig. 21) despite the fact that dissolution was particularly intense at Site 563 (text-fig. 22). Assuming that the Site 563 dissolution record is representative of the North Atlantic, these increases in carbonate flux at ca 15.5 and ca 10.5 Ma cannot be attributed to decreased dissolution. This suggests that these increases were caused by increased supply of carbonate.

### Distribution of Dominant Taxa, Site 563

<table>
<thead>
<tr>
<th>% <em>Globocassidulina subglobosa</em></th>
<th>% <em>Cibicidoides mundulus</em></th>
<th>% <em>C. lamontdohertyi</em></th>
</tr>
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<tbody>
<tr>
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</tbody>
</table>

**TEXT-Figure 13**

Relative abundances of taxa which are most abundant in the late Oligocene to early middle Miocene at Site 563.
The carbon isotopic, seismic stratigraphic, and accumulation comparisons indicate that the greatest changes in bottom-water conditions occurred in the late early to middle Miocene (ca 20–10 Ma) (text-fig. 24). Between 20 and 10 Ma, abyssal circulation was reorganized. Peak erosion occurred at ca 20–17 and 12–11 Ma in the North Atlantic (reflectors R2 and X and reflector Merlin). These intervals apparently were associated with increased dissolution at Site 563 (text-fig. 22). The eastern basins became better ventilated at ca 15 Ma, associated with increased carbonate flux (text-fig. 21). Carbonate flux also increased at 19–18 and 10.5 Ma. Benthic foraminiferal oxygen isotope values increased globally between 14.8–13.5 Ma (text-fig. 24). From 14.8–14.4 Ma, this was primarily a result of a drop in bottom-water temperatures, whereas from 14.4–13.5 Ma ice volume also increased (Miller et al. 1987).

It is tempting to relate these abyssal circulation changes to tectonics, for tectonic change undoubtedly contributed to bottom-water changes. Unfortunately, the correlations of tectonic changes are difficult to evaluate with the same precision as other paleoceanographic events. For example, many small transform faults offset the Reykjanes Ridge in the Oligocene-early Miocene. Between Anomaly 6 time and Anomaly 5 time these transforms ceased to be active, sealing off sills in the Reykjanes Ridge (text-fig. 24) (Miller and Tucholke 1983; Tucholke and Mountain 1986). This constrains the timing to between 20 and 10 Ma, with the best estimate as approximately midway between Anomalies 6 and 5 (ca 15 Ma) (Tucholke and Mountain 1986). The history of the Greenland-Scotland Ridge has been even more ambiguous and controversial. Early studies assumed that the ridge was a barrier to deep-water circulation until about 15 Ma (Talwani, Udintsev et al. 1976). Closer evaluation suggested connection through the eastern (Faeroe-Shetland Channel) and western (proto-Denmark Straits) portions of the Greenland-Scotland Ridge since the Eocene (Miller and Tucholke 1983). Most simple thermal subsidence models indicate that the first deep-marine connection across the Iceland-Faeroe portion of the Greenland-Scotland Ridge occurred at about 15 Ma (text-fig. 24) (Talwani, Udintsev et al. 1976; Thiede and Eldholm 1983; Miller et al. 1986). However, the Reykjanes Ridge was subjected to two periods of uplift: ca 13–10 Ma and ca 3 Ma (text-fig. 24) (Luyendyk et al. 1979; Tucholke and Mountain 1986); presumably this uplift affected the Iceland hot spot and the Greenland-Scotland Ridge. Simple thermal subsidence models, therefore, would not be applicable, and connections across the Iceland-Faeroe portion of the ridge may have existed during the Eocene-early Miocene (Tucholke and Mountain 1986).

Timing and cause of faunal changes

Oligocene abyssal benthic foraminiferal assemblages at Sites 563 and 558 differed from Eocene North Atlantic assemblages by absence of characteristic Eocene taxa: *Nuttallides truempyi* (Nuttall), *Clinapertina* spp., and *Abyssamina* spp. (e.g. Tjalsma and Lohmann 1983; Miller 1983; Wood et al. 1985). Major benthic foraminiferal changes occurred in the late Eocene-earliest Oligocene throughout the deep sea, be-

**TEXT-Figure 14**

Relative abundances of taxa which are most abundant in the late middle to late Miocene at Site 563.
beginning at ca 39.5 Ma and lasting until the time of the δ¹⁸O increase at 36–35 Ma (e.g. Corliss et al. 1984; Miller et al. 1985a). Benthic foraminiferal changes subsequently were minor at abyssal locations such as Sites 563 and 558 during the Oligocene, and there were few first or last occurrences during the Oligocene at these sites and other Pacific and Atlantic locations (text-figs. 6, 7; Miller et al. 1985a; Thomas 1985; Wood et al. 1985). Abyssal Oligocene benthic foraminiferal faunas in the North Atlantic (e.g. Sites 549, 558, 563, Barbados; text-figs. 6, 7; Miller et al. 1985; Wood et al. 1985) were dominated by *Cibicidoides praemundulus* Berggren and Miller, *Globocassidulina subglobosa*, *Oridorsalis* spp., and *Gyroidinoides* spp.; buliminids were important at upper abyssal depths (about 2–3 km). At bathyal depths, Oligocene faunal changes were greater (Tjalsma 1983).

*Nuttallides umbonifera* reached an acme in the “middle” Oligocene in the Atlantic (Miller 1983; Boersma 1985). This acme occurred in the North Atlantic at the deepest (>3.5 km paleodepth) Sites 119, 400, and 10 (text-fig. 23), but is absent from North Atlantic and Caribbean locations shallower than about 3.5 km paleodepth (Sites 563, 558, and Barbados). In the South Atlantic this acme extended to sites as shallow as 1 km (Boersma 1985; Tjalsma, pers. comm. 1985). In the modern ocean, this taxon is associated with waters which are most corrosive to calcite (Bremer and Lohmann 1982). The acme of this taxon in the “middle” Oligocene is associated with a reduction in North Atlantic deep water supply (text-fig. 23), which presumably resulted in older, more carbonate corrosive water (Miller and Fairbanks 1985). This acme occurred at shallower depths in the South Atlantic, suggesting that the reduced North Atlantic deep water formation allowed greater expansion of corrosive waters from the south.

The greatest benthic faunal changes at Sites 558 and 563 occurred during the late early to middle Miocene. Absolute abundance data indicate that the changes began at about 19 Ma; stratigraphic ranges (extinctions) and relative abundance data do not reflect the changes until about 16 and 17 Ma, respectively. By 14–13.5 Ma the benthic foraminiferal assemblage at sites 563 and 558 was comprised of the same taxa which are present in the modern ocean. The faunal changes began before the bottom-water temperature drop evidenced by the δ¹⁸O increase at 14.8–13.5 Ma (text-fig. 24). The change in bottom conditions exemplified by the isotopic increase probably contributed to the benthic faunal changes. However, it could not have triggered the changes.

