Neogene planktonic foraminiferal biostratigraphy of the northeastern Gulf of Mexico

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ABSTRACT: We have evaluated the planktonic foraminiferal biostratigraphy of several Gulf of Mexico Eureka boreholes, emphasizing the Miocene depositional history of the northeastern region (De Soto Canyon). The E68-136 borehole (De Soto Canyon; 1826', 557 m present depth) provides the most continuous Miocene record, although deposition was punctuated by several short (<2.0 m.y.) hiatuses. The E66-73 borehole (De Soto Canyon; 2802', 854 m present depth) provides an uppermost lower to upper Miocene and upper Pleistocene record. E68-151 (north of the Florida Escarpment; 4340', 1323 m present depth) provides a discontinuous record of lower, upper middle, and upper upper Miocene sediments. By integrating planktonic foraminiferal biostratigraphy with nanoplankton biostratigraphy and Sr-isotope stratigraphy, we were able to estimate the ages of the hiatuses associated with six distinct unconformities at E68-136 (23.7-23.2 Ma; 18.0-16.5 Ma; 16.3-15.2 Ma; 14.1-13.6 Ma; 10.4-9.5 Ma; 5.0-1.9 Ma), three at E66-73 (~11.5-10.8 Ma; 10.3-9.2 Ma; 6.5-1.7 Ma), and two at E68-151A (19.0-12.6 Ma; 12.5-6.9 Ma). We correlate these unconformities with previously reported unconformities from other deep-sea locations, although their causes (i.e., whether related to sea-level or deep-water changes) remain uncertain. We relate a distinct Pliocene unconformity to intensification of the Loop Current associated with the closure of the Isthmus of Panama.

INTRODUCTION

Cenozoic planktonic foraminiferal biostratigraphy of the Gulf of Mexico developed with the efforts of industry and drilling by the Deep Sea Drilling Project (DSDP). In particular, regional zonations were developed for Neogene planktonic foraminifera, and their global correlations were established (Berggren et al. 1986; Lamb and Beard 1972; Smith and Beard 1973; Smith and McNeely 1973; Poag 1977; Stude 1984; Bouma, Coleman, et al. 1986). While Gulf of Mexico zonations for the Miocene-Pliocene use global and regional biomarkers, Pleistocene planktonic foraminiferal biostratigraphy of this area relies largely on eustaticographic variations in abundances of taxa (Williams 1984; Thunell 1985; Neff 1983; Johnson 1988; Martin 1990; Martin and Johnson 1989) supplemented by a few regional last occurrences (Stude 1984).

Various Neogene planktonic and benthic foraminiferal zonal schemes have been developed from numerous exploration wells drilled in the Gulf of Mexico, but most of them have not been published. Stude (1984) published a zonation developed by Exxon, and noted that this scheme is similar to those used by other oil companies and consulting micropaleontologists working in the Gulf of Mexico Basin. Because this and similar zonations were developed largely from cutting samples, they rely entirely on stratigraphic last occurrences ("tops"). In addition, most published studies have not fully addressed the Miocene biostratigraphy of the Gulf of Mexico. Thus, there are large gaps in our understanding of the Miocene biostratigraphy of the Gulf of Mexico.

The main part of our study area is located in the northeastern Gulf of Mexico (De Soto Canyon area), dominated by the strong surface-deep water Loop Current (see Mullins et al. 1987 for details). We selected five Eureka boreholes (E66-73, E68-136, E67-128, E68-141, and E68-151A; text-fig. 1) for planktonic foraminiferal biostratigraphic study. These boreholes were among those drilled by Shell Oil Company during the late 1960's that reportedly contain Miocene sections (van Markhoven, unpublished). One additional borehole was examined from the western Gulf of Mexico (E67-114A). Some of these 1000' (300 m) boreholes penetrated the entire Neogene section (such as E66-136, E68-151A and E67-73), while others only penetrated upper Neogene (upper Miocene-Recent) strata. These continuously cored boreholes provide the material needed to evaluate Neogene (particularly Miocene) planktonic foraminiferal biostratigraphy of the northeastern Gulf of Mexico.

Planktonic foraminiferal biostratigraphy of these boreholes was previously investigated by F.P.C.M. van Markhoven of Shell Oil Company during the late 1960's. These unpublished results formed the basis for the calibration of benthic foraminiferal stratigraphic ranges used by van Markhoven et al. (1986) and Berggren and Miller (1989). In the course of benthic foraminiferal studies (Katz and Miller, this volume), it was recognized that some of the planktonic foraminiferal first and last occurrences observed did not agree with the unpublished results of van Markhoven, partly as a result of increased sample resolution and advances in planktonic foraminiferal biostratigraphy. Our preliminary examination indicated that there were problems in the correlations of this important database to the Geomagnetic Polarity Time Scale (GPTS). Therefore, we began this study of the Miocene Eureks sections to evaluate the ages and to correlate these sections to the GPTS.

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METHODOLOGIES

Samples were obtained from the Eureka boreholes stored at the Corpus Christi (TX) repository by A.E. Edwards (Woods Hole Oceanographic Institution) in 1985. Additional samples were obtained by D. Schnitker (U. Maine) in 1987 after the cores were moved to Austin (TX). The cores had been hevily sampled by previous investigators, and material has shifted within the liners since it was first obtained. Every effort was made to obtain samples as closely spaced as possible and to be certain of the original position of the samples; however, because of core degradation, this was not always possible.

Samples were processed at Lamont-Doherty Geological Observatory. They were soaked in a hydrogen peroxide solution (3%), washed through a 63µm sieve with a sodium metaphosphate solution, and air-dried. Planktonic foraminifera were qualitatively picked from the greater than 150µm size fraction; the smaller than 150µm size fraction was checked for biostratigraphically significant taxa. We use the planktonic foraminiferal biostratigraphic scheme of Kennett and Srinivasan (1983) for the Miocene, and that of Berggren et al. (1983) for the Pliocene. Nanofossil biostratigraphic data were provided by M.-P. Aubry (this volume).

The technique of graphic solution (age-depth diagrams) was used to determine accumulation rates and to define the ages of hiatuses. Age-depth diagrams require that the ages of events are known. We use the Geomagnetic Polarity Time Scale (GPTS) of Berggren et al. (1985). Although Cande and Kent (1992) have made large changes (≥2 m.y.) to the Paleogene GPTS, Neogene changes are generally minor except for the middle/late Miocene boundary interval. In addition, planktonic biostratigraphy has not been recalibrated to their GPTS and thus we decided to use the Berggren et al. (1985) time scale. We use the planktonic foraminiferal age estimates of Berggren et al. (1985) except as noted (Table 1); nanofossil age estimates are those of Berggren et al. (1985) as modified by Backman et al. (1990) and this study (Table 1). However, middle Miocene foraminiferal age estimates were derived by Berggren et al. (1985) exclusively from the magnetobiostatigraphic relationships established at Site 563 (33°N, western North Atlantic; Miller et al. 1985). The middle Miocene age estimates from this site are tenuous because of uncertain polarity interpretations from Chronozones C5Bn through C5AA (~15-12 Ma; cf., Miller et al. 1985) with Wright and Miller (1992); both chronologies are provided for datum levels in Table 1). Therefore, we sought a more direct means to evaluate biostratigraphic correlations of the Eureka boreholes with this and other magnetostratigraphically constrained sites.

We employed graphic correlation techniques (depth-depth diagrams) to compare the Eureka biostratigraphy with other boreholes. Graphic correlation plots the first and last occurrences in sections against one another as depth-depth diagrams. This technique was established by Shaw (1964) and has been applied by various investigators (e.g., Miller 1977; Dowsett 1988; 1989; Martin et al. 1990). Graphic correlation is particularly useful for evaluating biostratigraphic correlations in sections and boreholes that lack magnetostratigraphy or other independent correlations. In graphic correlation, a “line of correlation” (LOC) must be determined to correlate between sections. In normal cases, first occurrences should be above the LOC, while last occurrences should fall below it.

