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# 1. PLANKTONIC FORAMINIFERAL BIOSTRATIGRAPHY OF LEG 166[1]

James D. Wright[2] and Dick Kroon[3]

## ABSTRACT

Planktonic foraminifers recovered from Leg 166 drilling showed a progression from well-preserved to poorly preserved specimens with increasing depth. The high carbonate production and shedding from the Great Bahama Bank diluted the pelagic components to the extent that planktonic foraminifers had scattered occurrences, particularly in the lower Pliocene and/or uppermost Miocene sections in Sites 1003–1005 and Site 1007. A reasonable planktonic foraminiferal biostratigraphic framework was possible for these sites because samples from thin, clay-rich layers contained moderately to well-preserved specimens throughout the lower Pliocene to Miocene interval. Better preservation of the specimens occurred in these layers because they were dominated by terrigenous sedimentation.

The planktonic foraminiferal zonation shows that Neogene sediments with a basal age of earliest Miocene were recovered from Holes 1003A–1003C. Four unconformities were identified on the basis of planktonic foraminiferal taxa. Upper Pliocene to Holocene sediments were recovered from Hole 1004. Sediment diagenesis prevented placement of the Pliocene/Pleistocene boundary. Middle Miocene to Pleistocene sediments were recovered from Holes 1005A–1005C. A large unconformity separates the lowermost upper Miocene and lower Pliocene sediments. At Site 1006, a complete middle Miocene to Pleistocene section was recovered, in contrast to the sites more proximal to the Bahamian platform. The lower Pliocene recorded high sedimentation rates. Holes 1007A–1007C recovered Neogene and uppermost Oligocene sediments. Three prominent unconformities were identified at the Pliocene/Pleistocene boundary, upper/lower Pliocene boundary and the Miocene/Pliocene boundary. The lower upper Miocene to uppermost Oligocene section appears to be complete at this site.

## INTRODUCTION

Understanding the rates, magnitude, and timing of sea-level change is a research priority for the Ocean Drilling Program (e.g., Imbrie et al., 1987; Watkins and Mountain, 1990; National Research Council, 1990; JOIDES Long Range Plan, 1996). The Bahamas Transect (Leg 166; Eberli, Swart, Malone, et al., 1997) was drilled to recover the sea-level record over the past 25 m.y. in a passive continental margin setting dominated by carbonate sedimentation. The sedimentary record of sea-level changes over this interval is characterized by large (>30 m), rapid (<0.5 m.y.) events (e.g., Miller et al., 1996). The most likely mechanism for these sea-level changes is glacio-eustasy because it can account for the magnitude and abruptness of these changes.

One of the primary objectives of Leg 166 was to document the timing, rates, and magnitudes of glacio-eustatic changes recorded in the sedimentary sequences along the leeward side of the Great Bahama Bank. Large-scale sea-level fluctuations over the past 25 m.y. (e.g., Haq et al., 1987) produced a series of prograding sedimentary sequences that resulted in the large carbonate platform that exists today. Five sites (Sites 1003–1007) recovered Neogene carbonate sediments along a transect in the Florida Straits designed to date the sedimentary sequences observed in seismic records (Fig. 1) (Eberli, Swart, Malone, et al., 1997). Sites 1003 and 1007 were drilled on the distal portion of the GBB slope and contain almost complete Neogene sequences. Sites 1004 and 1005 were drilled on the middle and upper slopes, respectively. Upper Pliocene to Holocene sediments were recovered from Site 1004, whereas an upper middle Miocene to Holocene sequence was recovered from Site 1005. A complete middle Miocene to Holocene sequence was recovered from Site 1006,

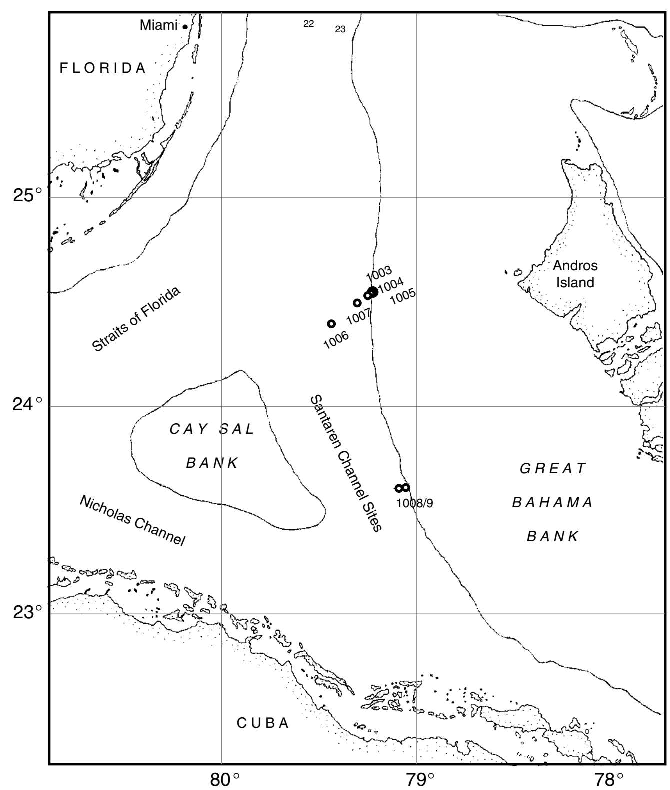


Figure 1. Location map of the Bahamas showing Leg 166 sites.

[1]Swart, P.K., Eberli, G.P., Malone, M.J., and Sarg, J.F. (Eds.), 2000. *Proc. ODP, Sci. Results,* 166: College Station TX (Ocean Drilling Program).

[2]Department of Geological Sciences, University of Maine, Orono ME 04401, USA. (Present address: Department of Geological Sciences, Rutgers University, Piscataway NJ 08854-8066, USA.) jdwright@rci.rutgers.edu

[3]Department of Geology and Geophysics, University of Edinburgh, Grant Institute, West Mains Road, Edinburgh EH9 3JW, Scotland, United Kingdom.

which was drilled in the Florida Straits. Sites 1008 and 1009 were drilled to the south and were positioned to meet the fluid-flow objective of Leg 166.

## METHODS

Samples of approximately 20-$cm^3$ volume were processed on board the ship and in shore-based laboratories. Processing included soaking in a Calgon solution and washing through a 63-µm sieve. Shipboard processing dried the samples under a heat lamp, whereas the shore-based processing dried the samples overnight in an oven at 50°C. More indurated sediments required light crushing and agitation in a heated Calgon solution. The >150-µm fraction was examined for planktonic foraminifers. In rare instances, the 63- to 150-µm fraction was studied for zonal markers if the markers were absent from the larger size fraction. The zonal scheme of Blow (1969), with slight modifications by Kennett and Srinivisan (1983) and Curry, Shackleton, Ritcher, et al. (1995), was used to subdivide the Neogene into planktonic foraminiferal zones. Age estimates for Cenozoic datum levels are taken from Berggren et al. (1995a, 1995b), except for the first occurrence (FO) of *Globigerinoides conglobatus* at 6.2 m.y. (Chaisson and Pearson, 1997) (Table 1).

## RESULTS

### Site 1003

Sediments recovered from three holes cored at Site 1003 provide a record for the lowermost Miocene through the Pleistocene. The abundance of planktonic foraminifers varies throughout the recovered sequence. Planktonic foraminifers are abundant and well preserved throughout the Pleistocene interval, but preservation rapidly deteriorates in the lower Pliocene sediments. The lowermost upper, middle, and lower Miocene sediments are characterized by moderately to poorly preserved tests; abundances vary from barren to abundant. The more terrigenous intervals in the lower Miocene sequence contain more abundant, better preserved microfossils. Three unconformities were found within the Miocene. It is not clear whether the Oligocene/Miocene boundary was penetrated. Planktonic foraminiferal events for Site 1003 are listed in Table 1 and shown in Figure 2.