The initiation of the faunal changes may have been triggered by productivity changes in the late early Miocene. At about 19–18 Ma, carbonate flux increased (text-fig. 21), planktonic foraminiferal and benthic foraminiferal fluxes increased (text-fig. 22), and we infer that productivity increased. Increased primary production would have caused increased carbonate and increased carbon fluxes. Assuming that productivity increased throughout the North Atlantic, there would have been large, global changes in deep-sea chemistry (e.g. pH, total CO₂, and nutrient distribution). We speculate that the “modern” assemblage was better accommodated to higher primary and benthic production rates.
The benthic foraminiferal turnover in the Miocene was a global phenomenon (e.g., Woodruff 1985; Thomas 1985), and we acknowledge the possibility that the faunal changes may have been triggered by events outside of the Atlantic. For example, Leckie and Webb (1983, 1986) suggested that climatic conditions deteriorated in the Ross Sea region of Antarctica by the late early Miocene based upon their study of foraminifera from Site 270. If their chronology is correct, the southern high-latitudes cooling preceded the global δ¹⁸O increase in the early middle Miocene, and changes in Antarctic bottom water production may have contributed to the benthic faunal changes.

The faunal changes in the western North Atlantic continued until about 13.5 Ma. The taxonomic turnover had ended and the fauna at Sites 563 and 558 was comprised entirely of taxa which occur in the modern ocean. Our limited abundance comparisons with modern core tops suggest that the fauna at Site 563 from 14–8 Ma was similar in abundance to the present-day assemblage (text-fig. 11) (i.e. an *N. umbonifera*-P. wuellerstorfi assemblage). Nevertheless, many authors (e.g. Schnitker 1974; Thomas 1986a, b) noted that large benthic foraminiferal abundance fluctuations and several LO and FO occurred in the North Atlantic between the middle Miocene and present. The use of the term “modern” fauna is, therefore, quite subjective. Boltovskoy (1980), for example, argued that the “modern” fauna has existed since before the Oligocene. Still, it is clear that beginning at 13.5 Ma, the benthic foraminiferal taxonomic composition at our western North Atlantic locations was the same as the present-day fauna.

By 13.5 Ma, the benthic foraminiferal fauna had apparently accommodated itself to a dramatically different ocean than that prior to 19 Ma: one with well-ventilated eastern basins, higher production rates, particularly intense fluctuations in dissolution, and lower bottom-water temperatures. Subsequent deep-water changes caused large faunal abundance changes, but no taxonomic changes. For example, fluctuations of North Atlantic deep water supply, production and
Accumulation Rate of Taxa, Site 563 (\# cm\(^{-2}\) kyr\(^{-1}\))

![Diagram showing accumulation rates of different taxa over time.]

**TEXT-Figure 17**

Absolute accumulation rate of taxa which are most important in the late middle to late Miocene at Site 563. Compare with text-figure 14.

Accumulation rates of carbon and carbonate, and degree of eastern basin ventilation caused rapid (10\(^{3}-10^{4}\) yr) abundance changes since at least the late Miocene (e.g. Schnitker 1974, 1984; Lohmann and Curry 1983). Despite these dramatic changes in bottom-water conditions and benthic foraminiferal abundances, taxonomic composition of benthic foraminiferal assemblages in the western North Atlantic has remained unchanged since 13.5 Ma.

Both the Eocene-Oligocene (Corliss et al. 1984; Miller et al. 1985) and Miocene benthic foraminiferal changes began prior to the primary harbingers of deep-sea circulation changes, the major rapid \(\delta^{18}O\) increases at ca 35 and 14.8-13.5 Ma. We suggest that the “Paleogene” benthic foraminiferal assemblage was affected by productivity and bottom-water changes which began before the major bottom-water temperature drops recorded by oxygen isotopes. The benthic foraminifera which survived these changes (the “modern” taxa) were tolerant enough to withstand the 2-4°C temperature drops. For example, the taxa which were adapted to the Paleogene oceans were already on the decline in the early Miocene (text-fig. 16). Productivity and circulation changes contributed to the ultimate demise of this assemblage. Although the bottom-water temperature drop at 14.8-13.5 Ma had some effect, most of the remaining benthic foraminiferal taxa tolerated this environmental change.

**CONCLUSIONS**

Western North Atlantic Sites 563 and 558 provide a well-constrained chronology of Oligocene-Miocene benthic foraminiferal changes calibrated to biostratigraphy and magnetostratigraphy. Some stratigraphic ranges from these sites are synchronous (within 1-2 my) with ranges at other Atlantic, Caribbean and Pacific locations. Other taxa are clearly diachronous, although they may still be biostratigraphically useful locally.

Comparison of the relative abundances (percentages) of benthic foraminifera with their absolute accumulation rates (fluxes) shows that the percentages of many taxa accurately record changes in their fluxes (e.g. *Nuttallides umbonifera*, *Planulinauelteristeri*). Percentages of others may vary independently of their fluxes (e.g. *Oridorsalis* spp.). Analyses of relative abundance data may be misleading, especially those which emphasize abundant taxa such as *Oridorsalis* spp.

Abysal North Atlantic benthic foraminiferal assemblages were relatively stable in the Oligocene-early Miocene following a period of faunal changes in the late Eocene-earliest Oligocene. At Sites 563 and 558, a buliminid assemblage disappeared in the late Oligocene due to subsidence from the upper abyssal (2-3 km) to lower abyssal (>3 km) zones. At the deepest sites (>3 km) in the North Atlantic (119, 400, 10), *Nuttallides umbonifera* dominated the “middle” Oligocene, correlating with reduced circulation inferred from carbon isotope comparisons.

Examination of stratigraphic ranges, relative abundances, and absolute accumulation rate shows accelerated faunal turnover from about 19 to 13.5 Ma (late early to early middle Miocene). Seismic stratigraphic, isotopic, accumulation, and
TEXT-Figure 18
Absolute accumulation rate of taxa which were most important in the late Oligocene to early Miocene at Site 563. Compare with text-figure 13.

PLATE 1
Scale = 100 µm

1a-b  Karreriella chapapotensis (Cole)
   Site 563 16-2, 117–123 cm.

2a-b  Vulinulina spinosa Cushman
   Site 563 21-4, 31–37 cm.

3a-b  Karreriella subgialbra (Guembel)
   Site 563 6-5, 121–127 cm.

4a-b  Bolivina antegressa Subbotina
   Site 558 24-1, 34–38 cm.

5a-b  Spiroplectammina cubensis (Cushman and Bermudez)
   Site 558 26-1, 93–97 cm.

6a-b  Karreriella cubensis Cushman and Bermudez
   Site 558 24-1, 34–38 cm.

7a-b  Bolivina huneri Howe
   Site 563 15-6, 100–106 cm.

8a-b  Pyrulina extensa Cushman
   Site 563 2-4, 34–39 cm.

9a-b  Eggerella Bradyi (Cushman)
   Site 563 6-5, 121–127 cm.

10  "Eggerella" sp.
    Site 563 2-4, 34–39 cm.

11  Stilostomella aculeata (Cushman and Renz)
    Site 563 16-3, 110–116 cm.

12  Stilostomella subspinosa (Cushman)
    Site 563 10-2, 90–96 cm.
Accumulation Rate of Taxa, Site 563 ($cm^{-2} kyr^{-1}$)

Oridorsalis spp.  
Gyroidinoides spp.  
Stilostomella spp.

TEXT-Figure 20
Absolute accumulation rates at Site 563. Compare with text-figure 19.

We follow van Morkhoven et al. (1986) in assigning this species to Anomalainoides. It is rare in the lower Oligocene at Site 558 and common in the Oligocene to lower middle Miocene at Site 563.