We compared our biostratigraphic results from the Eureka boreholes with data from DSDP Sites 563 (Miller et al. 1985) and 608 (43°N, eastern North Atlantic; Miller et al. 1991). Following the method of Shaw (1964), these sites are used as Standard Reference Sections (SRS). Although both sites have limitations, they contain the best Miocene magnetostratigraphic records available for correlation to the GPTS and mid-latitude biostratigraphic markers (Miller et al. 1985; Miller et al. 1991). The Miocene section at Site 563 contains 27 biostratigraphic first occurrences (FO) and last occurrences (LO), 20 of which we found in the Eureka boreholes studies. Site 608, taken from higher latitude, contains 25 biostratigraphic events, but only 11 were identified in the Eureka boreholes.

We do not adopt the Composite Standard Reference Section (CSRS) or Composite Standard Time Units (CSTU) approaches. These methods may induce errors by adjusting levels of events, although it has been argued that the amount of the error introduced is minor (Shaw 1964; Miller 1977). Nevertheless, we avoid using composite sections because there is no objective means to evaluate errors introduced into the system by such adjustments.

Strontium isotope (87Sr/86Sr) stratigraphy provides an effective relative age correlation tool for portions of the Cenozoic (Burke et al. 1982; DePaolo and Ingam 1985), particularly lower Miocene sections (DePaolo 1986; Hodell et al. 1991; Miller et al. 1991). We analyzed the upper Oligocene and lower Miocene sections at E68-136 and E68-151 for 87Sr/86Sr stratigraphy. Sr-isotope analyses were performed on more than 200 specimens of mixed planktonic foraminiferal taxa picked from the
### TABLE 1

Miocene biostratigraphic events and age estimates.

<table>
<thead>
<tr>
<th>Event</th>
<th>Age (Ma)</th>
<th>Reference</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FO Globorotalia plesiotenella</td>
<td>not available</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>FO Neogloboquadrina acostaensis</td>
<td>10.2</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>3</td>
<td>FO Paragloboquadrina mayerzhikensis</td>
<td>10.4</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>4</td>
<td>FO Globorotalia menardensis</td>
<td>11.3</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>5</td>
<td>FO Globorotalia foksi robusta</td>
<td>11.5</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>6</td>
<td>FO Globorotalia foksi robusta</td>
<td>12.6</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>7</td>
<td>FO Globorotalia praefohsi</td>
<td>not available</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>FO Globorotalia foksi</td>
<td>not available</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>FO Globorotalia foksi fohsi</td>
<td>13.4</td>
<td>using correlations and chronology at Site 563 of Miller et al. (1985)</td>
</tr>
<tr>
<td>10</td>
<td>FO Globorotalia praefohsi</td>
<td>13.5</td>
<td>using correlations at Site 563 and chronology of Wright and Miller (1992)</td>
</tr>
<tr>
<td>11</td>
<td>FO Globorotalia peripherocutis</td>
<td>14.1</td>
<td>using correlations at Site 563 and chronology of Wright and Miller (1992)</td>
</tr>
<tr>
<td>12</td>
<td>FO Orbula nautilis</td>
<td>15.2</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>13</td>
<td>FO Globigerinoidea sicanaea</td>
<td>16.6</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>14</td>
<td>FO Praecorbulina gl. glomerosa</td>
<td>16.3</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>15</td>
<td>FO Terebratula dissimilis</td>
<td>17.6</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>16</td>
<td>FO Globorotalia praescutula</td>
<td>19.0</td>
<td>Miller et al. (1991)</td>
</tr>
<tr>
<td>17</td>
<td>FO Globorotalia kugleri</td>
<td>21.5</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>18</td>
<td>FO Globorotalia kugleri</td>
<td>22.7</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>19</td>
<td>FO Subborina sellii</td>
<td>22.6</td>
<td>using correlations at Site 563</td>
</tr>
<tr>
<td>20</td>
<td>FO Globorotalia debiscens</td>
<td>23.2</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>21</td>
<td>FO Globigerinoides primorcius</td>
<td>common not available</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>FO Globigerinoides fohsi lebato</td>
<td>13.1</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>23</td>
<td>FO Globigerinatella insignis</td>
<td>not available</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>FO Discoraster hamatus</td>
<td>8.65</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>25</td>
<td>FO Discoraster hamatus</td>
<td>10.0</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>26</td>
<td>FO Caimaster coadis</td>
<td>10.8</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>27</td>
<td>FO Caimaster calyclus</td>
<td>10.0</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>28</td>
<td>FO Helicosphaera amphiopera</td>
<td>16.2</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>29</td>
<td>FO Sphenolithus heteromorphus</td>
<td>13.6</td>
<td>Backman et al. (1990)</td>
</tr>
<tr>
<td>30</td>
<td>FO Discoraster kugleri</td>
<td>12.0</td>
<td>using correlations at Site 563, Miller et al. (1985) and chronology of Wright and Miller (1992)</td>
</tr>
<tr>
<td>31</td>
<td>FO Discoraster fohsi</td>
<td>23.6</td>
<td>Backman et al. (1990)</td>
</tr>
<tr>
<td>32</td>
<td>FO Reticulofenestra bisecta</td>
<td>23.7</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>33</td>
<td>FO Zygophyllum bipugatis</td>
<td>24.6</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>34</td>
<td>FO Sphenolithus cipreensis</td>
<td>25.2</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>35</td>
<td>FO Sphenolithus belemnos</td>
<td>20.0</td>
<td>Backman et al. (1990)</td>
</tr>
<tr>
<td>36</td>
<td>FO Discoraster fahncup</td>
<td>8.2</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>37</td>
<td>FO Globorotalia apina nanus</td>
<td>22.6</td>
<td>using correlations at Site 563</td>
</tr>
<tr>
<td>38</td>
<td>FO Globigerinoides atsiamarum</td>
<td>20.9</td>
<td>Berggren et al. (1985)</td>
</tr>
<tr>
<td>39</td>
<td>FO Praecorbulina gl. glomerosa</td>
<td>16.2</td>
<td>Berggren et al. (1985)</td>
</tr>
</tbody>
</table>

For ages before 15 Ma, growth bands may also be used to estimate absolute age, with a minimum accuracy of ±0.05 Ma. This estimation was made using the correlation of the 

\[
{^{87}Sr} / {^{86}Sr} = \text{constant}\times (\text{Ma} - 15)^{1.78}
\]

with a maximum accuracy of ±1 Ma. For ages younger than 15 Ma, this method is not applicable. For ages up to 0.000059 m.y., yielding a stratigraphic resolution of better than ±0.5 m.y. for this interval. The rate of increase of 

\[
{^{87}Sr} / {^{86}Sr} \text{ was lower during the late Eocene to Oligocene (0.000030 m.y. from 38-25 Ma) and stratigraphic resolution is lower (±1 m.y.); Miller et al. 1988). Sr-isotope age estimates were determined using the equations:}
\]

\[
\text{(Age, Ma)} = 11.9056.91 - 16777.17 \times (\text{87-Sr}/86-Sr)
\]

\text{for 25-15 Ma (Miller et al. 1991) and}

\[
\text{(Age, Ma)} = 20.3927.9 - 28758.84 \times (\text{87-Sr}/86-Sr)
\]

\text{for 38-25 Ma (Miller et al. 1988).}

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We integrated our planktonic foraminiferal biostratigraphy with calcareous nannoplankton biostratigraphy (Aubry, this volume) and Sr-isotope stratigraphy using graphical solution and correlation techniques. By doing this, we have determined gaps in deposition (hiatuses) and inferred the position of unconformities. The unconformities inferred from integrated stratigraphy are not generally associated with lithologic discontinuities, and are thus paraconformities.