Hole 1003A contains moderately to well-preserved upper Pliocene to Pleistocene planktonic foraminiferal assemblages (Zones N19–N22) (Fig. 2). The base of Zone N22 (2.0 Ma) is located between Cores 166-1003A-14X and 15X on the basis of the first occurrence (FO) of the zonal marker *Globorotalia truncatulinoides* in Sample 166-1003A-14X-CC. The FO of *Globorotalia tosaensis,* which delineates the Zone N20/N21 boundary (3.2 Ma), was found in Sample 166-1003A-17X-CC. Typically diverse upper Pliocene planktonic foraminiferal faunas including *Globorotalia limbata, Globorotalia exilis, G. tosaensis,* and *Neogloboquadrina humerosa,* are present in Cores 166-1003A-15X through 17X. Additional useful bioevents, including the last occurrences (LOs) of *Dentoglobigerina altispira* (3.0 Ma) and *Sphaeroidinellopsis* spp. (3.12 Ma), are identified within this interval in Sample 166-1003B-17X-CC.

Blow (1969) defines the base of Zone N20 by the FO of *Neogloboquadrina acostaensis pseudopima.* Specimens of *N. acostaensis* were rare in the Leg 166 sites and were not separated into subspecies. Berggren (1977) marked the lower/upper Pliocene (PL2/PL3 boundary) with the LO of *Globorotalia margaritae.* In Hole 1003A, the LO of *G. margaritae* lies in Sample 166-1003A-18X-CC, and is used to approximate the lower boundary of Zone N20 (3.6 Ma).

Planktonic foraminifers are rare to common in the upper part of the lower Pliocene sequence and preservation ranges from poor to good. Planktonic foraminiferal faunas within Cores 166-1003B-18X through 26X are assigned to Zone N19 on the basis of the presence of *G. margaritae* and *Globorotalia tumida* (Fig. 2). The LO of *Globigerina nepenthes* (4.18 Ma) and the FO of *G. conglobatus* (6.2 Ma) were found in Sample 166-1003A-23X-CC and in Sample 166-1003B-38X-CC, respectively.

**Table 1. Depth levels for planktonic foraminiferal events in Leg 166 sites.**

| | | Depth (mbsf) | | | | |
|---|---|---|---|---|---|---|
| Event | Age (Ma) | Site 1003 | Site 1004 | Site 1005 | Site 1006 | Site 1007 |
| T *Globigerinoides obliquus* | 1.3 | 98.36 | 109.6 | 182.9 | 69.35 | 22.57 |
| T *Globigerinoides extremus* | 1.77 | 109.05 | | | 88.2 | 53.54 |
| B *Globorotalia truncatulinoides* (N21/N22) | 2 | 123.75 | | 190.51 | 97.69 | 53.54 |
| T *Globorotalia exilis* | 2.2 | 132.7 | | | 107.18 | 53.54 |
| T *Globorotalia miocenica* | 2.3 | 132.7 | | | 116.8 | |
| T *Globorotalia limbata* | 2.3 | | | | 135.36 | 53.54 |
| T *Globorotalia pertenuis* | 2.6 | | 186.43 | 203.45 | | |
| T *Dentoglobigerina altispira* | 3.09 | 142.9 | | 226.72 | 145.42 | 200.34 |
| T *Sphaeroidinella* spp. | 3.12 | 147.24 | | 226.72 | | 200.34 |
| B *Globorotalia tosaensis* (N20/N21) | 3.2 | 151.27 | | | 154.78 | 200.34 |
| B *G. miocenica* | 3.55 | | | | 173.25 | |
| T *Globorotalia margaritae* (N19/N20) | 3.58 | 159.33 | | 260.17 | 173.25 | 200.34 |
| T *G. nepenthes* | 4.18 | 197.98 | | 274.1 | 240.28 | 200.34 |
| T *Globorotalia cibaoensis* | 4.6 | | | | 352.68 | |
| B *Globigerinoides conglobatus* | 6.2 | 355.61 | | | 436.04 | 327.87 |
| B *G. margaritae* (N19/N20) | 6.4 | | | | 454.96 | |
| B *G. cibaoensis* | 7.7 | | | | 483.07 | 327.87 |
| B *G. extremus* | 8.1 | | | | 492.05 | 327.87 |
| B *Neogloboquadrina humerosa* | 8.5 | 355.61 | | | | |
| B *Neogloboquadrina acostaensis* | 10.9 | | | 582.36 | 595.39 | 481.69 |
| T *Neogloboquadrina mayeri* (N14/N15) | 11.4 | 561.04 | | 595.78 | 595.39 | 481.69 |
| B *G. nepenthes* (N13/N14) | 11.8 | 630.52 | | 651.82 | 625.08 | 532.75 |
| T *Fohsella* (N12/N13) | 11.9 | 641.3 | | 670.9 | 639.96 | 542.48 |
| B *Fohsella fohsi* (N11/N12) | 12.7 | 802.55 | | | 682.02 | 742.12 |
| T *Fohsella praefohsi* (N10/N11) | 13.6 | 910.76 | | | | 791.54 |
| B *Globorotalia peripheroacuta* (N9/N10) | 14.8 | | | | | 800.2 |
| T *Praeorbulina sicana* | 14.8 | 910.76 | | | | |
| B *Orbulina universa* (N8/N9) | 15.1 | 910.76 | | | | 808.39 |
| B *P. sicana* | 16.4 | 1089.72 | | | | 910.25 |
| T *Catapsydrax dissimilis* | 17.3 | 1089.72 | | | | 925.35 |
| B *Globigerinatella insueta* | 18.8 | 1140 | | | | 973.41 |
| B *Globigerinoides altiapertura* | 20.5 | 1204.13 | | | | 1086.75 |
| T *Globorotalia kugleri* | 21.5 | 1204.13 | | | | 1099.62 |
| B *G. kugleri* | 23.8 | | | | | 1213.71 |

Note: B = base, T = top.