Anomalainoides spissiformis (Cushman and Stainforth)
Plate 6, figures 4a-c

Anomalina alazanensis Nuttall var. spissiformis CUSHMAN and STAINFORTH 1945, p. 71, pl. 14, fgs. 5a-c.
Anomalina spissiformis Cushman and Stainforth.—TJALMSA and LOHMANN 1983, p. 23, pl. 20, fgs. 4a-c.

This species is abundant in the lower Oligocene at Site 558 with sporadic occurrences in the lower to middle Miocene. It is common in the lower Oligocene and lower to middle Miocene at Site 563.

Astronomion pusillum Hornibrook
Plate 4, figures 6a-b

Astronomion pusillum HORNIBROOK 1961, p. 96, pl. 12, fgs. 229, 236.—MILLER 1983, p. 431, pl. 3, fig. 3.

This species is abundant at Site 563, although absent from Cores 2-10. It is common to abundant at Site 558 but absent from Cores 2-11.

Bolivina antegressa Subbotina
Plate 1, figures 4a-b

Bolivina antegressa SUBBOTINA 1953, p. 226, pl. 10, fgs. 11-16.—MILLER, CURRY and OSTERMANN 1985b, pl. 4, fig. 11.—MILLER and KATZ 1987, pl. 2, fgs. 1a-b.

Bolivina tectiformis Cushman.—TJALMSA 1983, p. 739, pl. 1, fgs. 3a-b.
TEXT-Figure 21
Miocene carbon isotopic comparisons of Site 563 (western North Atlantic) and 608 (eastern North Atlantic) and mass accumulation rate (MAR; g/cm²/kyr). Isotopic comparisons after Miller et al. (1986b).

PLATE 2
Scale = 100 μm

1a–b *Uvigerina havanensis* Cushman and Bermudez
Site 563 21-4, 31–37 cm.

2 *Uvigerina hispida* Schwager
Site 563 13-3, 123–128 cm.

3 *Bulimina impendens* Parker and Bermudez
Site 563 15-4, 110–115 cm.

4a–b *Buliminella grata* Parker and Bermudez
Site 563 15-4, 110–115 cm.

5a–b *Ehrenbergina gibbera* Galloway and Heminway
Site 563 1-3, 18–24 cm.

6a–b *Bulimina jarvisi* Cushman and Parker
Site 558 24-1, 34–38 cm.

7a–b *Bulimina alazanensis* Cushman
Site 563 22-3, 110–116 cm.

8a–b *Bulimina glomarchallengeri* Tjalsma and Lohmann
Site 563 21-5, 20–25 cm.
TEXT-Figure 22
Mass accumulation rates of benthic and planktonic foraminifera computed using constants (K) in table 3, compared with dissolution history derived from text-figure 4.

We follow Miller and Katz (1987) in adopting Subbotina's taxon and including forms both with and without a medial ridge. This species is abundant in the lower Oligocene with a single possible occurrence in the middle Miocene at Site 558 and common to abundant in the lower to middle Miocene at Site 563.

_Bolivina hueri_ Howe
Plate 1, figures 7a-b

_Bolivina hueri_ Howe 1939, p. 66, pl. 9, figs. 3-4.—MALLORY 1939, p. 201, pl. 16, fig. 21. —TJALSMA and LOHMANN 1983, p. 23, pl. 11, figs. 5a-b.—MILLER 1983, p. 431, pl. 4, fig. 6.

The last occurrence of this taxon in the middle Miocene may be biostratigraphically useful. This species is common in the upper Oligocene and lower Miocene at Site 558 with possible occurrences in the lower Oligocene, and it is common in the lower Oligocene to middle Miocene at Site 563.

_Bulimina alazanensis_ Cushman
Plate 2, figures 7a-b

_Bulimina alazanensis_ CUSHMAN 1927a, p. 161, pl. 25, fig. 4.—TJALSMA and LOHMANN 1983, p. 24, pl. 14, fig. 4.—MILLER, CURRY and OSTERMANN 1985b, pl. 4, fig. 6.
_Bulimina cf. alazanensis_ Cushman.—MILLER 1983, p. 431, pl. 3, fig. 13.

This long-ranging taxon (Eocene-Recent) shows considerable variability in the nature of its striae; we noted many specimens with subparallel striae and others with anastomosing striae, particularly in the Oligocene. In addition, abyssal members of this species lack a distinctly triangular test (Miller 1983). This species is common in the lower Oligocene and middle Miocene at Site 558, common to abundant in the lower Oligocene, absent from the upper Oligocene and abundant in the Miocene at Site 563.
TEXT-Figure 23
Comparison of carbon isotopic records with the distributions of *Nuttallides umbonifera* (Cushman) at Sites 119 (circles), 400 (squares), and 10 (triangles). Site 119 and 400 data after Miller (1983); Site 10 data from this study. The western Atlantic-Pacific comparison shows Site 563 (open circles) and Pacific Sites 77 (pluses) and 574 (X's); a smoothed line was drawn through the Pacific data using an 11-point Gaussian convolution filter (after Miller and Fairbanks 1985). The eastern versus western basin comparison shows Sites 563 (open circles), 119 (closed circles), and 400 (squares) (after Miller et al. in press; Site 400 data after Miller, Curry and Fairbanks, unpublished).

*Bulimina goniarchallengeri* Tjalsma and Lohmann
Plate 2, figures 8a-b

*Bulimina goniarchallengeri* TJALSA and LOHMAN 1983, p. 25, pl. 13, figs. 8-12c.—MILLER 1983, p. 431, pl. 3, fig. 11.—MILLER, CURRY and OSTERMAN 1985b, pl. 4, fig. 1.

This species is absent from Site 558. It is abundant in the lower Oligocene at Site 563 and ranges into the Miocene elsewhere (van Morkhoven et al. 1986).

*Bulimina impendens* Parker and Bermudez
Plate 2, figure 3

*Bulimina impendens* PARKER and BERMEDEZ 1937, p. 514, pl. 58, figs. 7a-c, 8.—PROTO DECIMA and BOLLI 1978, p. 791, pl. 2, figs. 11-12.—TJALSA and LOHMAN 1983, p. 25, pl. 14, figs. 2a-b.

Our specimens are not typical; Miocene specimens (e.g. pl. 2, fig. 3) lack the reticulate surface texture characteristic of the later chambers, while Oligocene specimens show only moderate development of this texture. This species is common in the lower Oligocene at Site 558 and common in the lower Oligocene and lower Miocene at Site 563.

*Bulimina Jarvisi* Cushman and Parker
Plate 2, figures 6a-b

*Bulimina Jarvisi* CUSHMAN and PARKER 1936, p. 39, pl. 7, figs. 1a-c.—PROTO DECIMA and BOLLI 1978, p. 791, pl. 2, fig. 13.—TJALSA and LOHMAN 1983, p. 25, pl. 13, figs. 4-5b.—MILLER, CURRY and OSTERMAN 1985b, pl. 4, fig. 3.

This species is common in the Oligocene at Site 558, abundant in the lower Oligocene and rare in the upper Oligocene at Site 563, with a single isolated occurrence in the middle Miocene. In other Atlantic and Caribbean locations we examined (Sites 548, 549, Barbados), it ranges no higher than the top of the Oligocene; however, in the Pacific this taxon ranged into the middle Miocene (Douglas and Woodruff 1981; Woodruff 1985) (text-fig. 10).