RESULTS

**Eureka 68-136**

**Biostratigraphy & Sr isotopes**

This borehole from the upper De Soto Canyon (present depth 1826’ (557m) was sampled at an average interval of 17’ (~5m).

Planktonic foraminifera are common to abundant throughout the section, and preservation is good to excellent. This borehole provides the most continuous record of Neogene deposition; however, our planktonic foraminiferal studies indicate that several zones are missing or condensed. As discussed above, we use biostratigraphy and Sr-isotope stratigraphy to infer stratigraphic gaps (paraconformities) and to estimate sedimentation rates.

Sedimentation rates were 61.3’/m.y. (18.7m/m.y.), 41.7’/m.y. (12.7m/m.y.), and 25.6’/m.y. (7.8m/m.y.) during the early, middle, and late Miocene, respectively. Early Pliocene rates were 50.4’/m.y. (15.5m/m.y.), while late Pliocene sedimentation rates were 14.4’/m.y. (4.4m/m.y.). Our biostratigraphic (zonal) determinations differ from those of van Markhoven (unpublished), particularly in the middle Miocene to upper Miocene section (Zones N12, N14, N16, and N17; text-fig. 2).

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Lower Miocene

As at many other locations, lower Miocene planktonic foraminiferal zonations are difficult to recognize at E68-136 due to diachrony, unconformities, and poorly developed zonal markers. The Zone N4a/N4b boundary is indeterminable in this borehole due to either an unconformity (text-fig. 2) or diachrony of the FO of *Globorotalia dehiscens* or the FO of *Globorotalia kugleri* (see below).

We identify the Zone N4/N5 boundary (text-fig. 2) based on the primary zonal criterion (LO *Globorotalia kugleri*). We place the Zone N5/N6 boundary at the level of the FO of *Globorotalia praescutula* (text-fig. 2). We do not use the zonal criterion for the base of Zone N6, the FO of *Globigerinitaella insueta* (Blow 1969; Kennett and Srivivasan 1983) because we have evidence that its FO is diachronous: 1) it has a single isolated occurrence at the top of Zone N6 at Site 608 (eastern North Atlantic) at the same level as the LO of *Catapsydrax dissimilis* (Chronozone CSD, ~17.6 Ma; Miller et al. 1991); and 2) at Site 563 in the western North Atlantic, it did not appear until Zone N8 (within the range of *Globigerinoides sicanus*; Chronozone CSC, ~16.6 Ma) (Miller et al. 1985). Miller et al. (1991) suggested that the FO of *G. praescutula* (age estimate ~19.0 Ma based on correlations at Site 608) may be used to subdivide Zones N5 and N6. It is interesting that, at E68-136, the FO of *G. insueta* at 2645’ is close to the FO of *G. praescutula* at 2627’.

The base of Zone N7 cannot be distinguished at this borehole due to the diachronous LO of *Catapsydrax dissimilis*, which defines the Zone N6/N7 boundary. This taxon falls far below the LO predicted by the planktonic foraminiferal data (text-figs. 3, 4, 6, 7). Sr isotopes document that *C. dissimilis* disappeared about 3.4 m.y. earlier than expected at this location (text-fig. 4; ~21 Ma versus the 17.6 Ma global LO of Berggren et al. (1985) (see Discussion).

**Middle Miocene**

Middle Miocene planktonic foraminiferal zones are represented at E68-136 with the exception of Zone N15 (see below; text-fig. 2). Zones N10 through N12 rely on the middle Miocene *Globorotalia foksi* lineage. We apply the taxonomic concept for this lineage of Kennett and Srivivasan (1983), which differs from that of Banner and Blow (1965) and Bolli and Saunders (1985) in the concept of *Globorotalia praefohsi*. The evolutionary lineage of *Gt. peripheroacuta-Gt. praefohsi* (sensu Kennett
Table 4
Relative abundance of *Globorotalia* foehsi group at E68-136. R = rare (1-2 specimens); F = few (3-5); C = common (≥5).

<table>
<thead>
<tr>
<th>Depth (fbsl)</th>
<th>peri- pheneucota</th>
<th>praefoehsi</th>
<th>foehsi lobata</th>
<th>foehsi robusta</th>
</tr>
</thead>
<tbody>
<tr>
<td>2387</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2394</td>
<td>-</td>
<td>-</td>
<td>R</td>
<td>C</td>
</tr>
<tr>
<td>2406</td>
<td>-</td>
<td>R</td>
<td>F</td>
<td>-</td>
</tr>
<tr>
<td>2424</td>
<td>-</td>
<td>R</td>
<td>F</td>
<td>R</td>
</tr>
<tr>
<td>2446</td>
<td>C</td>
<td>R</td>
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<td>C</td>
<td>C</td>
<td>F</td>
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<td>-</td>
</tr>
<tr>
<td>2486</td>
<td>R</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

and Srinivasan (1983) - *Gt. foehsi foehsi* is well represented at E68-136, although the FO of *Gt. foehsi robusta* (text-fig. 2; Table 4). This indicates the presence of Zone N10, a thin or absent Zone N11, and a thick Zone N12. Zone N13, the interval from the LO of *Gt. foehsi robusta* (2387') to the FO of *G. nepenthis* (2564'), is 23' (7m) thick at E68-136. We found that *Cassigerinella chiplensis* last occurs within this zone (2366', text-fig. 2), as reported elsewhere by Kennett and Srinivasan (1983).

Upper Miocene
The upper Miocene section at E68-136 contains Zones N16 and N17. Zone N16 is thin (only 48' and 14.6m) and the lower part of the zone is missing as a result of an unconformity (text-fig. 2). We are not able to subdivide Zone N17 because the FO of *Pulleniatina primalis*, marking the base of Zone N17B, was not identified in this borehole. The FO of *Pulleniatina primalis* (a predominantly Indo-Pacific taxon) was found in the uppermost Pliocene (PL6) at another Eureka borehole, E67-135 (Brunner and Keigwin 1981). Based on their study and ours, this FO may be regionally diachronous, and therefore may not be reliable as a zonal marker. We were not able to apply the zonal criterion for lowermost Pliocene Zone N18 (sensu Berggren et al. 1985, p. 217, fig. 2; from the FO of *Tumida tumida* to the FO of *S. dehiscens*). We recognize Pliocene sediments at 2026' using the FO of *Globorotalia cibaeensis*, *Gt. pertenuis*, *Gt. multicomarata*, and *Gt. exilis*.

Pliocene to Pleistocene
At E68-136, Zone PL1 (71' thick) is recognized by the concurrent ranges of *Gt. cibaeensis* and *G. nepenthis*. The first occurrence of the former was used to define the base of Zone PL1 (Berggren 1977), with a magnetostratigraphic age estimate of 5.3 Ma (Berggren et al. 1985; this age estimate may be significantly too young; W.A. Berggren, in press); the latter has an age estimate of 3.9 Ma (Berggren et al. 1985). Further subdivision of Zone PL1 is not possible at E68-136 because of an unconformity and the absence of zonal criteria. For example, the typical cool-water form *Globorotalia punctulata*, which marks the Zone PL1a/PL1b boundary, does not occur in this area (also see Brunner and Keigwin 1981). The last occurrences of *Globorotalia multicomarata* and *Globoplacodina altispira* at 1985' are truncated by an unconformity (see below), with Zones PL2 to PL6 missing.