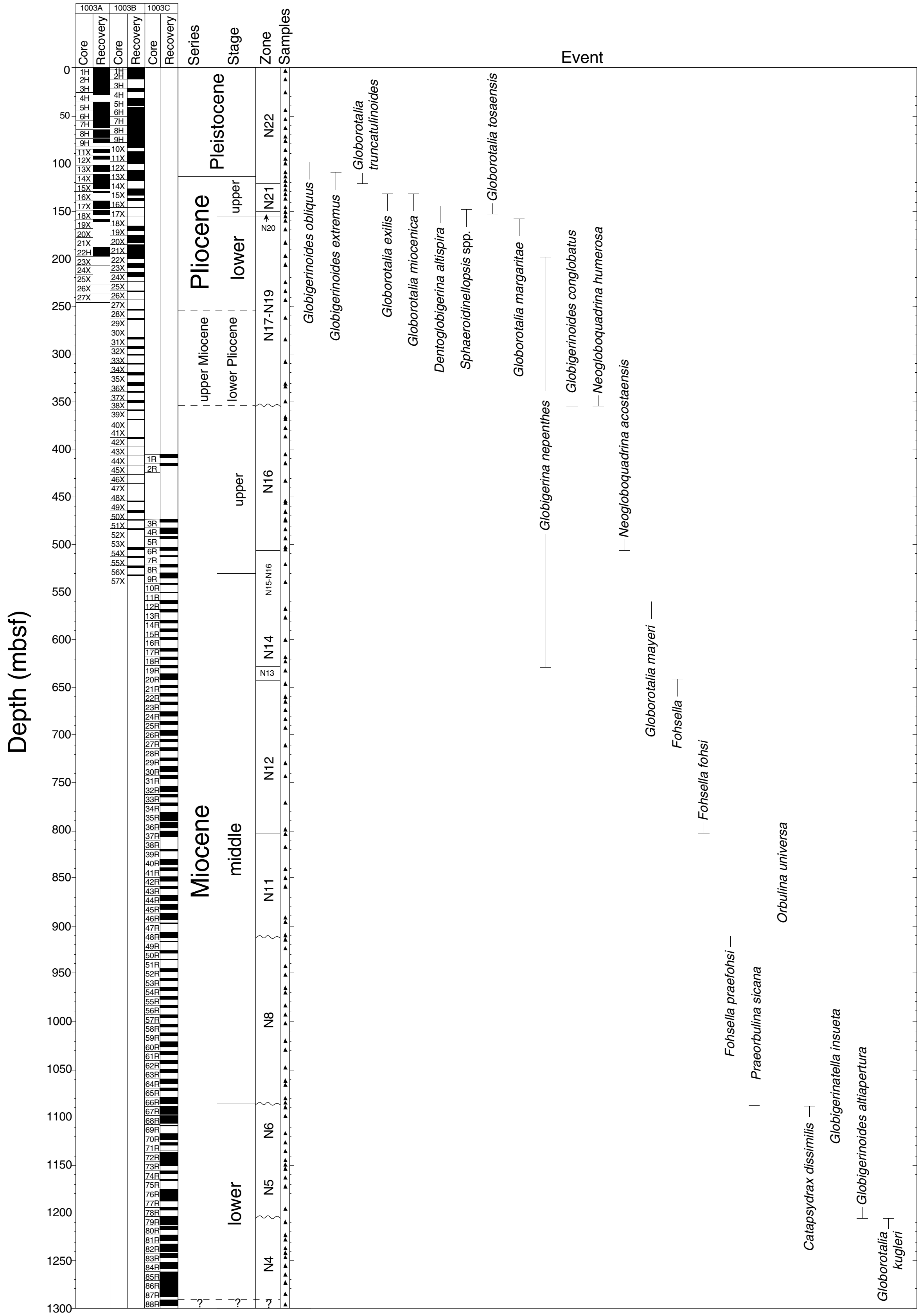


Figure 2. Planktonic foraminiferal zonation for Site 1003. Core recovery is indicated by the black shading. Sampling levels for the biostratigraphic analysis are indicated by solid triangles. The first and last occurrence of indicator species are shown in the right panel.

Planktonic foraminiferal specimens are generally rare and poorly preserved in Cores 166-1003B-39X to 54X, which makes zonal assignment difficult in this interval. Sample 39X-1, 41-43 cm, contains upper Miocene N16 species including *N. acostaensis, Globorotalia lenguaensis,* and *Globorotalia merotumida.* There is no evidence for the presence of upper Miocene Zone N17 because *N. humerosa* (FO at 8.5 Ma) is absent in this interval. Samples 166-1003C-6R-CC and 8R-CC contain numerous *Neogloboquadrina continuosa* and *G. merotumida* specimens but no *N. acostaensis*.

Berggren et al. (1985) pragmatically placed the middle/upper Miocene boundary with the FO of *N. acostaensis* (base of Zone N16), but this interpretation was subsequently shown to be incorrect (Berggren et al., 1995a). Furthermore, specimens of *N. acostaensis* recorded only scattered occurrences in this section (Fig. 2). For graphical purposes, the middle/upper Miocene boundary at Site 1003 is identified on the basis of the FO of the nannofossil species *Discoaster hamatus* (Kroon et al., Chap. 15, this volume). Zone N15 is a gap zone between the FO of *N. acostaensis* and LO of *Neogloboquadrina mayeri*. The top of *N. mayeri* was found in Sample 166-1003C-14R-2, 37–40 cm, marking the N14/15 boundary. Because the FO of *N. acostaensis* may be unreliable, the interval between Samples 166-1003C-6R-CC and 14R-2, 37–40 cm, was assigned to an undifferentiated Zone N15–16. The FO of *Globigerina nepenthes* defines the base of Zone N14 and occurs between Samples 166-1003C-19R-CC and 20R-CC. Zone N13 is the “gap” between the FO of *Globigerina nepenthes* and FO of *Fohsella* spp., delineating the lower boundary. In Hole 1003C, only Sample 166-1003C-20R-CC is assigned to this zone.

The middle Miocene *Fohsella* bioseries, which forms the basis for the middle Miocene N9–N12 zonation, is represented by most of the taxa in this group at Site 1003 (Fig. 2). However, the FO of *Globorotalia praefohsi,* which denotes the lower limit of Zone N11, coincides with the FO of *Orbulina universa* in Sample 166-1003C-47R-CC. This association in Hole 1003C indicates that Zones N9 and N10 are absent or that there is either an extremely condensed section.

The lower/middle Miocene boundary is identified by the FO of *Praeorbulina sicana* between Samples 166-1003C-66R-CC and 1003C-67R-3, 114–116 cm (Fig. 2). This level also marks the upper limit of Zone N6. The FO of *Catapsydrax dissimilis,* the indicator of the lower boundary of Zone N7, and the FO of *P. sicana* occur in adjacent samples, indicating that Zone N7 is missing. The FO of *Globigerinatella insueta,* which correlates with the lower boundary of Zone N6, is found in Sample 166-1003C-72R-3, 27–29 cm. The next biohorizon recognized is the FO of *Globigerinoides altiapertura* (20.5 Ma) in Sample 166-1003C-78R-2, 121–123 cm. Rare *Globorotalia kugleri* specimens are found in Section 166-1003C-79R-5, 94–96 cm. The top of its age range is 21.5 Ma; thus, another hiatus or very condensed section separates Zones N4 and N5.

Samples from the bottom of Hole 1003C are characterized by the presence of the lowermost Miocene planktonic foraminiferal assemblages. The Oligocene/Miocene boundary is indicated by the FO of *G. kugleri*. Only rare specimens of this species are found in the bottom section and cannot be relied upon to mark the boundary. Specimens of Oligocene character occur including *Globigerina ciperoensis,* but this species is known to cross the boundary. We cannot place the boundary on the basis of the distribution of the age-diagnostic species of planktonic foraminifers.

## Site 1004

Sediments recovered from Hole 1004A provide a record for the uppermost Pliocene through Pleistocene sections. Planktonic foraminifers are abundant and well preserved in the uppermost Pleistocene interval (Cores 166-1004A-1H and 2H). Planktonic foraminifers recovered from Hole 1004A are generally poorly preserved in the samples examined except in the uppermost Pleistocene sediments. Below this level, abundances vary considerably from barren to abundant, whereas preservation is only poor to moderate. Reworking of a few older Miocene specimens is noted in several samples. Planktonic foraminiferal events are listed in Table 1 and shown in Figure 3.