*Bulimina grata* Parker and Bermudez
Plate 2, figures 4a-b

*Bulimina grata* PARKER and BERMEDEZ 1937, p. 515, pl. 59, figs. 6a-c.—TJALSA and LOHMAN 1983, p. 26, pl. 12, figs. 7a-b.

*Bulimina cf. grata* Parker and Bermudez.—MILLER 1983, p. 433, pl. 4, fig. 13.

The last occurrence of this taxon in Zones N9–N11 is biostratigraphically useful (text-fig. 8). It is common from the lower Oligocene to the lower middle Miocene at Site 558 and common to abundant from the lower Oligocene to the middle middle Miocene at Site 563.

*Cassidulina crassa* d'Orbigny
Plate 3, figures 1a-b

*Cassidulina crassa* D'ORBIGNY 1839, p. 56, pl. 7, figs. 18-20.

This species is common at Site 558 and common in the uppermost Oligocene to the middle Miocene with a possible single isolated occurrence in the upper Miocene at Site 563.

*Cassidulina havanensis* Cushman and Bermudez
Plate 3, figures 3a-c

*Cassidulina havanensis* CUSHMAN and BERMEDEZ 1936a, p. 36, pl. 6, fig. 11.—MILLER 1983, p. 433.—MILLER, CURRY and OSTERMAN 1985b, pl. 4, figs. 12-13.
This species is characterized by a pinched periphery and flattened chambers, as opposed to *C. crassa*, which has a rounded axial view. It is common in the Oligocene with single occurrences in the lower and middle Miocene at Site 558, common to abundant in the Oligocene and lower middle Miocene, rare in the lower Miocene and absent in the upper Miocene at Site 563.

*Cassidulinia* sp. 1

Lack of surface relief makes SEM micrographs of this taxon unsuitable. Test is small and compressed, typically with seven chambers in the final whorl; aperture is on the axial periphery. Secondary chamberlets are often difficult to distinguish and this small taxon may therefore be mistaken for other genera (*e.g.* *Epistominella*). This taxon is common in the Oligocene to lower middle Miocene with a single occurrence in the upper Miocene at Site 558 and common in the Oligocene to middle Miocene at Site 563.

*Cibicidoides bradyi* (Trauth)
Plate 7, figures 2a-c

*Truncatulina dutemplei* BRADY (not d'Orbigny) 1884, p. 665, pl. 95, fig. 5 (type figure).

*Truncatulina bradyi* TRAUTH 1918, p. 235 (type reference).

*Cibicidoides hattienensis* (Coryell and Rivero).—TJALSMA and LOHMANN 1983, p. 26, pl. 17, figs. 6a–b.—MILLER 1983, p. 433, pl. 2, fig. 5.

*Cibicidoides bradyi* (Trauth).—PFLUM AND FRERICHS 1976, pl. 3, figs. 6, 7.

*Cibicidoides bradyi* (Trauth).—MILLER and KATZ 1987.

Tjalsma and Lohmann (1983) used Coryell and Rivero's (1940) species for Eocene-Oligocene forms, although the latter had illustrated an upper middle Miocene form. Miller and Katz (1987) pointed out that *Cibicidoides hattienensis* Coryell and Rivero is a junior synonym of *Cibicidoides robertsonianus* (Brady). They noted that *C. hattienensis* of Tjalsma and Lohmann (not Coryell and Rivero) is *C. bradyi* (Trauth), which is common to very abundant at Sites 558 and 563.

*Cibicidoides dickersoni* (Bermudez)
Plate 7, figures 4a–c

*Cibicides dickersoni* BERMUDEZ 1937, p. 244, pl. 21, figs. 8–9.

*Cibicides dickersoni* (Bermudez).—TJALSMA 1983, p. 739, pl. 10, figs. 1a–2c.

This species is distinguished from the closely related taxon *C. eocaenas* by its less domed axial periphery, generally more chambers per whorl, and more strongly curved spiral sutures. It is common in the Oligocene to the middle Miocene at Site 558 and rare in the Oligocene to the lower Miocene at Site 563.

*Cibicides eocaenas* (Guembel)
Plate 8, figures 3a–c

Rotalia eocaenas GUEMBEL 1868, p. 650, pl. 2, figs. 87a–b.

*Cibicides tuxpamensis* (Cole).—TJALSMA and LOHMANN 1983, pl. 28, pl. 18, figs. 3a–4c; pl. 22, figs. 1a–3c.—MILLER, CURRY and OSTERMANN 1985b, pl. 1, figs. 1–3.

We follow van Markhoven et al. (1986) in placing forms previously assigned to *C. tuxpamensis* in Guembel's species which has priority. *Cibicides eocaenas* is absent from Site 558 and common in the Oligocene at Site 563.

*Cibicides cf. eocaenas* (Guembel)
Plate 8, figures 4a–c

This small *Cibicides* taxon has a large umbonal boss with five or six chambers in the final whorl with a flat spiral side and an inflated umbilical side. It may be a juvenile of *C. eocaenas* or *C. dickersoni*. It is rare in the Oligocene at Site 558 and common in the lower Oligocene and rare in the upper Oligocene to upper Miocene at Site 563.

*Cibicides grimsdalei* (Nuttall)
Plate 8, figures 1a–c

*Cibicides grimsdalei* NUTTALL 1930, p. 291, pl. 25, figs. 7–8, 11.

*Cibicides grimsdalei* (Nuttall).—SCHNITKER 1979, pl. 11, figs. 1–3.—TJALSMA and LOHMANN 1983, p. 26, pl. 18, figs. 2a–
TEXT-Figure 24
Oceanographic setting for benthic foraminiferal changes during the Miocene. Benthic foraminiferal changes and western North Atlantic dissolution record after this paper. Benthic isotopic changes after Miller and Fairbanks (1985) and Miller et al. (1986b). Rock stratigraphic, tectonic, and climatic records after Miller and Tucholke (1983), Mountain and Tucholke (1985), Miller et al. (1987), and this paper. Pacific record after Keller and Barron (1983) and Mayer et al. (1985).

Cibicidoides havanensis (Cushman and Bermudez)
Plate 7, figures 5a-c

Cibicides havanensis CUSHMAN and BERMUDEZ 1937, p. 28, pl. 3, figs. 1-3.
Cibicides havanensis (Cushman and Bermudez).—TJALSMA and LOHMANN 1983, p. 27, pl. 22, figs. 4a-c.—MILLER 1983, p.

PLATE 4
Scale = 100 μm

1a-c Nonionellina sp.
Site 563 10-2, 90–96 cm.

2a-b Pulvella quinqueloba (Reuss)
Site 563 10-2, 90–96 cm.

3a-b Melonis sphaeroides Voloshinnova
Site 563 8-2, 114–120 cm.

4a-b Pullenia bulloides (d’Orbigny)
Site 563 10-2, 90–96 cm.

5a-b Melonis barleeanum (Williamson)
Site 563 1-1, 119–125 cm.

6a-b Astronomon pusillum Hornibrook
Site 563 1-3, 18–24 cm.