Zone N22 is recognized at 1926' by the FO of *Globorotalia truncatulinoides*. The presence of *Globorotalia miocenica* and *Gt. exilis* in this sample is attributed to reworking of Pliocene sediment into Zone N22; this interpretation is supported by nanofossil data (Aubry, this volume). We use the FO of *Gt. truncatulinoides*, the basal criterion of Zone N22, to approximate the base of the Pleistocene (see Discussion for details). The base of Zone N23 is recognized by one of the two primary criteria (Blow 1969), the FO of *Globigerinella calida calida* at 1907' (the other criterion, the FO of *Sphaeroidinella dehiscens* excavata was not recognized). This level is just below the FO of *Globigerinella ruber* (pink) (1890'). Stone and Keller (1985) also used the FO of *G. calida calida* to recognize Zone N23 in the Middle America Trench region. We suggest that the FO of *Gn. ruber* (pink) may serve as an appropriate secondary criterion for the base of Zone N23 because the FO of this taxon appears to be apparently coeval with the FO of *G. calida calida*. *Gn. ruber* (pink) first occurred in the middle-late Pleistocene (Saito et al. 1981). The proximity of the FO of *G. truncatulinoides* (1926') to the FO of *G. calida calida* (1907') and *Gn. ruber* (pink) (1890') may indicate that much of the lower Pleistocene may be missing (i.e., Zone N22 is very thin).

Unconformities
We use biostratigraphic and Sr-isotope stratigraphic data to infer unconformities (see Methods). In general, physical criteria were not used to identify unconformities, with the exception of the unconformity at 2386' (unconformity U2; text-fig. 2). Two distinct unconformities are present at E68-136: upper middle to lower upper Miocene (Zone N15, unconformity U2) and Pliocene (Zones PL2-PL6, unconformity U1). We initially interpreted the lower to lower middle Miocene section at E68-136 as otherwise continuous because all other planktonic foraminiferal zones are represented. However, nanofossil biostratigraphy indicates that the lower to middle Miocene section is punctuated
by unconformities (Aubry, this volume). This prompted us to integrate foraminiferal, nannofossil, and Sr-isotope stratigraphy, and to recognize four possible unconformities in the lower to middle Miocene section.

**Lowermost Miocene Unconformity**

An unconformity (U6 on text-fig. 2) may be indicated at 2755', by the absence of Zone N4a. *Globorotalia dehiscens* (23.2 Ma) first appears at the same level (2755') as *Globorotalia kugleri* (23.7 Ma). This indicates a possible hiatus from 23.7-23.2 Ma. In addition, we found that both *Globigerina ciperoensis* and *Globigerina angulisuturalis* last occur just below 2755', elsewhere these taxa range into Zone N4a (e.g., Site 563, Miller et al. 1985), supporting a paraconformity at this level (text-fig. 2). An alternate interpretation ascribes the absence of Zone N4a to diachrony: either the FO of *G. dehiscens* predated its previously known global first occurrence or the FO of *Globorotalia kugleri* is younger at this location than previously reported. The strontium isotope age estimate for this level (23.8 Ma) is very close to the FO of *G. kugleri*. Thus, it is possible...
that the FO of *Gastopod dehiscent* could be diachronous, although Sr-isotope resolution is not sufficient to unambiguously differentiate between the two first occurrences. Nannofossils (Aubry, this volume) do not indicate an unconformity at this level, although an older unconformity is suggested below 2800' (text-fig. 2).

Sr-isotopes indicate that there may also have been a hiatus from ~22-20 Ma (text-fig. 4). This would require that the LO of *Gastopod kugleri* and *Subbotina sella* were premature. However, we are suspicious of the Sr-isotope data below ~2700' (text-fig. 4) because they are consistently 1-2 m.y. older than the biostratigraphic age estimates. We note that data below 2700' show considerable scatter, and non-monotonic increases with respect to depth (text-fig. 2), indicating that this section may have suffered from minor diagenetic alteration.

**Uppermost Lower Miocene Unconformity**

A possible uppermost lower Miocene nonconformity (U5 on text-fig. 2) is situated between 2586' and 2627', separating Zone N8 from undifferentiated Zone N6/N7 (text-fig. 4). We estimate that the hiatus occurred from ~18.0-16.5 Ma (text-fig. 4). This unconformity is difficult to determine using planktonic foraminifera alone because the Zone N6/N7 zonal marker, *C. pygmaea* *dissimilis*, is obviously diachronous at this borehole (text-figs. 2, 3, 5, 6, 7). Sr-isotope stratigraphy is consistent with an unconformity; ages uniformly decrease upsection from ~2500 to ~2600', where there is a sharp change (text-fig. 4). Nannofossil biostratigraphic studies of Aubry (this volume) indicates the presence of an unconformity near this level because Zone NN2 is overlain by Zone NN4 (text-fig. 2).
Lowermost middle Miocene Unconformity

A lowermost middle Miocene unconformity (U4 on text-fig. 2) may lie between 2546′ and 2535′, as indicated by the FO of Praeorbulina glomerosa (16.3 Ma) in the former sample and the FO of Orbulina suturalis (15.2 Ma) in the latter (text-fig. 3; maximum duration 16.3-15.2 Ma). We are uncertain of this unconformity because we obtained no samples from this 11′ interval. However, we suspect that there is a gap based on the low sedimentation rates (about 10′/m.y.; ~3m/m.y.) estimated for this interval. While this unconformity was not recognized using nannofossil alone (text-fig. 2), integration of foraminiferal and nannofossil data also indicate low sedimentation rates and a possible gap. The LO of Helicosphaera ampliaperta (16.2 Ma; Berggren et al. 1985; = the basal criterion for Zone NN5) is at 2546′, while the FO of Orbulina suturalis is only 9′ above this (2535′; 15.2 Ma; Berggren et al. 1985; text-fig. 3). Shaw diagram comparisons with Sites 563 and 608 (text-figs. 6, 7) illustrate the relationship among these taxa, and graphically documents this gap.

Middle Middle Miocene Unconformity

An unconformity (U3 on text-fig. 2) may lie in the middle middle Miocene near 2486′. S. heteromorphus (13.6 Ma; Bannman et al. 1990) last occurs in the same sample (2486′) that Globorotalia periphera first appears (14.1 Ma; Miller et al. 1991), indicating a possible short hiatus of 0.5 m.y. Sr isotope age estimates are consistent with this break (text-fig. 4), although Sr isotopic resolution begins to deteriorate in the interval 16-14 Ma (Miller et al. 1991). Zone N11 is condensed or missing because the FO’s of Gt. praefoki and Gt. fohsi fohsi occur in adjacent samples (text-fig. 2). This is also consistent with an unconformity at this level, although the brevity of Zone N11 may be an artifact of our species concept. Nannofossil biostratigraphy indicates a dramatic gap at the same level, with Zone NN8 (younger than 10.8 Ma) overlying Zone NN5 (older than 13.6 Ma). However, although the presence of an unconformity is indicated by nannoplankton, foraminifera, and Sr-isotopes, the nannoplankton data indicate a much longer hiatus than the others. We interpret the identification of Zone NN8 at this level as downhole contamination (i.e., C. coaflit is caved downhole; text-figs. 3, 4). A Shaw diagram (text-fig. 6) shows that the FO of C. coaflit is anomalously low at E68-136; a FO falling below the LOC can be explained by contamination. Alternatively, this section may represent a series of upper middle Miocene slumps intercalated with in situ Zone NN8 (Aubry, this volume; see below for discussion).
Upper Middle Miocene Unconformity

An unconformity (U2 on text-fig. 2) is indicated by the absence of Zone N15 (upper middle Miocene). Paragloborotalia mayeri last occurs at 2346', and Neogloboquadrina acostaenensis and N. cf. humerosa first occurs in the next sample, 2326' (text-fig. 5), indicating that there is a stratigraphic gap between Zones N14 and N16 partim. N. cf. humerosa reportedly first occurs at middle of late Zone N16, which may indicate that the FO of N. acostaenensis is not a true global FO and that the lower part of N16 is missing. It should be noted that there are no any samples available within the interval between 2346' and 2326', which may suggest an alternative interpretation with an extremely condensed Zone N15. However, we place an unconformity here because of the following physical and faunal evidence:

1) There is a high proportion of iron-stained foraminiferal tests associated with the upper middle Miocene, particularly at 2346' (18.98%) and 2326' (16.3%) (text-fig. 5). [Over 1000 specimens were quantitatively counted for each sample. Almost all of the stained tests are pyrite-filled.]