It is not possible to place the N21/N22 zonal boundary (2.0 Ma) accurately using planktonic foraminifers because of the poor preservation and low abundances in the lower Pleistocene and uppermost Pliocene sediments (Fig. 3). The FO of *G. truncatulinoides* marks this boundary and occurs in Sample 1004A-13X-CC. Calcareous nannofossils indicate that this level is in the mid-Pleistocene and that the Zone N21/N22 boundary should occur within or below Core 166-1004A-19X. Foraminifers are rare at best and poorly preserved in Cores 166-1004A-14X through 19X. Taxa in Sample 166-1004A-22X-CC include *G. limbata* and *Globorotalia pertenuis,* placing this level in the upper Pliocene Zone N21.

## Site 1005

Site 1005 is the closest of the sites drilled on Leg 166 to the Great Bahama Bank. The upper Pleistocene sediments (Cores 166-1005A-1H to 14X) contain abundant, well-preserved planktonic foraminifers. The lower Pleistocene section (Cores 166-1005A-15X to 23X) yields sparse to common specimens with poor preservation in general. The shift from well to poorly preserved assemblages coincides with the change from unaltered to partially dolomitized carbonate. Planktonic foraminiferal events are listed in Table 1 and shown in Figure 4.

The upper Pleistocene section (Cores 166-1005A-1H through 14X) contains abundant, well-preserved foraminifers, whereas the lower Pleistocene (Cores 166-1005A-15X-CC through 23X-CC) generally yields sparse to common, poorly preserved specimens. *Globorotalia truncatulinoides* is present throughout both intervals, indicating the extent of Zone N22 from the top of the borehole to the depth between Samples 166-1005A-23X-CC and 24X-CC (Fig. 4).

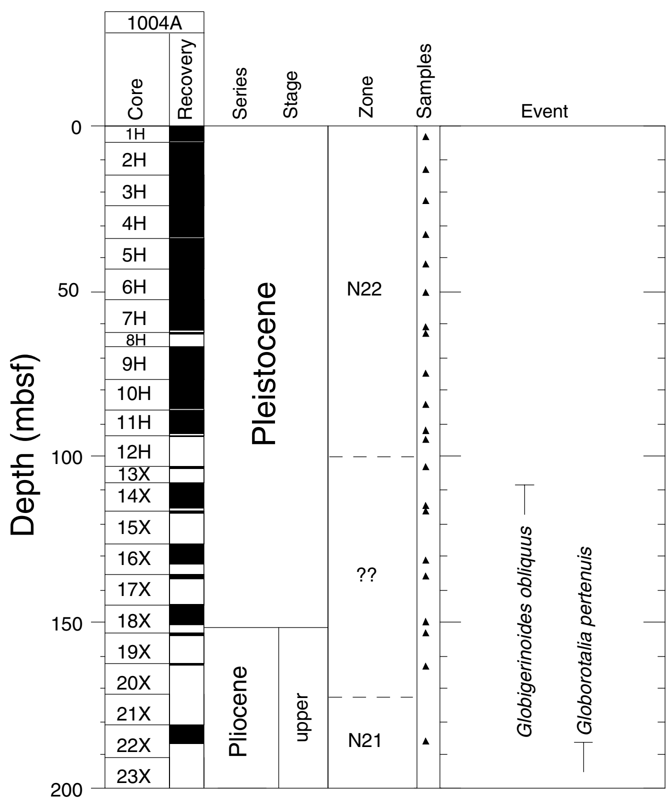


Figure 3. Planktonic foraminiferal zonation for Site 1004. Core recovery is indicated by the black shading. Sampling levels for the biostratigraphic analysis are indicated by the triangles. The first and last occurrence of indicator species are shown in the right panel.

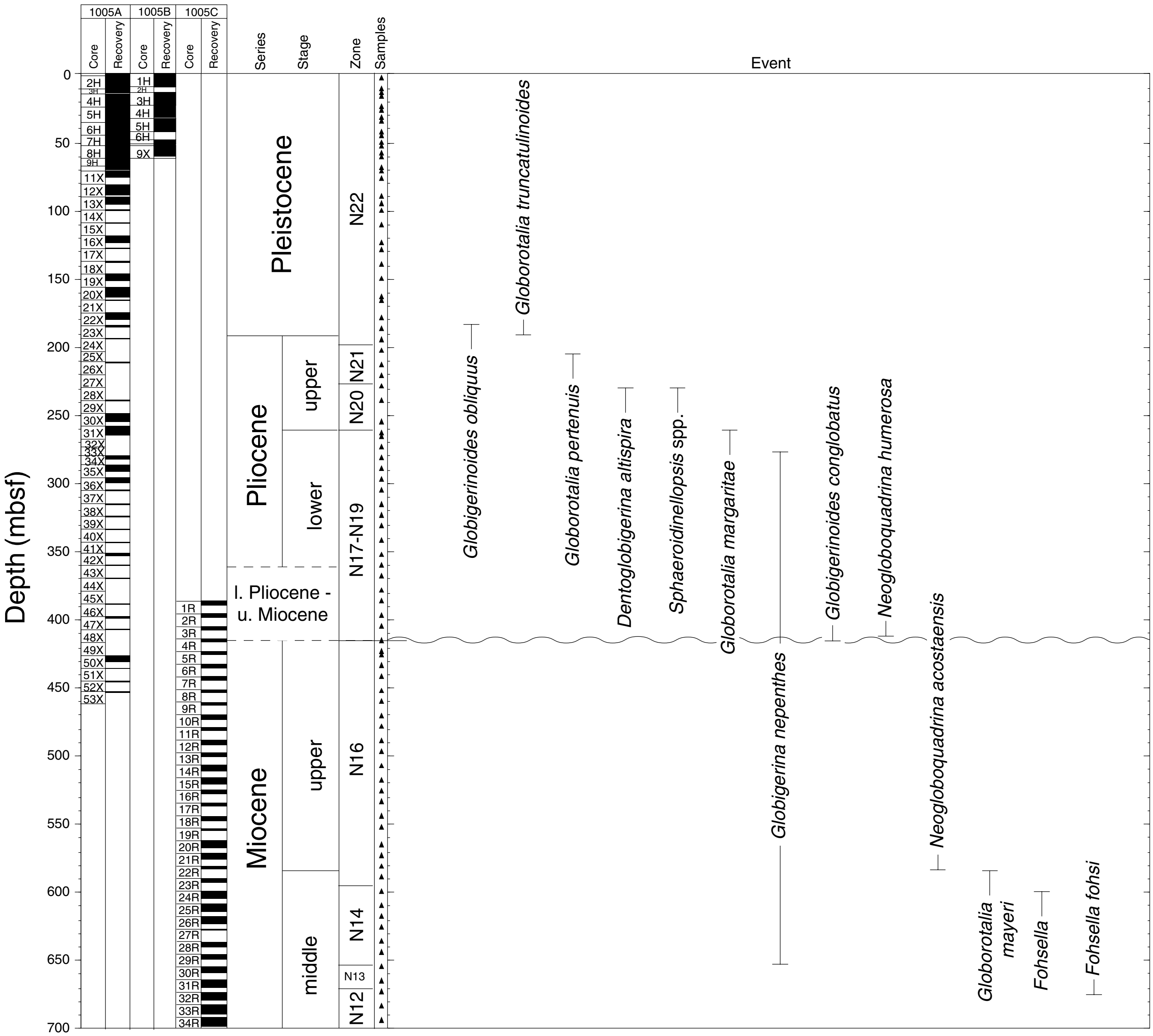


Figure 4. Planktonic foraminiferal zonation for Site 1005. Core recovery is indicated by the black shading. Sampling levels for the biostratigraphic analysis are indicated by the triangles. The first and last occurrence of indicator species are shown in the right panel.