7a-b Nonion havanense Cushman and Bermudez
Site 563 9-4, 109–114 cm.
This taxon is characterized by its extremely biconvex test and large pores on the spiral side. It may be mistaken for C. mundulus (= C. kullenbergi) in the Miocene since that taxon can become distinctly biconvex. Cibicidoides havanensis is common in the Oligocene to lowermost middle Miocene at Site 558; at Site 563, it is common to abundant in the lower Oligocene, rare in the upper Oligocene and common in the lower to lower middle Miocene.

*Cibicidoides lamontohertyi* Miller and Katz, n. sp.

*Description:* Small Cibicidoides, biconvex (sometimes asymmetrical) with, typically, 11 chambers in final whorl. Spiral side translucent; three whorls visible. Generally with translucent umbilical plug. Tendency to develop crenulate periphery in final chambers and pinched axial margin. Umbilical sutures on earlier chambers strongly curved. Last few chambers tending to uncoil, and sutures becoming more radial, terminating along umbilical-extrumbilical line. Early chambers thus tending to be more triangular, later chambers more banana-shaped.

*Type locality:* Bay of Biscay, North Atlantic, 45°01.9'N, 07°58.5'W, 4447 m present depth, approximately 4000 m Oligocene depth.

*Type sample:* DSDP Leg 12, Site 119, Sample 15-CC.

*Type level:* Upper Oligocene, probably Zone NP24, Zone P21 (ref. in Miller 1983).

*Remarks:* This species is characterized by its uncoiled later chambers and its unusual umbilical sutures. It is distinctly flatter than the Neogene *C. mundulus*, and usually flatter than the Paleogene *C. praemundulus*. It is also consistently smaller than *C. mundulus-praemundulus* in our material. Originally, it was noted in the deep abyssal Bay of Biscay. We found this taxon to be common to abundant at Sites 558 and 563 throughout the Oligocene and Miocene. Examination of material from throughout the Atlantic shows that this species is primarily found at abyssal sites in the Oligocene.

*Cibicidoides laurisae* (Mallory)

*Cibicidoides laurisae* MALLORY 1959, p. 267, pl. 24, figs. 8a-c.
*Cibicidoides aff. laurisae* (Mallory) - TJALSMA and LOHMANN 1983, p. 27, pl. 17, figs. 2a-c. - MILLER 1983, p. 433, pl. 2, figs. 3, 4. - TJALSMA 1983, p. 742, pl. 8, figs. 2a-c.
*Cibicidoides laurisae* (Mallory). - MILLER, CURRY and OSTERMANN 1985b, pl. 2, figs. 4-6.

*Cibicidoides laurisae* can be distinguished from *Anomalinoideas pseudogrosserugosus* by: 1) higher coiling with more rapidly enlarging chambers, especially in axial and umbilical views; 2) a more acute periphery; 3) seven or more chambers in the final whorl versus four to seven chambers, although Tjalsma (1983) noted up to nine in *A. pseudogrosserugosus*; 4) subrounded to kidney-shaped test versus a rounded to subrounded test. *Anomalinoideas pseudogrosserugosus* generally has less curved spiral sutures, has spiral-side chambers that tend to be more quadrate and lacks spiral infilling that can occur in *C. laurisae*. Both tend to be plano-convex to concavo-convex, although *C. laurisae* tends to be more strongly concave. Forms with apparently transitional characteristics were noted in the upper Oligocene-lowermost Miocene at Sites 563 and 558. These had less quadrate chambers and some infilling, and were more strongly concave than typical *A. pseudogrosserugosus*; we assigned these to *A. pseudogrosserugosus*. *Cibicidoides laurisae* has a single occurrence in the lower Oligocene at Site 558 and is restricted to the lowermost Oligocene at Site 563.

*Cibicidoides mexicanus* (Nuttall)

*Cibicidoides mexicanus* NUTTALL 1932, p. 33, pl. 9, figs. 7-9.
*Cibicidoides mexicanus* (Nuttall). - TJALSMA 1983, p. 742, pl. 3, fig. 5; pl. 9, figs. 1a-2c.

This taxon occurs in a single sample (21-7, 30-35) in the lower Oligocene at Site 563.

*Cibicidoides mundulus-praemundulus* group

*Cibicidoides mundulus* (Brady, Parker and Jones)

*Cibicidoides mundulus* (Brady, Parker and Jones) - MILLER, CURRY and OSTERMANN 1985b, pl. 2, figs. 4-6.

*Truncatulina mundula* BRADY, PARKER and JONES 1888, p. 228, pl. 45, figs. 25a-c.

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**PLATE 5**

*Scale = 100 μm*

1a-c *Anomalinoideas capitatus* (Guembel)  
Site 563 22-3, 110-116 cm.

2a-c *Gavelinella micra* (Bermudez)  
Site 563 22-2, 3-8 cm.

3a-b *Osangularia mexicana* (Cole)  
Site 563 21-5, 20-25 cm.

4a-c *Anomalinoideas pseudogrosserugosus* (Colom)  
Site 558 20-1, 118-122 cm.

5a-c *Nuttallides umbonifera* (Cushman)  
Site 563 1-3, 18-24 cm.

6a-b *Epistominella exigua* (Brady)  
Site 563 1-3, 18-24 cm.
Cibicidoides praeamundulus Berggren and Miller

Cibicidoides praeamundulus BERGGREN and MILLER, in van Morkhoven et al. 1986.
Cibicidoides ungerianus (d'Orbigny).—TJALSCA and LOHMANN 1983, p. 28, pl. 18, figs. 1a-c, pl. 21, figs. 3-5.—MILLER 1983, p. 435, pl. 2, figs. 6, 7.—MILLER, CURRY and OSTERMANN 1985b, pl. 1, figs. 4-6.

Cibicidoides mundulus is a senior synonym of the common, well-known species C. kullenbergi. Tjalsma (1983) noted the evolution of C. mundulos from a taxon he termed C. ungerianus. Berggren (pers. comm.) noted that C. ungerianus (d'Orbigny) is a shallow water form and is not related to the deep-sea taxon illustrated by many authors including Tjalsma (1983), Tjalsma and Lohmann (1983), and Miller (1983). Berggren and Miller (in van Morkhoven et al. 1986) erected the name C. praeamundulus for the Paleogene forms antecedent to C. mundulus. In our material, C. mundulus has 11-13 chambers in the final whorl while C. praeamundulus has 11 or fewer chambers. The spiral side of C. mundulus may be domed whereas C. praeamundulus tends to be flatter. Cibicidoides mundulus has a thicker flaring keel. Cibicidoides praeamundulus is abundant at Sites 558 and 563. Core 16 at Site 563 and Cores 18-19 at Site 558 contain forms transitional from C. praeamundulus to C. mundulus.

Cibicidoides robertsonianus (Brady)
Plate 7, figures 1a-c
Planorbulina robertsonianus BRADY 1881, p. 65 (type reference).
Truncatulina robertsonianus BRADY 1884, p. 664, pl. 95, figs. 4a-c (type figure).
Cibicidoides robertsonianus (Brady).—PFLUM and FREIRICH 1976, pl. 3, figs. 3-5.

This species is rare to common in the Miocene at Site 558 and rare to very rare at Site 563. We noted several specimens in the lower Oligocene at Site 563 which were reminiscent of C. robertsonianus.

Cibicidoides sp. 4
Plate 8, figures 5a-c

This species is rare in the Miocene at Site 558 and rare in the middle to upper Miocene at Site 563. This taxon may be related to C. dickersoni. Due to uncertain taxonomy, we did not include Cibicidoides sp. 4 in census or range charts.