2) Biostratigraphic evidence indicates not only that Zone N15 is likely missing, but also that the lower part of Zone N16 is missing. Two specimens transitional from Globorotalia merotumida to Globorotalia plesirotumida appear at 2326', which may indicate the presence of upper Zone N16. In addition, many 5-chambered forms assigned to Neogloboquadrina cf. humerosa occur at 2326' (text-fig. 5). The 5-chambered N. cf. humerosa are considered to be precursor forms of N. humerosa, which reportedly first occurs much higher (middle of Zone N16) than N. acostaenensis at DSDP Site 397 (North Atlantic; Salvadorini and Cita 1979).

3) Discaster hamatus (10.0 Ma) and Cainaster calycus (10.0 Ma; first occur at the same level as N. acostaenensis (10.2 Ma), indicating that Zone NN9 and lowermost N16 are missing.

We have shown that Zone N15 is missing or extremely condensed at several mid-latitude locations, such as Site 563 (Miller et al. 1985), as it is at E68-136. Because of this, the Shaw diagram comparing Site 563 (33°38'N and 43°46'W) and E68-136 shows no discontinuity at this level. It is not clear if there is an unconformity at this level at Site 563, or if there is diachrony in either the LO of Paragloborotalia mayeri or the FO of N. acostaenensis at mid-latitudes (see discussion). However, we believe that the evidence is clear that there is an unconformity at E68-136 at this level, as indicated by the physical criteria (staining) and by the absence of lower Zone N16.

Pliocene Unconformity

A distinct unconformity (U2) is recognized at 1955' by the juxtaposition of the LOs of G. nepenthes (3.9 Ma), Gt. margaritae (3.4 Ma), Gt. multiformata (2.9 Ma) and Gt. altispira (2.9 Ma) at this level with the FO of Globorotalia truncatulinoides (1.9 Ma) in the next sample examined (1926'). This indicates that Zones PL1 partim to PL6 are missing (hiatus 3.9-1.9 Ma); the thin Zone N22 indicates that part of this zone may also be missing as indicated by the nannofossil data (Aubry, this volume). As shown in text-figure 2, this gap is distinct because many FOs (e.g., Globorotalia truncatulinoides, Globorotalia tosaensis, Spheerooidinae dehiscens dehiscens, Pulledinina obliquiloculata, and Globorotalia inflata) are noted at 1926' just above the LO of Globigerina nepenthes, Globorotalia multiformata and Globorotalia altispira (1955'). The presence of Globorotalia exilis and G. miocenica at 1926' is attributed to reworking (see above). This unconformity was detected by van Morkhoven (unpublished planktonic foraminiferal data, see text-fig. 2) and by calcareous nannofossils (Aubry, this volume). However, Aubry estimates that the hiatus is longer (4.5 to 1.68 Ma) than indicated from foraminifera, because the LO of Triquetrotahedrus rugosus (age estimates of 4.5 Ma) occur immediately below the FO of Gephyrocapsa oceanica (age estimates of 1.68 Ma; Aubry, this volume).

Comparison with nannofossil biostratigraphy

There is a discrepancy between planktonic foraminiferal and nannofossil zonations at E68-136. Sediments assigned to middle Miocene foraminiferal Zones N11-N12 are assigned to uppermost middle to lowermost upper Miocene nannofossil Zone NN8, while those assigned to upper Zone N12-N13 partim are interpreted as sediments transported downslope (Aubry, this volume). Because we interpret the Globorotalia folki lineage at E68-136 to represent an evolutionary biosequence, we attribute the discrepancy between foraminiferal and nannofossil biostratigraphy to downhole contamination of the nannofossils (see further discussion below). Alternatively, the foraminifera may represent slumped middle Miocene specimens sandwiched between intervals of in situ upper Miocene (Aubry, this volume).
Comparison with Sites 563 and 608

In addition to showing the E68-136 unconformities discussed above, our Shaw diagrams indicate that there are two possible unconformities at Site 563 (text-fig. 6).

1) the juxtaposition of the FO of *Orbulina suturalis* (the base of Zone N9) and the FO of *Globorotalia peripheracaucita* (the base of Zone N10) indicates the absence of Zone N9 at Site 563. This may be due to an unconformity or to the possible diachronous FO of the latter taxon (Miller et al. 1985). This relationship is also shown by the depth-depth diagram comparing Site 563 with E66-73 (text-fig. 6).

2) the juxtaposition of the FO of *Globigerina nepenthis* and the LO of *Globorotalia foksi robusta* indicates the absence of Zone N13 at Site 563. This may be due to an unconformity or to the possible diachronous range of either taxon (Miller et al. 1985).

Figure 6 does not illustrate the lower Miocene unconformity noted at Site 563 by Miller et al. (1985) and Wright and Miller (1992) because of a sample gap at E68-136. Comparison of Site 608 with E68-136 confirms the presence of unconformities U6 and U5 at E68-136 (text-fig. 7); unconformity U3 is not discernible due to the absence of key taxa at high latitude Site 608 (text-fig. 7).

Eureka 66-73

Biostratigraphy

E66-73 was drilled in De Soto Canyon (present depth 2802', 854m). Our average sampling interval is 17' (5m), similar to that at E68-136. This borehole contains uppermost lower Miocene to Pleistocene deposits. Planktonic foraminifera are abundant and well preserved except for a middle Miocene dissolution interval (text-fig. 8).

Miocene sedimentation rates were much higher at E66-73 than at E68-136. Middle Miocene sedimentation rates averaged 115'/m.y. (~35m/m.y.), about three times higher than at E68-136. Late Miocene sedimentation rates averaged 89'/m.y. (~27m/m.y.). No Pliocene sediments were recovered (text-fig. 8). Our zonal determinations at this borehole differ from those of van Morkhoven (text-fig. 8). In particular, we recognize a very thick Zone N17 (about 300', ~90m) that was correlated with Zones N14/15-N16 by van Morkhoven.

Uppermost Lower to Middle Miocene

We identify uppermost lower to middle Miocene Zones N8 through N12 at this borehole (text-fig. 8). Zone N8 spans the early to middle Miocene boundary; the presence of nanofossil Zone NN4 at the base of the borehole indicates that lower Miocene sediments were penetrated. Zone N13 is apparently absent and Zone N14 is condensed (see below for details). There are some differences between E66-73 and E68-136:

1) E66-73 contains a moderately thick (56', ~17m) Zone N15, as is indicated by two samples that lie between the FO of *Pf. mayeri* and the LO of *N. acostaensis*.

2) while Zone N13 is apparently missing here, it is present at E68-136, although it is thin (62', ~19m).

3) Zone N12 (about 270', ~82m) is much thicker here than at E68-136 (about 90', ~27m), despite the strong dissolution in the upper part of the zone.

Upper Miocene

The lower part of Zone N16 is missing at E66-73 (text-fig. 8), as it is at E68-136 (text-fig. 2). This is based on the FO of *N. acostaensis* at the same level as the FO of *N. praehumerosa*. As mentioned above, N. praehumerosa was derived directly from *N. acostaensis*, and its first occurrence at Site 387 is within the middle of Zone N16 (Salvatorini and Cita 1979).
The thick Zone N17 at E66-73 (about 290′, ~88m) may be subdivided by the FO of *Pulleniatina primaris*, which defines the base of Zone N17B (6.2 Ma; Kennett and Srinivasan 1983; 5.8 Ma; Berggren et al. 1985). *P. primaris* first occurs at 2858′, just below an unconformity recognized by the FO of the late Pleistocene marker *G. ruder* (pink). As previously mentioned, *P. primaris* may not be reliable as a zonal marker in this area because it may be either diachronous or too rare. For instance, it first occurs in Zone PL6 at E67-135 (Brunner and Keigwin 1981), while we did not find it at E68-136.