The absence of *G. truncatulinoides* in Sample 166-1005A-24X-CC indicates that this level is in Zone N21. No sediments were recovered from Core 166-1005A-25X, and Sample 166-1005A-26X-1, 62–64 cm, contains an abundant, moderately preserved upper Pliocene fauna including *G. tosaensis, G. exilis,* and *G. pertenuis.* The absence of *D. altispira* and the presence of *G. pertenuis* indicate that the age of this sample is between 2.6 and 3.0 Ma (Zone N21). No sediments were recovered from Cores 166-1005A-27X and 28X, but an upper Pliocene fauna was found in Cores 166-1005A-29X and 30X. The absences of *G. tosaensis* and *G. margaritae* indicate that this interval correlates to Zone N20 (3.2–3.55 Ma).

Planktonic foraminifers are common to abundant and moderately preserved in the interval from Cores 166-1005A-31X to 41X, although in some samples only few foraminifers can be found. Lower Pliocene assemblages, particularly the presence of *G. margaritae,* indicate that this section corresponds to Zone N19 (Fig. 4). Samples 166-1005A-42X-CC to 53X-CC contain rare to common specimens that are poorly preserved, making age assignment difficult. Although the lower Pliocene fauna is similar to the upper Miocene fauna, it should contain the delicate species *G. margaritae* and rare *G. tumida* (the indicator of lower Pliocene Zone N19). Both species are absent in the interval from Samples 166-1005A-42X-CC to 53X-CC (Fig. 4). *Globigerinoides conglobatus,* a proxy for the FO of *G. tumida,* is found down hole through Sample 166-1005A-48X-CC at a level of 415 mbsf. However, the FO datum of *G. conglobatus* is slightly older than that of *G. tumida,* occurring in the uppermost upper Miocene (Messinian). Therefore, it is possible that uppermost Messinian sediments are in and above Core 166-1005A-48X.

The severe decline in preservation and abundance of planktonic foraminifers in the lower Pliocene sediments necessitates discrete sampling from clay-rich layers within the cores because they contain better preserved taxa. Below Core 166-1005A-48X, assemblages contain *G. lenguaensis, G. merotumida,* and *N. continuosa,* placing this interval in upper Miocene Zone N16 (Fig. 4). The juxtaposition of the lower Pliocene (Sample 166-1005A-48X-CC) with lowermost upper Miocene (Sample 166-1005C-5R-1, 33–36 cm) indicates an unconformable Miocene/Pliocene boundary at approximately 415 mbsf. The base of the upper Miocene, Zone N16, is indicated by the FO of *N. acostaensis* between Samples 166-1005C-21R-2, 97–99 cm, and 23R-1, 84–88 cm (582 mbsf).

The uppermost middle Miocene Zone N15 is represented only by Sample 166-1005C-23R-1, 84-88 cm (Fig. 4). The LO of *N. mayeri* (11.4 Ma) is found in Sample 166-1005C-24R-2, 52–54 cm, and places the top of Zone N14 at 596 mbsf. The base of Zone N14 (11.8 Ma) is placed at 651 mbsf between Samples 166-1005C-29R-1, 65–67 cm, and 30R-3, 18–20 cm, as indicated by the FO of *Globigerina nepenthes*. The LO of the *Fohsella* species marks the upper limit of Zone N12 between Samples 166-1005C-31X-CC and 32R-1, 100–102 cm (670 mbsf). The bottom of Hole 1005C (700 mbsf) is still within the middle Miocene planktonic foraminiferal Zone N12.

## Site 1006

Sediments recovered from Site 1006 yield common to abundant middle Miocene to upper Pleistocene planktonic foraminifers. Biostratigraphic control at Site 1006 is very good, and almost all planktonic foraminiferal zones from the upper middle Miocene to Pleistocene were found. The abundant pelagic biogenic components are less diluted by platform-derived material, and microfossil preservation is less affected by diagenesis than in the upper slope sites. Site 1006 has an expanded lower Pliocene section that is ideal for paleoceanographic studies. Preservation of microfossils is generally good throughout, which allows a reliable, high-resolution biostratigraphy for Site 1006. Planktonic foraminiferal events are listed in Table 1 and shown in Figure 5. A more detailed middle Miocene-early Pliocene planktonic foraminiferal biostratigraphy for Site 1006 is presented in Kroon et al. (Chap. 15, this volume).

The lowest level of *G. truncatulinoides,* marking the base of Zone N22 (2.0 Ma), occurs in Sample 166-1006A-10H-CC (Fig. 5). Below this level, we find the FOs of the upper Pliocene planktonic foraminifers *G. exilis* (2.2 Ma; Sample 166-1006A-12H-CC), *Globorotalia miocenica* (2.3 Ma; 166-1006A-13H-CC), *G. limbata* (2.4 Ma; 166-1006A-15H-CC), and *D. altispira* (3.0 Ma; 166-1006A-16H-CC). The N20/N21 boundary (3.2 Ma) is marked by the FO of *G. tosaensis* and occurs between Samples 166-1006A-16H-CC and 17H-CC (155 mbsf). The lower limit of Zone N20 is placed between Samples 166-1006A-19H-CC and 20H-CC (173 mbsf), based on the FO of *G. miocenica* (3.55 Ma). Coeval with this level is the LO of *G. margaritae* (3.58 Ma).

Lower Pliocene Zones N18 and N19 extend from Sample 166-1006A-19H-CC through 42H-CC; the boundary between Zones N18/N19 was tentatively placed between Samples 166-1006A-42X-CC and 43X-CC, on the basis of the FO of *Sphaeroidinella dehiscens* (5.2 Ma) in Sample 166-1006A-42X-CC (Fig. 5). Specimens of this species were rare in the Leg 166 holes. However, this level coincides with the Miocene/Pliocene boundary and corroborates the placement of the boundary as indicated by the FO of *Discoaster quinqueramus* (Kroon et al., Chap. 15, this volume). Within Zone N19, the LO of *Globigerina nepenthes* (4.2 Ma) is recorded between Samples 166-1006A-25H-CC and 26H-CC (240 mbsf). The LO of *Globorotalia cibaoensis* (4.6 Ma) is found between Samples 166-1006A-38X-CC and 39X-CC (353 mbsf).

Upper Miocene planktonic foraminiferal events, the FOs of *G. conglobatus* (6.2 Ma) and *G. margaritae* (6.4 Ma), are found between Samples 166-1006A-47X-CC and 48-CC (436 mbsf) and Samples 1661006A-49X-CC and 50X-CC (455), respectively (Fig. 5). However, the LO of small *Reticulofenestra* spp. (6.5 Ma) occurs much higher, at a level of 419 mbsf (Kroon et al., Chap. 15, this volume). Either the FOs of *G. conglobatus* and *G. margaritae* are older in this area or the age for the top of the LO of small *Reticulofenestra* spp. is too young.