Eggerella bradyi (Cushman)
Plate 1, figures 9a-b
Verneulina bradyi CUSHMAN 1911, pt. 2, p. 67, figs. 107a-c.
Eggerella bradyi (Cushman).—PHLEGER and PARKER 1951, p. 6, pl. 3, figs. 1, 2.—MILLER 1983, p. 435, pl. 5, fig. 5.

Our specimens are low spired as in the modern form illustrated by Phleger and Parker. We have not observed the higher-spired form illustrated by Phleger et al. (1953, pl. 5, figs. 8, 9) from the Recent. This species is common to abundant from the uppermost lower Oligocene through the upper Miocene at Site 558 and rare in the lower Miocene and abundant in the middle to upper Miocene at Site 563.

"Eggerella" sp.
Plate 1, figure 10

This coarse-grained agglutinated form lacks surface features and is difficult to photograph. It apparently ranges from the Eocene (Miller 1983; Miller and Katz 1987) to at least the upper Miocene. It is common from the uppermost lower Oligocene to the middle middle Miocene at Site 558 and rare to common in the Oligocene to upper Miocene at Site 563.

Ekherbergina gibbera Galloway and Heminway
Plate 2, figures 5a-b
Ekherbergina serrata Reuss var. gibbera GALLOWAY and HEMINWAY 1941, p. 427, pl. 32, figs. 5a-d.
Ekherbergina gibbera Galloway and Heminway.—DOUGLAS 1973, pl. 10, figs. 4, 5.

Our specimens differ from Galloway and Heminway's illustration in that ours are more spinose and have a more pronounced enrolled stage. They first appear in the upper middle Miocene at Sites 558 and 563 and range to the top of the section.

Epistominella exigua (Brady)
Plate 5, figures 6a-b
Pseudolumina exigua BRADY 1884, p. 696, pl. 103, figs. 13-14.
Epistominella exigua (Brady).—PHLEGER, PARKER and PEIR-
SON 1953, p. 43, pl. 9, figs. 35–36.—MILLER 1983, pp. 435–436, pl. 3, fig. 4.

This species is rare in the lower Oligocene and common to abundant in the upper Oligocene to Miocene at Site 558. It is rare in the Oligocene and common to abundant in the Miocene at Site 563.

_Gavelinella microa_ (Bermudez)
Plate 5, figures 2a-c

_Cibicides micras_ BERMUDEZ 1949, p. 302, pl. 24, figs. 34–36.

_Gavelinella microa_ (Bermudez).—TJALSMA and LOHMANN 1983, p. 31, pl. 16, figs. 7a-b; pl. 20, fig. 7.—MILLER 1983, p. 437, pl. 3, figs. 15–16.

There are possible occurrences of this species in the lower Oligocene at Site 558. They are common in the lowermost Oligocene at Site 563.

_Globocassidulina subglobosa_ (Brady)
Plate 3, figure 4

_Cassidulina subglobosa_ BRADY 1881, p. 60 (type reference).

_Cassidulina subglobosa_ Brady.—BRADY 1884, p. 430, pl. 54, figs. 17a-c (type figure).

_Globocassidulina subglobosa_ (Brady).—TJALSMA and LOHMANN 1983, p. 31, pl. 16, fig. 9.—LOHMANN 1978, p. 26, pl. 2, figs. 8, 9.

This species is abundant at Sites 558 and 563.

_Gyroidinoides_ sp.
Plate 6, figures 5a-c

This form is common in the lower middle Miocene at Site 563. It displays the chamber shape and arrangement of _Gyroidinoides_ but possesses a gapping, subcircular aperture.

_Hanzawaia amphiphila_ (Guembel)
Plate 6, figures 3a-b

_Rotalia amphiphila_ GUEMBEL 1868, p. 652, pl. 2, figs. 9a-b.

_Cibicides cushmani_ NUTTALL 1930, p. 291, pl. 23, figs. 3, 5–6.

_Hanzawaia cushmani_ (Nuttall).—TJALSMA and LOHMANN 1983, p. 32, pl. 17, figs. 1a-c.—MILLER 1983, p. 437, pl. 1, fig. 12.

We follow Berggren (in van Morkhoven et al. 1986) in placing _H. amphiphila_ as the senior synonym of _H. cushmani_. It is common in the lower Oligocene at Sites 558 and 563. In the Atlantic, this taxon may be restricted to the Eocene–Oligocene (text-fig. 10), although it ranges into the Miocene of the Pacific (Woodruff 1985).

_Karreriella chapapotensis_ (Cole)
Plate 1, figures 1a-b

_Textularia chapapotensis_ COLE 1928, p. 206, pl. 33, fig. 9.

_Karreriella chapapotensis_ (Cole).—TJALSMA and LOHMANN 1983, p. 32, pl. 9, figs. 2a-b.

This species is common from the Oligocene to the lower middle Miocene and in the upper upper Miocene at Site 558. It is rare in the Oligocene and common in the Miocene at Site 563.

_Karreriella cubensis_ Cushman and Bermudez
Plate 1, figures 6a-b

_Karreriella cubensis_ CUSHMAN and BERMUDEZ 1937, p. 4, pl. 1, figs. 18–19.—TJALSMA and LOHMANN 1983, p. 33, pl. 9, figs. 4a-b.

This form may be assignable to _Siphotextularia_ sp. (Miller and Katz 1987). It is present in low abundances throughout Site 563, and is restricted to the Oligocene at 558.

_Karreriella subglobra_ (Guembel)
Plate 1, figures 3a-b

_Gaudryina subglobra_ GUEMBEL 1868, p. 602, pl. 1, figs. 4a-b.

_Gaudryina bradyi_ CUSHMAN 1911, p. 67, fig. 107.

_Karreriella bradyi_ (Cushman).—CUSHMAN 1937, p. 135, pl. 16, figs. 6–11.—BARKER 1960, pl. 46, figs. 1–4.

_Karreriella subglobra_ (Guembel).—TJALSMA and LOHMANN 1983, p. 34, pl. 9, figs. 1a-b.

This species is rare in the lower Oligocene and common in the middle to upper Miocene at Site 558. It is common from the lower Oligocene to middle Miocene at Site 563.

_Laticarinina pauperata_ (Parker and Jones)
Plate 3, figures 7a-b

_Pulvinulina repanda_ Fichtel and Moll, var. _menardii_ d’Orbigny, subvar._pauperata_ PARKER and JONES 1865, p. 395, pl. 16, figs. 50, 51a–b.

_Laticarinina pauperata_ (Parker and Jones).—PHLEGER, PARKER and PEIRSON 1953, p. 49, pl. 11, figs. 5, 6.

The first occurrence of this taxon is diachronous (text-fig. 9). There is a single isolated occurrence in the Oligocene at Site

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**PLATE 7**

Scale = 100 μm

1a–c _Cibicidoides robertsonianus_ (Brady)
Site 563 9–6, 113–118 cm.

2a–c _Cibicidoides bradyi_ (Trauth)
Site 563 8–2, 114–120 cm.

3a–c _Cibicidoides mundulus_ (Brady, Parker and Jones)
Site 563 9–2, 114–120 cm.

4a–c _Cibicidoides dickersoni_ (Bermudez)
Site 563 21–4, 31–37 cm.