**Pliocene—Pleistocene**

Unlike E68-136, the entire Pliocene section is missing at E66-73. In addition, *G. ruder* (pink) first occurs at the same level as *Gt. truncatulinoides*, indicating that Pleistocene Zone N22 is missing. The primary zonal markers for N23, *G. calida calida* and *Sphaerodinella dehiscens excavata*, were not found at this borehole. We use the alternate zonal criterion of the FO of *G. ruder* (pink) (see above).

**Unconformities**

We identified four possible unconformities at this borehole. The numbers given to these unconformities (U1-U4) are local and do not necessarily correspond with those at E68-136 and E67-128. For example, unconformities U1 and U2 apparently correlate between E68-136 and E66-73, but U3 at E68-136 is an older surface than U3 at E66-73 (see Discussion for correlation of unconformities among boreholes).

**Upper Middle Miocene Unconformity (ies)**

A possible unconformity (U4 on text-fig. 8) occurs at 3358′ at the top of a zone of strong dissolution in the upper middle Miocene. This is indicated by the occurrence of *C. coelitus* immediately above a section interpreted by Aubry (this volume) as transported from the nanofossil data. She suggests that a mixture of Zones NN6-NN8 was transported downslope during Bichon NN8 and overlain by in situ Zone NN8; text-fig. 8). Because of dissolution, foraminiferal relationships are uncertain.

There may be another upper middle Miocene unconformity (U3 on text-fig. 8) at ~3338′. *G. nepenthes* appears at 3338′, immediately above the apparent LO of *Gt. fohsi robusta* at 3340′ (text-fig. 8). This indicates that Zone N13 is missing. Zone N13 is absent in middle latitude Site 563 either due to an unconformity or to the diachronous occurrences of these two taxa (Miller et al. 1985). However, Zone N13 is well developed at lower-latitude E68-136 (see above) and at Jamaica (Berggren, in press). Therefore, its absence at E66-73 may indicate an unconformity. U3 (text-figs. 8, 9). Alternatively, it is possible that the interval from ~3400′ to 3338′ is Zone N13 if the LO of the *Gt. fohsi* lineage at 3400′ is a true LO and the specimens of *Gt. fohsi*
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**TEXT-Figure 8**

Biostatigraphy of E66-73. U1-U4 are inferred unconformities. * 2 specimens are interpreted as in situ, although it is possible that they are reworked.

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**Lower Upper Miocene Unconformity**

An unconformity (U2 on text-fig. 8) may separate the middle Miocene (3276'; Zone N15) from the upper Miocene (3258'; upper Zone N16). This is indicated by the simultaneous FO of 5-chambered *N. praehumerosa* and of *N. acostaensis*. As noted above, *N. praehumerosa* was derived from *N. acostaensis* in the middle of Biochron N16 (Salvatiorini and Cita 1979). This indicates that *N. acostaensis* first occurs above an unconformity at E66-73, as it is at E6-136. However, this unconformity is difficult to detect in the age-depth plot (text-fig. 9) because no
firm age estimate is available for the FO of *N. praehumerosa*. We roughly estimate its duration as ~1.3 m.y (10.5 Ma-9.2 Ma); from upper Zone N15 to a level within Zone NN9 based on extrapolation of sedimentation rates between datum levels; Table 1, text-fig. 9).

**Pliocene-lower Pleistocene Unconformity**

This unconformity (U1 on text-fig. 8) lies between 2843' and 2858', indicating that the entire Pliocene and lower Pleistocene are not represented (duration at least 4.8 m.y. from ~6.5 to 1.68 Ma based on nannofossil biostratigraphy; text-fig. 7). It separates the uppermost Miocene section indicated by the FO of *Pulleniina primaalis* (N17B) and the absence of other Pliocene species (e.g., *Gt. margaritae*, *Gt. exilis*, *Gt. miocenica*) from the upper Pleistocene Zone N25, recognized by the FO of *Gt. ruber* (pink). Many taxa, such as *Gt. truncatulinoides*, *Globorotalia crassaformis*, *Globorotalia inflata*, *Gt. tumida tumida*, and *Gt. ruber* (pink) appear at 2843' (text-fig. 8).

**Comparison with nannofossil biostratigraphy**

The greatest biostratigraphic problem encountered at this borehole is the identification of Zone NN8 (uppermost middle to lowermost upper Miocene; Aubry, this volume) in sediment that we identify as Zones N11-N12 (middle Miocene; text-fig. 8). Aubry (this volume) interprets this section as a mixture of Zones NN6-NN7 that was transported downslope during Biochron NN8 and overlain by *in situ* Zone NN8. Similar nannofossil relations are observed at E68-136, supporting this interpretation (text-fig. 2; Aubry, this volume). Nevertheless, we interpret the entire section as *in situ* middle Miocene, and suggest that the young nannofossils represent downhole contamination. Our evidence for this is:

1) the evolutionary lineage of *Gt. foehsi* group is particularly well developed at E66-73, showing the following succession: FO of *Gt. peripheracuta*, LO *Gt. peripheroronda*, FO *Gt. praefohsi* (sensu Kennett and Srivasan 1983), FO *Gt. foehsi foehsi*, FO *Gt. praefohsi* (sensu Banner and Blow 1965), FO *Gt. foehsi lobata*, FO *Gt. foehsi robusta* and LO *Gt. foehsi* spp. (text-fig. 8; Table 5). This succession would be difficult to identify if middle Miocene downslope transport had occurred as described above.

2) the age-depth and depth-depth diagrams show that *C. coalius* (zonal criterion for the base of Zone NN8) is out of place relative to other biostratigraphic markers (text-figs. 9, 10).

3) benthic foraminifera show consistent biofacies successions indicative of largely *in situ* middle Miocene deposition (Katz and Miller, this volume).

Nannofossil-foraminiferal biostratigraphic relationships at E66-73 differ from Sites 563 in the earliest late Miocene. At E66-73, *D. hamatus* first occurs prior to *N. acostaensis* within Zone N15 (text-fig. 8), while at Site 563, they both first occur together at the base of Zone N16. In the Buff Bay section of Jamaica, *D. hamatus* appears in uppermost Zone N14 (Aubry, in press; Berggren, in press). This either requires a significant unconformity at this level at Site 563, or diachrony between these two taxa (see Discussion, Diachrony). In any case, these relationships call into question the age estimates for the FO of *D. hamatus* (10.0 Ma; Berggren et al. 1985; 10.5 Ma, Backman et al. 1990) and/or the FO of *N. acostaensis* (text-fig. 9). This limits our ability to detect and evaluate the duration of the hiatus associated with unconformity U2 (text-figs. 9, 10).
TEXT FIGURE 10
Depth-Depth diagram, E66-73 versus Site 563. Numbers correspond to biostratigraphic levels given in Table 1.

Eureka 68-151

Biostratigraphy & Sr-isotopes

E68-151A was drilled on the lower Florida Escarpment (present depth 4340', 1323m; text-fig. 11). This borehole was sampled at an average interval of 163' (~5m). It contains a thick lower Miocene sequence (>200', >60m). Planktonic foraminifera are abundant and well preserved throughout the section.

The average early Miocene sedimentation rates were 23'/m.y. (~6m/m.y.). The middle Miocene is poorly preserved. Our results from this borehole are similar to those of van Morkhoven (unpublished; text-fig. 11).

Upper Oligocene

We recognized undifferentiated Oligocene to lowermost Miocene deposits in one sample provided by R.C. Tjalsma (Unocal) that contains Globigerina ciperoensis (last occurrence in lower Miocene Zone N4a), while van Morkhoven (unpublished) reported this as upper Oligocene.

Lower Miocene

The primary criterion for Zone N4 (Gt. kugleri) is absent at this borehole. The FO of Globigerinoides altiapertus (4628') is used to approximate the Zone N4/N5 boundary (Berggren et al. 1985; text-fig. 11). Zones N6 through N8 are missing.