The base of *Globigerinoides extremus* (8.3 Ma) is a useful datum in the upper Miocene because the FO of this species is coeval with *Globorotalia plesiotumida,* the marker for the base of Zone N17 (Berggren et al., 1995b). At Site 1006, *G. extremus* first appears between Samples 166-1006A-53X-CC and 54X-CC (492 mbsf) (Fig. 5). The base of Zone N16 is marked by the FO of *N. acostaensis* (10.9 Ma). This event occurs between Samples 166-1006A-64X-CC and 65X-CC (595 mbsf). The LO of *N. mayeri* (11.4 Ma) between Samples 166-1006A-64X-CC and 65X-CC (595 mbsf) defines the N14/N15 zonal boundary. The juxtaposition of *N. acostaensis* and *N. mayeri* indicates that Zone N15 is not present at Site 1006, and is, therefore, either missing or very condensed. Within Core 166-1006A-65X, there is a series of firmgrounds indicative of a break in continuous sedimentation (Eberli, Swart, Malone, et al., 1997). The short middle Miocene Zone N13, characterized by the absences of *Globigerina nepenthes* and the *Fohsella* spp., is found in Sample 166-1006A-68X-CC. This zone could possibly extend farther down hole, but the preservation of the planktonic foraminifers in the next two lower core-catcher samples of Cores 166-1006A-69X and 70X is insufficient to make a zonal assignment. The interval including Samples 166-1006A-71X-CC through 77X-CC, the lowest part of Hole 1006A, corresponds to Zones N11 and N12, as indicated by the presence of *Fohsella fohsi fohsi, Fohsella fohsi robusta,* and *Fohsella fohsi lobata* (Zone N12), and *Fohsella praefohsi* (Zone N11).

## Site 1007

The sedimentary sequence recovered from the three holes cored at Site 1007 consists of a 1230-m-thick interval of upper Oligocene to Pleistocene sediments. The section includes a relatively condensed Pleistocene interval compared to Pleistocene sequences at the other transect sites higher up on the slope of the Great Bahama Bank. Pleistocene calcareous microfossils are abundant and moderately to well preserved. The expanded upper Pliocene section lies unconformably below the Pleistocene interval and yields varying abundances of microfossils. The preservation varies from poor to moderate to good. Another unconformity separates the lower and upper Pliocene, and the lower Pliocene is a thick, continuous sequence. The Miocene/Pliocene boundary occurs between Cores 166-1007B-32X (289 mbsf) and 1007C-1R-1 (303 mbsf). It is impossible to locate the boundary more precisely because of the poor preservation and absence of nannofossil and planktonic foraminiferal marker species. Several Miocene planktonic foraminiferal events occur between Samples 166-1007C-3R -CC (323.35 mbsf) and 1007C-4R-2, 9–10 cm (332.39 mbsf), indicating the presence of an unconformity similar to those found at Sites 1003 and 1005. Calcareous microfossils in the upper Miocene sediments are highly variable and preservation is generally poor, although a few samples yield well-preserved faunas.

The middle/upper Miocene boundary is placed between Samples 166-1007C-19R-1, 67–70 cm (475.87 mbsf), and 20R-2, 121-123 cm (487.51 mbsf). A well-constrained biostratigraphy is provided by the nannofossils and planktonic foraminifers for the lower and middle Miocene interval. The lower/middle Miocene boundary occurs between Samples 166-1007C-63R-1 and 65R-3, 99–103 cm, at a level of 910 mbsf. The lower-middle Miocene biostratigraphic sequence appears to be continuous. Three intervals of reduced sedimentation occur within the sequence and are correlated to the time-equivalent hiatuses at Site 1003. The microfossils mainly occur within the clayey intervals and show varying states of preservation from poor to good. The base of the sedimentary sequence is assigned to the upper Oligocene calcareous nannofossil Zone NP25 and the planktonic foraminiferal Zone P22. In summary, the numerous biohorizons (Table 1; Fig. 6), including most marker species for zonal assignment, provide sufficient detail to construct a reliable biostratigraphy for the sedimentary sequence recovered at Site 1007.

The planktonic foraminiferal assemblages of Holes 1007A and 1007B are typically abundant and well preserved in the upper Pliocene and the Pleistocene. Samples 166-1007A-1H-CC and 166-1007B-1H-CC to 5H-CC contain highly diverse assemblages typified by *G. truncatulinoides* and *G. tosaensis* (Fig. 6). The presence of *G. tosaensis* in Samples 166-1007A-1H-CC indicates that the upper part

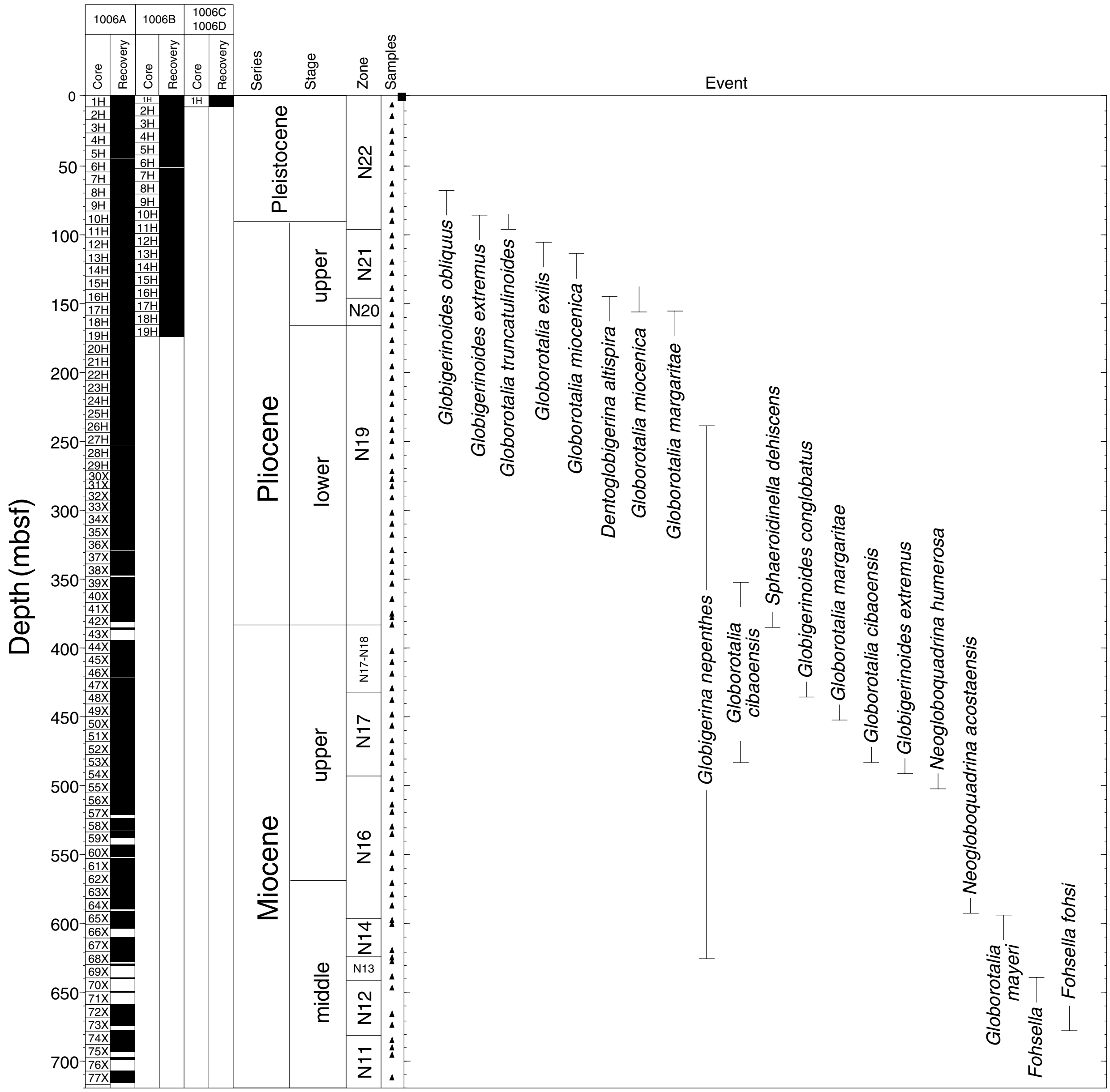


Figure 5. Planktonic foraminiferal zonation for Site 1006. Core recovery is indicated by the black shading. Sampling levels for the biostratigraphic analysis are indicated by the triangles. The first and last occurrence of indicator species are shown in the right panel.

of the Pleistocene is missing at this site because the top of the *G. tosaensis* range is 0.6 Ma. The presence of *G. truncatulinoides* assigns this interval to Zone N22.