5a–c _Cibicidoides havanensis_ (Cushman and Bermudez)
Site 563 14–7, 10–15 cm.
558 but it is common in the Miocene at Site 558, and common in the middle to upper Miocene at Site 563.

Melonis barleeanaum (Williamson)
Plate 4, figures 5a-b

Nonionia barleeana WILLIAMSON 1858, p. 32, pl. 3, figs. 68, 69.
Nonion barleeanaum (Williamson).—PHLEGER, PARKER and PEIRSON 1953, p. 30, pl. 6, fig. 4.
Melonis barleeanaus (Williamson).—PFLUM and FRERICHS 1976, pl. 7, figs. 5, 6.

This species is distinguished from Melonis sphaeroides in its nearly parallel sides in axial view. It occurs in two samples in the Oligocene and is abundant in the Miocene at Site 558. It is absent in the Oligocene, rare in the lower Miocene, and abundant in the middle to upper Miocene at Site 563.

Melonis sphaeroides Voloshinova
Plate 4, figures 3a-b

Melonis sphaeroides VOLOSHINOVA 1958, p. 153, pl. 3, figs. 1a, b. Melonis pompioides (Fichtel and Moll).—PFLUM and FRERICHS 1976, pl. 7, figs. 7, 8.—LOHMANN 1978, p. 29, pl. 1, figs. 12, 13.

This taxon is the abyssal representation of Melonis pompioides (Fichtel and Moll) (see discussion in van Morkhoven et al. 1986). There is a single isolated occurrence in the lower Oligocene at Site 558; but in the middle to upper Miocene at Site 558 it is common. There is a single isolated occurrence in the upper Oligocene at Site 563; but the form is abundant in the lower middle Miocene.

Nonion havenense Cushman and Bermudez
Plate 4, figures 7a-b

Nonion havenense CUSHMAN and BERMUDEZ 1937, p. 19, pl. 2, figs. 13-14.—TJALMSA and LOHMANN 1983, p. 17, pl. 7, figs. 6a-b.

This taxon is abundant in the lower Oligocene and rare to common in the remaining section at Site 558. It is abundant in the lowermost Oligocene and rare to common in the remaining section at Site 563.

Nuttallides umbonifera (Cushman)
Plate 5, figures 5a-c

Pulvinilinella umbonifera CUSHMAN 1933, p. 90, pl. 9, figs. 9a-c.

Epistominella (?) umbonifera (Cushman).—PHLEGER, PARKER and PEIRSON 1953, p. 43, pl. 9, figs. 33-34.
Nuttallides umbonifera (Cushman).—MILLER 1983, p. 439, pl. 1, figs. 1-3.—MILLER, CURRY and OSTERMAN 1985b, pl. 7, figs. 10, 11.

This species is common to abundant at Sites 558 and 563.

Osangularia mexicana (Cole)
Plate 5, figures 3a-b

Pulvinulinae culter (Parker and Jones) var. mexicana COLE 1927, p. 31, pl. 1, figs. 15-16.
Osangularia mexicana (Cole).—TJALMSA and LOHMANN 1983, p. 35, pl. 20, fig. 6.—MILLER, CURRY and OSTERMAN 1985b, pl. 3, figs. 7, 8.

This form is very rare in the lower Oligocene at Site 558 and abundant in the lower Oligocene at Site 563.

Planulina renzi Cushman and Stainforth
Plate 6, figures 1a-c

Planulina renzi CUSHMAN and STAINFORTH 1945, p. 72, pl. 15, figs. 1a-c.—TJALMSA 1983, p. 743, pl. 3, fig. 4; pl. 6, figs. 6-7.

This species is absent at Site 558, and has very rare occurrences in the upper Oligocene to the middle Miocene at Site 563.

Planulina wuellerstorfi (Schwager)
Plate 6, figures 2a-c

Anomalina wuellerstorfi SCHWAGER 1866, p. 258, pl. 7, figs. 105, 107.
Cibicidoides wuellerstorfi (Schwager).—PFLUM and FRERICHS 1976, p. 116, pl. 4, figs. 2-4.
Planulina wuellerstorfi (Schwager).—PHLEGER, PARKER and PEIRSON 1953, p. 49, pl. 11, figs. 1-2.—LOHMANN 1978, p. 26, pl. 2, figs. 1-4.

This taxon appears suddenly in the middle Miocene at various Atlantic and Pacific locations (text-fig. 8). It is abundant in the middle middle Miocene to upper Miocene at Sites 558 and 563.

Pullenia bulloides (d'Orbigny)
Plate 4, figures 4a-b
Nonionina bulloides D'ORBIGNY 1826, p. 293.

PLATE 8
Scale = 100 μm

1a-c Cibicidoides grimsdalei (Nuttall)
Site 563 20-4, 20-26 cm.

2a-c Cibicidoides mexicanus (Nuttall)
Site 563 21-7, 30-35 cm.

3a-c Cibicidoides eocaenas (Guembel)
Site 563 21-7, 30-35 cm.

4a-c Cibicidoides cf. C. eocaenus (Guembel)
Site 563 21-7, 30-35 cm.

5a-c Cibicidoides sp. 4
Site 563 2-1, 33-38 cm.
Pullenia bulloides (d’Orbigny).—LOHMANN 1978, p. 26, pl. 1, figs. 10, 11.—MILLER, CURRY and OSTERMANN 1985b, pl. 7, fig. 3.

We included forms assignable to Pullenia eocenica Cushman and Seiglus (see Tjalsma and Lohmann 1983, p. 36, pl. 16, fig. 1). This form is abundant at Sites 558 and 563.

**Pullenia quinqueloba** (Reuss)

Plate 4, figures 2a-b

Nonionna quinqueloba REUSS 1851, p. 71, pl. 5, figs. 31a–b.

Pullenia quinqueloba (Reuss).—TJALSMA and LOHMANN 1983, p. 36, pl. 16, fig. 2.—MILLER 1985, pl. 4, figs. 9–10.

This species is abundant at Sites 558 and 563.

**Pyryrina extensa** Cushman

Plate 1, figures 8a–b

Pyryrina extensa CUSHMAN 1923, p. 156.—BARKER 1960, p. 152, pl. 73, figs. 18–19.

This species is rare at Site 558, and rare in the Miocene at Site 563.

**Spiroplectammina cubensis** (Cushman and Bermudez)

Plate 1, figures 5a–b

Spiroplectoides cubensis CUSHMAN and BERMUDEZ 1937, pl. 1, figs. 44–46.

Bolivinopsis cubensis (Cushman and Bermudez).—DOUGLAS 1973, pl. 3, fig. 5.

Spiroplectammina cubensis (Cushman and Bermudez).—MILLER, GRADSTEIN and BERGGREN 1982, p. 22, pl. 2, fig. 1.

This species is common in the Oligocene at Site 558. It is rare in the uppermost lower Oligocene to lower Miocene at Site 563 and ranges to the top of the Oligocene in the Pacific (Douglas 1973).

**Stilostomella acaleata** (Cushman and Renz)

Plate 1, figure 11

Ellipsonodosaria muttalli Cushman and Jarvis var. acaleata CUSHMAN and RENZ 1948, p. 32, pl. 6, fig. 10.