Sr-isotope measurements provide crucial age constraints on the lower Miocene section (text-figs. 11, 12). They document that:

1) the section between 4675' and 4494' was deposited from ~22.5-19.0 Ma (text-fig. 12).

2) the LO of Catapsydrax dissimilis (4511') may be truncated by the unconformity between 4494' and 4492', although its absence at 4494' may be attributed to diachrony (text-fig. 11).

3) the age estimate of the FO of S. belennos (Aubry, this volume; 20.0 Ma, Buczkow et al. 1990) is correct for correlation to the GPTS of Berggren et al. (1985).

4) the age estimate of the FO of Globigerinoides altiapertus (21.6 Ma based on its first occurrence in early Zone N5, Berggren et al. 1985) is correct within the error of the sample interval.

5) the age estimate for the LO of Paragloborotalia opima nana is correct (21.7 Ma; based on its LO at Site 563 in Sample 15-2, 117 cm, 292.17 meters below seafloor, Miller et al. 1985; this is identified as the base of Chronzone C6Ar by Wright and Miller 1992).
6) the FO of *D. druggi* (23.6 Ma; Backman et al. 1990) and the FO of *Globigerinoides primordius* (25.8 Ma; Berggren et al. 1985) are consistent with the Sr-isotope age estimates considering that these taxa first occur above the large sample gap (text-fig. 12).

*Middle Miocene*

The middle Miocene section is thin (text-fig. 11). Zone N12 is extremely condensed (found in the interval 4492' to 4491'; text-fig. 11) and Zones N8-N11 and N13-N15 are missing. Sr isotopes also indicate that the foraminifera are middle Miocene (Table 3). Aubry (this volume) interprets this section as sediments reworked during late Miocene Biochron NN9. If she is correct, then the foraminiferal component consists largely of reworked taxa with no evidence of *in situ* middle Miocene. We counter her interpretation with the suggestion that the foraminifera are *in situ* and that the more easily mixed nannofossils represent downhole mixing.

*Upper Miocene*

Zone N16 is missing. Zone N17 is recognized in this borehole by the FO's of *Gt. pleistiotumida*, *Globorotalia primitiva*, and *Gt. primitiva-Gt. margaritae margaritae* transition at 4485' (text-fig. 11).

*Unconformities*

Two distinct unconformities occur in the middle Miocene at E68-151 (text-figs. 11, 12). The numbers given to these unconformities (U1-U2) are local and do not correspond with those at E68-136 and E66-73.
TEXT-Figure 12
Sr-isotope and biostratigraphic age estimates versus depth, E68-151A. Numbers correspond to biostratigraphic levels and age estimates given in Table 1. Sr-isotope age estimates are given in Table 3. @ represents alternative age for *Gt. fohsi fohsi* and *Gt. praefohsi* (Table 1). Open triangle = older than FO *Globorotalia praesculata*, 19.0 Ma (Miller et al. 1991).

**Upper Lower to Middle Miocene Unconformity**

An unconformity (U2 on text-fig. 11) is recognized by a Sr-isotope age estimate of 19.0 Ma at 4494' (text-fig. 12) and middle Miocene (Zone N12) at 4492'. The age estimate for the lower surface of the unconformity is supported by the absence of *Globorotalia praesculata* (FO 19.0 Ma; Miller et al. 1985; text-fig. 12). The simultaneous FOS of *Gt. peripheroacuta*, *Gt. praefohsi* and *Gt. fohsi fohsi* at 4492' indicate the absence of Zones N10 and N11 and a thin Zone N12 above the unconformity. Age estimates for the upper surface of the unconformity are uncertain because the ages of the FO of *Gt. fohsi fohsi* and *Gt. praefohsi* are uncertain. Based on the Site 563 magnetostratigraphy of Miller et al. (1985), the FO of *Gt. praefohsi* is estimated as roughly 13.9 Ma (Chrom C5AC; Berggren et al. 1985) (Table 1). Using the revised magnetostratigraphy of Site 563 (Wright and Miller 1992), *Gt. praefohsi* first occurred in Chron C5AA (~13 Ma) (Table 1). Using the Site 563 biostratigraphy and magnetostratigraphy of Miller et al. (1985), *Gt. fohsi fohsi* appears in Chronzone C5ABn (13.4 Ma) (Table 1). The revised magnetostratigraphy for Site 563 (Wright and Miller 1992) indicates that *Gt. fohsi fohsi* first appeared during a normal magnetochron at the base of Chron C5Ar (12.6 Ma) (Table 1). Our best estimate (using the revised chronology of Wright and Miller 1992) indicates age estimate for the upper surface of the unconformity of ~12.6 Ma (i.e., after the FO of *Gt. fohsi fohsi*). Therefore, we estimate the duration of the hiatus as 6.4 m.y. (19.0-12.6 Ma).

**Upper Middle to Lower Upper Miocene Unconformity**

An unconformity (U1 on text-fig. 11) separates middle Miocene sediments at 4491' from upper Miocene sediments at 4485' (text-figs. 11, 12). A Sample at 4485' contains *Gt. pleiostomumida*, *Gt. primitiva*, *Gt. primitiva-Gt. marginariae marginae* transitional forms, *G. nepenthes* (FO, 11.3 Ma; Berggren et al. 1985), and *N. acostaensis*, indicating that Zones N15, N16, and the lower part of N17 are missing. These taxa first occur in this sample together with the LO of *Pg. mayeri* (10.4 Ma; Berggren et al. 1985) that is apparently reworked up one sample. The FO of *Gt. primitiva* is calibrated to 6.9 Ma (Benson et al., in preparation), marking the uppermost Tortonian stage. Nanofossil data indicate the section from 4485' and above is Zone N11b, which is equivalent to Zone N17. Both the planktonic foraminiferal and nanofossil data suggest that an unconformity between 4485' and 4491' separates Zone N12 from upper Zone N17, and that there was a hiatus from ~12.6 to 6.9 Ma; text-fig. 12.

**Other Boreholes (E68-141, E67-114A, E67-128)**

We examined three other Eureka boreholes reported to contain Miocene sections. E68-141 (present depth 5277', 1609m) contains an undifferentiated Zone N17-N18 (uppermost Miocene to lowermost Pliocene) and Zone N19 (text-fig. 13). It also contains reworked middle Miocene taxa: *Paragloborotalia mayeri*, *Globorotalia peripheroronda*, and *Globorotalia fohsi fohsi* (text-fig. 13).

E67-114A from the western Gulf of Mexico (present depth 950', 289.6m) contains poorly defined Miocene to Pliocene Zones N16? to N19. It is very difficult to biostratigraphically correlate this borehole because it lacks zonal markers. The lower part of the section is poorly preserved (text-fig. 13).
E67-128 borehole (present depth 4903', 1495m) contains only Pliocene and Pleistocene sediments. An unconformity at 4940' separates Pliocene Zone N19 from Pleistocene Zone N22-N23. The juxtaposition of G. truncatulinoides, G. ruber (pink), G. nepentes, G. margaritae, and N. acostaensis indicates that the upper Pliocene is missing (text-fig. 13).

**DISCUSSION**

**Correlation of Epoch Boundaries**

**Oligocene/Miocene Boundary**

The Oligocene/Miocene boundary is one of the most controversial boundaries of the Cenozoic (Berggren et al. 1985). It is not marked by any distinct faunal crisis, although a dramatic glacioeustatic lowering is associated with this boundary (Miller et al. 1989, 1991). Poor unit stratotypes for the upper Oligocene and lower Miocene and the lack of a boundary stratotype complicate correlations. The base of the lower Miocene stratotype Aquitanian Stage in France is disconformable. The base contains Globorotalia dehiscens, marking Zone N4b (Jenkins 1966). Berggren et al. (1985) reviewed the numerous foraminiferal and nannofossil biostratigraphic criteria used to recognize this boundary. Foraminiferal events include the following:

1. FO of Globigerinoides primordius (Blow 1969). This has been shown to be substantially older than the Oligocene/Miocene boundary (Berggren et al. 1985). This taxon appears in upper Zone P22 at E68-136 (text-fig. 2).