Samples 166-1007B-6H-CC to 22X-CC appear to represent an expanded sequence of upper Pliocene Zone N21. Planktonic foraminiferal assemblages are highly diverse and the preservation varies from moderate to good, although the preservation deteriorates somewhat in the lowest part of the upper Pliocene. Several samples contained abundant reworked Zone N19 planktonic foraminifers, making zonal assignment difficult. Most of the samples in this interval are characterized by the presence of *G. tosaensis, G. limbata, G. miocenica,* and *G. extremus* (Fig. 6). The LO of last of these three species occurs in Sample 1007B-6H-CC. Based on the ages of their LOs (2.3 Ma for *G. miocenica,* 2.4 Ma for *G. limbata,* and 1.8 Ma for *G. extremus*) and juxtaposition with the FO of *G. truncatulinoides,* a hiatus is placed just below the Pliocene/Pleistocene boundary.

Samples 166-1007B-23X-3, 66–68 cm, to 31X-CC yield diverse lower Pliocene assemblages. The planktonic foraminifers are generally abundant and preservation is moderate to good in the upper part of this interval. Planktonic foraminifers in the lowest lower Pliocene (Samples 166-1007B-30X-CC and 31X-CC) are poorly preserved. These assemblages are characterized by *D. altispira, G. margaritae,* and *Globigerina nepenthes* (Fig. 6). The latest occurrences of *D. altispira* (3.1 Ma), *G. margaritae* (3.6 Ma), and *Globigerina nepenthes* (4.12 Ma) are in Sample 166-1007B-23X-3, 66–68 cm. The FOs of *G. tosaensis* (3.2 Ma) and *G. miocenica* (3.6 Ma) occur in Sample 166-1007B-22X-CC, indicating that the lower/upper Pliocene boundary is unconformable, extremely condensed, or there is substantial reworking of lower Pliocene specimens.

Samples 166-1007B-32X-1, 68–69 cm (286.68 mbsf), to 166-1007C-3R-CC, 5–7 cm (323.35 mbsf), yield rare to abundant planktonic foraminifers with varying preservation. The FO of *G. conglobatus* in Sample 166-1007C-3R-CC, 5–7 cm, the lowermost sample of this sequence, indicates an age of 6.2 Ma for the lower boundary of this section (Fig. 6). The LO of the nannofossil small *Reticulofenestra* spp., 6.5 Ma, occurs 20 m above this level (Kroon et al.,

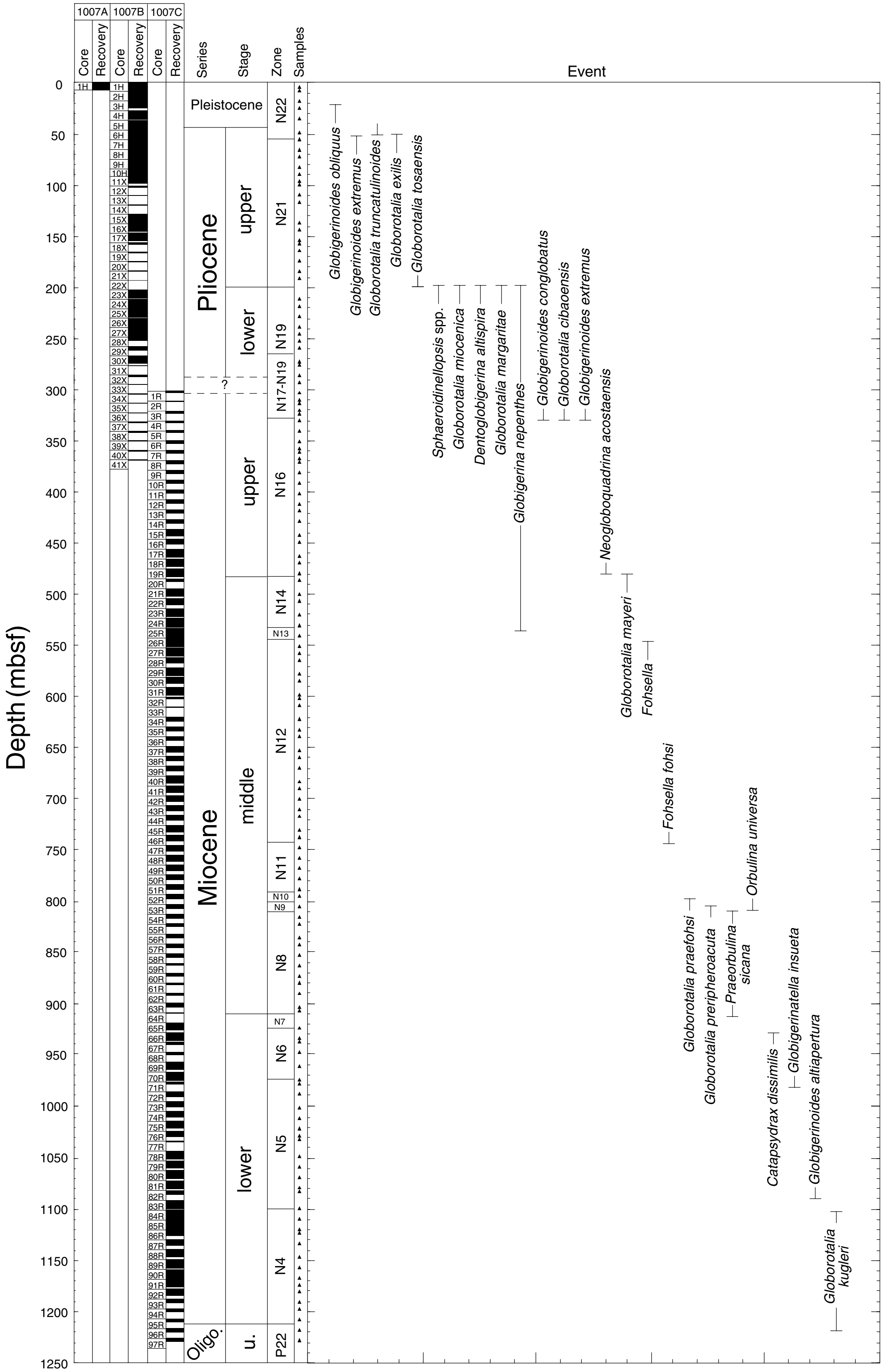


Figure 6. Planktonic foraminiferal zonation for Site 1007. Core recovery is indicated by the black shading. Sampling levels for the biostratigraphic analysis are indicated by the triangles. The first and last occurrence of indicator species are shown in the right panel.

Chap. 15, this volume). Either the FO of *G. conglobatus* is older in this area or the latest occurrence of small *Reticulofenestra* spp. is younger. Nonetheless, this overlap between *G. conglobatus* and the small *Reticulofenestra* spp. indicates that the interval between 303 and 328 mbsf is uppermost Miocene. The Miocene/Pliocene boundary lies above this interval, between 287 and 304 mbsf (Kroon et al., Chap. 15, this volume).