Stilostomella acaleata (Cushman and Renz).—TJALSMA and LOHMANN 1983, p. 36, pl. 14, fig. 12.—MILLER 1983, p. 439, pl. 4, fig. 1.

We included rare specimens with basal spines that lacked the ring of spines on the lower part of the chamber and may actually belong in *S. muttalli* (Cushman and Jarvis) or *S. abyssorum* (Brady). *Stilostomella acaleata* is common to abundant at Sites 558 and 563.

**Stilostomella curvatura** (Cushman)

Ellipsonodosaria curvatura CUSHMAN 1939, p. 71, pl. 12, fig. 6.

Stilostomella curvatura (Cushman).—BECKMANN 1953, p. 371, pl. 21, figs. 26–27.—TJALSMA 1983, p. 743, pl. 1, figs. 7, 11.

**Stilostomella spinosa** (Cushman)

Ellipsonodosaria curvatura Cushman var. spinosa CUSHMAN 1939, p. 71, pl. 12, fig. 11.

Stilostomella curvatura (Cushman) var. spinosa (Cushman).—BECKMANN 1953, p. 371, pl. 21, fig. 28.

**Stilostomella subsinosa** (Cushman)

Plate 1, figure 12

Ellipsonodosaria subsinosa CUSHMAN 1943, p. 92, pl. 16, figs. 6–7b.

Stilostomella subsinosa (Cushman).—TJALSMA and LOHMANN 1983, p. 36, pl. 14, figs. 16–17.—MILLER 1983, p. 440, pl. 4, fig. 2.

This species is abundant at Sites 558 and 563.

Tjalsma (1983) applied a tripartite division of Oligocene *Stilostomella* into a hispid (*S. subsinosa*), coarsely-spinose (*S. aculeata*), and curved (*S. curvatura*) forms. There may be some validity to this in that curved forms seem to be more characteristic of water depths shallower than 2.5 km in the Oligocene South Atlantic (Tjalsma, pers. comm. 1982). We noted that curved forms occur in abundance at water depths greater than 2.5 km in the Oligocene North Atlantic (Sites 563 and 558) and decided to lump all stilostomellas for this study. Still, separation of curved and straight forms should be made to determine if curved forms do in fact have different distributions.

Taxonomic confusion and oversplitting complicates differentiation of *Stilostomella*. Comparison of paratypes of *S. aculeata* at the U.S. National Museum shows curved forms which should be assigned to *S. curvatura* (which has priority), although the holotype (CC57461) is straight. *Stilostomella subsinosa* is a straight form which is otherwise identical with the curved *S. curvatura* var. *spinosa* (which also has priority). It may be best to recognize curved forms as merely varieties. However, to avoid taxonomic confusion over priority and use of subspecies status, we propose a tentative four-fold taxonomic division which was essentially employed by Beckmann (1953): *S. aculeata* (straight, coarsely spinose); *S. subsinosa* (straight, hispid); *S. curvatura* (curved, coarsely spinose); and *S. spinosa* (curved, hispid).

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**PLATE 9**

Scale = 100 μm

1a–c  *Cibicidoides lamontdohertyi* Miller and Katz, n. sp. Site 563 8–2, 114–120 cm.

2a–c  *Cibicidoides lamontdohertyi* Miller and Katz, n. sp. Holotype, Site 119 15–CC.

3a–c  *Cibicidoides lamontdohertyi* Miller and Katz, n. sp. Site 563 8–2, 114–120 cm.
*Uvigerina havanensis* Cushman and Bermudez
Plate 2, figures 1a–b

*Uvigerina havanensis* CUSHMAN and BERMUDEZ 1936b, p. 59, pl. 10, figs. 19–21.—TIJALMA 1983, pl. 2, figs. 8–10.

Costate species of *Uvigerina* are rare in our material, making identifications uncertain. We observed two types of costate *Uvigerina*. We assigned one form with thicker costae and few spines (except occasional apical spines) to *U. havanensis*. This form is rare in the Oligocene at Site 563 with possible occurrence in lowermost Miocene, and is abundant in one sample at Site 558 (26-1, 93–97 cm; lower Oligocene).

The other form tended to be hispido-costate, more uniserial, longer, with thinner costae. We assigned it to *U. cf. havanensis*. This form is restricted to the uppermost Oligocene-Miocene at Site 563.

*Uvigerina hispida* Schwager
Plate 2, figure 2

*Uvigerina hispida* SCHWAGER 1866, p. 249, pl. 7, fig. 95.

*Uvigerina chirana* CUSHMAN and STONE 1947, p. 17, pl. 2, fig. 25.—TIJALMA 1983, pl. 2, fig. 11.

This form occurs in one sample in the lower middle Miocene at Site 558. It is abundant in the lower to middle Miocene at Site 563.

*Vulvarina spinosa* Cushman
Plate 1, figures 2a–b

*Vulvarina spinosa* CUSHMAN 1927b, p. 111, pl. 23, fig. 1.—TIJALMA and LOHMANN 1983, p. 38, pl. 10, figs. 4a–5b.—MILLER and KATZ 1987, pl. 1, figs. 4a–b.

The last occurrence of this taxon in the middle Miocene may be biostratigraphically useful. It is common to abundant in the Oligocene to middle Miocene at Site 563 (LO in Zone N12 with questionable occurrences in lowermost Zone N16), and common to abundant in the Oligocene to middle Miocene (LO N9/10) at Site 558.

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PLATE 11
Scale = 100 μm

1a-b Globigerina venezuelana Hedberg 1937
Site 558 18-4, 16-21 cm.

2a-c Globoquadrina dehiscens (Chapman, Parr and Collins 1934)
Site 558 18-1, 92-96 cm.

3a-b Globorotalia kugleri Bolli 1957
Site 563 15-2, 117-123 cm.

4a-b Globorotalia kugleri Bolli 1957
Site 563 15-2, 117-123 cm.

5a-c Globigerinoides primordius Blow and Banner 1962
Site 563 16-5, 117-123 cm.

6a-b Catapsydrax dissimilis (Cushman and Bermudez 1937)
Site 563 13-5, 124-130 cm.


PLATE 12
Scale = 100 μm

1a-c Globorotalia praeostictula Blow 1959
Site 563 12-2, 110–116 cm.

2a-b Globigerinoides sicamus de Stefani 1952
Site 563 11-4, 112–118 cm.

3a-c Globorotalia peripheracuta Blow and Banner 1966
Site 563 9-5, 114–120 cm.

4 Praeorbula glomerosa (Blow 1956)
Site 563 11-2, 100 cm.

5a-c Globorotalia foehsi lobata Bermudez 1949
Site 563 6-3, 135–140 cm.

6a-b Globigerina nepenthis Todd 1957
Site 563 5-5, 130–136 cm.

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PLATE 13

Scale = 100 μm

1a-c Globorotalia siakensis Leroy 1939
Site 558 7-1, 78–83 cm.

2a-c Neogloboquadrina pachyderma Ehrenberg 1861
Site 563 4-1, 37–42 cm.

3a-c Neogloboquadrina pachyderma Ehrenberg 1861
Site 563 3-4, 36–41 cm.

4a-c Neogloboquadrina acostaensis Blow 1959
Site 563 3-4, 36–41 cm.

5a-c Globorotalia merotumida Blow and Banner (in Blow and Banner 1965)
Site 558 4-1, 81–86 cm.
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