The lowermost appearances of *G. cibaoensis* (7.7 Ma) and *G. extremus* (8.1 Ma) are found between Samples 166-1007C-3R-CC and 4R-2, 9–10 cm, at the same level as the lowermost occurrence of *G. conglobatus,* indicating the presence of an unconformity. The interval between Samples 166-1007C-4R-2, 9–10 cm, and 19R-1, 67–70 cm, is characterized by upper Miocene species. The absence of *N. humerosa* indicates that the sediments below the unconformity are assigned to Zone N16. The base of this zone is defined by the FO of *N. acostaensis* (10.9 Ma), which occurs between Samples 166-1007C-19R-1, 67–70 cm, and 20R-2, 121–123 cm (482 mbsf). The appearance of this species also approximates the middle/upper Miocene boundary and is consistent at Site 1007 with the nannofossil event used to place this boundary.

Middle Miocene Zone N14 is the concurrent range of *N. mayeri* and *Globigerina nepenthes* (Fig. 6). The LO of *N. mayeri* (11.3 Ma) at Site 1007 occurs between Samples 166-1007C-24R-6, 28–31 cm, and 25R-2, 2-5 cm (482 mbsf), immediately below the base of N16. The FO of *Globigerina nepenthes* (11.8 Ma) is between Samples 166-1007C-25R-2, 2-5 cm, and 26R-6, 53-55 cm (533 mbsf). Zone N13 is represented by one sample at Site 1007, Sample 166-1007C-25R-2, 2–5 cm. The top of the *Fohsella* lineage (11.9 Ma) and Zone N12 occurs in Sample 166-1007C-6R-6, 53–55 cm (550 mbsf). There are ~200 m of sediments within Zone N12, the base of which is marked by the FO of *G. fohsi fohsi* (13.2 Ma) between Samples 166-1007C-46R-3, 50–33 cm, and 47R-2, 0–2 cm at a level of 742 mbsf. The FO of *G. praefohsi* and the base of Zone N11 occurs in Sample 166-1007C-51R-3, 118–125 cm (791 mbsf). Zones N10 and N9 are represented by only one sample each at Site 1007. The base of Zone N10 is defined by the FO of *Globorotalia peripheroacuta* (14.8 Ma) between Samples 166-1007C-52R-3, 30–32 cm, and 53R-2, 80–87 cm (800 mbsf). The FO of *O. universa* (15.1 Ma) and top of Zone N9 occurs between Samples 166-1007C-53R-2, 80-87 cm, and 54R-1, 31-33 cm (808 mbsf). The lowermost zone in the middle Miocene is Zone N8 and is defined as the range from the FO of *P. sicana* (16.4 Ma) to the FO of *O. universa.* The base of *P. sicana* occurs between Samples 166-1007C-63R-1, 60–64 cm, and 65R-3, 99–103 cm (910 mbsf).

The uppermost lower Miocene Zone N7 is the interval between the LO of *C. dissimilis* (17.3 Ma) and the base of *P. sicana*. At Site 1007, Zone N7 is represented by only Sample 166-1007C-65R-3, 99–103 cm (921 mbsf) (Fig. 6). Planktonic foraminifers are rare and are not well preserved in this sample. However, samples above and below with similar abundances and preservation yielded several specimens of *P. sicana* and *C. dissimilis,* respectively, indicating that this zone is real. The marker for the base of Zone N6 (18.8 Ma) is the FO of *G. insueta.* At Site 1007, the abundance of this species is rare at best and its FO is found between Samples 166-1007C-70R-4, 106-109 cm, and 71R-1, 25–28 cm (973 mbsf).

Zone N5 spans the interval from the LO of *G. kugleri* (21.5 Ma) up to the FO of *G. insueta* (18.8 Ma). At Site 1007, this interval occurs from Sample 166-1007C-71R-1, 25–28 cm (975 mbsf), downhole to the base of Zone N5, which is found between Samples 166-1007C-83R-3, 28–30 cm, and 84R-3, 136–137 cm (1100 mbsf) (Fig. 6). Within Zone N5, the FO of *G. altiapertura* (20.5 Ma) is also a useful datum and occurs between Samples 166-1007C-81R-6, 2224 cm, and 83R-3, 28-30 cm (1087 mbsf). Zone N4 is the total range of *G. kugleri* (21.5 to 23.8 Ma). At Site 1007, this zone ranged between Samples 166-1007C-84R-3, 136–137 cm, and 95R-1, 148-150 cm (1100 to 1214 mbsf). Zone N4 is not subdivided into Zones N4b and N4a because the marker species, *Globoquadrina dehiscens,* is found sporadically at this site. Below Zone N4, Samples 166-1007C-96R-3, 0–2 cm, and 97R-1, 130–133 cm, are dominated by *G. ciperoensis, Globigerina angulisuturalis,* and *Globigerinoides primordius,* which are indicative of and consistent with the upper Oligocene assignment indicated by the nannofossils (Kroon et al., Chap. 15, this volume).

### Sites 1008/1009

Sites 1008 and 1009 recovered expanded sections of Pleistocene sediments. The presence of *G. truncatulinoides* restricts the foraminiferal zonation to Zone N22 for both sites. Upper Pliocene faunas and floras were found in the lower parts of the hole, indicating substantial reworking. Planktonic foraminifers recovered from Sites 1008 and 1009 are generally rare to common and preservation is very good in the upper parts of Holes 1008A and 1009A.

In Samples 166-1009A-1H-CC through 3H-CC, planktonic foraminiferal tests are transparent and seem to indicate a Holocene age. In the lower sections of both holes, planktonic foraminifers are common to abundant, but preservation deteriorated significantly with many specimens being completely recrystallized, discolored, or phosphatized. The presence of *G. truncatulinoides* in the lowermost samples at Holes 1008A and 1009A indicates that the recovered sediments from both sites are assignable to Zone N22. Reworking occurs throughout the lower intervals. Species from Zones N20 and N21, including *G. extremus, Globigerinoides fistulosis, G. miocenica,* and *G. limbata,* are found in Samples 166-1008A-7H-CC through 15H-CC and Samples 166-1009A-12 H-CC through 28H-CC.

## DISCUSSION AND CONCLUSIONS

Planktonic foraminifers recovered from Leg 166 drilling exhibited a progression from well-preserved to poorly preserved specimens with increasing depth. The high carbonate production and shedding from Great Bahama Bank diluted the pelagic biogenic sediment components to the extent that planktonic foraminifers show scattered occurrences, particularly in the lower Pliocene and/or uppermost Miocene in Sites 1003–1005 and Site 1007. However, a reasonable biostratigraphic framework could be constructed for these sites because thin layers dominated by terrigenous sedimentation contained moderately well preserved specimens throughout the lower Pliocene to Miocene interval. Because of the rarity of some age-diagnostic species, it was not always possible to place the zonal boundaries with certainty; however, the timing of foraminiferal biohorizons was consistent with the nannofossil biostratigraphy.

Most of the indicator species were found in sufficient number to render a more reliable biostratigraphic framework for the more distal sites (Sites 1006 and 1007). These sites also contained better preserved planktonic foraminifers and more complete Neogene sequences. For example, Sites 1003 and 1007 were drilled ~5 km apart and recovered similar sedimentary sequences. However, where Site 1003 recorded unconformities indicated by the juxtaposition of zonal taxa, Site 1007 recorded an apparently continuous section but with a reduced rate of sedimentation instead of hiatuses (Eberli, Swart, Malone, et al., 1997). Sedimentation rates at the most distal Site 1006 were the most constant, recording substantially higher rates in only the lower Pliocene.

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