2. FO of common Globigerinoides primordius (the “Globigerinoides abundance datum”). The FO of abundant Globigerinoides may approximate the boundary recognized by the FO of Globorotalia kugleri in some locations (e.g., Miller et al. 1989). However, this “datum” is diachronous (Lamb and Stainforth 1976; Miller et al. 1989).

3. LO of Globorotalia opima opima (Blow 1969), the zonal criterion for the base of Zone P22. This taxon disappeared in late Oligocene Chron C8 (28 Ma; Berggren et al. 1985).

4. FO of Globigerinoides trilobus s.l. (Keller 1981a). This taxon first appeared in the early Miocene after the sequential FO’s of Globorotalia kugleri and Globorotalia dehiscens (Berggren et al. 1985).

5. FO of Globorotalia dehiscens. Using this criterion would place Biochron N4a in the late Oligocene (Kennett and Srivivasan 1983; Srivivasan and Kennett 1983; Poore 1984). The FO of Gg. dehiscens (Berggren et al. 1985) has a magnetostratigraphic age estimate of 23.2 Ma.

6. FO of Globorotalia kugleri (Berggren et al. 1983, 1985; Berggren and Miller 1988; Miller et al. 1989). We follow Berggren et al. (1985) in recognizing the Oligocene/Miocene boundary by the FO of Globorotalia kugleri sensu stricto. Diagnostic features of Gt. kugleri have been documented by Miller et al. (1989), clarifying problems in using this taxon to recognize the boundary. The FO of Globorotalia kugleri sensu stricto has a magnetostratigraphic age estimate of 23.7 Ma (mid-Chron C6Cn; Berggren et al. 1985). Zone N4 of Berggren and Miller (1988) is recognized as a total range zone of Globorotalia kugleri sensu stricto (Bolli 1957); hence, we interpret this zone as lower Miocene.

Without designation of a boundary stratotype or revised unit stratotype, the recognition of the Oligocene/Miocene boundary (i.e., either at the FO of Globorotalia dehiscens or the FO of Globorotalia kugleri) remains arbitrary.

**Miocene/Pleistocene Boundary**

A Miocene/Pleistocene boundary stratotype was proposed at Capo Rosello, Agrigento, Sicily by Cita (1975) and was discussed in great detail. This boundary stratotype correlates with the base of the Zanclean Stage stratotype. Cita (1975, 1976) suggested that it could be recognized by the base of the Sphaerooidellopsis Acme-Zone at the base of the Trubi marls, immediately above the Globorotalia plesiostomida Zone. She estimated it to have an age of 5.1 Ma at the top of the Magnetochronozone 5 (5.3-5.4 Ma).

Berggren et al. (1983, 1985) suggested that the Miocene/Pleistocene boundary is biostratigraphically linked by the FO of Globorotalia dehiscens and the FO of Gt. tumida to the basal Gilbert Chron (5.3 Ma). We are unable to employ these criteria at the Eureka boreholes. We place the boundary at a level of 2026' at E68-136 using an alternative criterion, the FO of Globorotalia cibauensis. The FO of this taxon has a magnetostratigraphic age estimate of 5.3 Ma (Berggren et al. 1985), the same as the FO of Globorotalia dehiscens, although additional studies reveal that the FO might be substantially older (Berggren, in press). Gt. tumida tumida (FO of 5.2 Ma; Berggren et al. 1985) first occurs far above this level at E68-136, perhaps having a diachronous appearance in this region. We record the coiling changes of Globorotalia menardii s.l. (Gt. menardii B of Bolli and Saunders 1985) and Gt. pseudomioeccena from sinistral to dextral at 1996' at E68-136, just above the Miocene/Pleistocene boundary. Stude (1984) used this coiling change to define the base of N18 (5.4 Ma). Our data indicate that it might be slightly younger than this at E68-136.

**Pliocene/Pleistocene Boundary**

The Vrica Section (south of Crotone, Italy) is the Pliocene/Pleistocene boundary stratotype proposed by Selli et al. (1977) and approved by the IUGS International Commission on Stratigraphy. Magnetostratigraphic (Tauxe et al. 1983) and biostratigraphic (Backman et al. 1983) studies indicate that the boundary level of the Vrica stratotype is approximately 1.6 Ma, near the top of the Olduvai normal Subchronzone. This age is consistent with the FO of Cytrotripteron testudo (or the so-called “cold guests”; Sues 1983) and the FO of Gephyrocapsa oceanica (Collalongo et al. 1981; Berggren et al. 1985). More recent magnetostratigraphic studies of the Vrica section have shown the presence of an additional normal polarity interval above the propyle that has been assigned to the upper Olduvai Chronzone (Zijderveld et al. 1991). A revised astronomical calibrated age estimate of the Pliocene/Pleistocene boundary is 1.81 Ma (Hilgen 1991), whereas the magnetostratigraphic age estimate is 1.78 Ma (Cande and Kent 1992). Although the age estimate has changed, we use the 1.6 Ma estimate of Berggren et al. (1985) for the boundary here to maintain the relative chronology of magnetostratigraphic correlations.

A number of planktonic foraminiferal first and last occurrences have been used to correlate the Pliocene/Pleistocene boundary: the FO of Globorotalia altispina (Lamb and Beard 1972), the FO of Globigerinoides obtusus (Haq et al. 1977), the FO of Globorotalia truncatulinae, the LO of Globorotalia mioeccena, and the LO of Globigerinoides fistulosus. The two
foraminiferal events most frequently used to recognize this boundary in low-middle latitude sections are the FO of *Gt. truncatulinoides* and the FO of *Gn. fistulosus*. Berggren et al. (1985) estimated that *Gt. truncatulinoides* appeared at 1.9 Ma, just prior to the Olduvai Subchron. However, Dowsett (1988) used graphic correlation to show that this taxon first occurred at the Gauss/Matuyama boundary (~2.4 Ma) between 20° and 35° S in the southwest Pacific Ocean, approximately 0.5 m.y. earlier than it is found in the Atlantic and elsewhere in the Pacific. Using magnetostratigraphy, Weaver and Clement (1987) also found that this taxon had a latitudinal diachronous FO in the North Atlantic. The stratigraphic utility of the FO of *Gt. truncatulinoides* is limited because of this intra- and interbasinal hiatus. Despite this, many micropaleontologists still use the FO of *Gt. truncatulinoides* as a marker (Ericson and Wollin 1968; Poag 1972; Poore 1979; Brunner and Keigwin 1981; Srinivasan and Kennett 1981; Kennett and Srinivasan 1983: Weaver and Clement 1987). However, the LO of *Gn. fistulosus* provides a more reliable marker for correlating the Pliocene/Pleistocene boundary. The age estimate of this LO is 1.6 Ma, which is slightly younger than the Olduvai Subchron (Berggren et al. 1985).

In the Gulf of Mexico, Exxon used the LO of *Gt. miocenica* and/or *Lenticulina* sp. 1 to recognize the Pliocene/Pleistocene boundary (Stude 1984). According to our data, *Gt. miocenica* last occurred at about 2.15 Ma (text-fig. 3), about 0.5 m.y. earlier than the global age estimate for the LO of *Gn. fistulosus*. The absence of *Gn. fistulosus* in the northeastern Gulf of Mexico makes it impossible to locate precisely the Pliocene/Pleistocene boundary using planktonic foraminifers. The absence of this taxon implies that *Gn. fistulosus* may have a more restricted geographic distribution than *Gt. truncatulinoides*, although these two taxa are reportedly tropical and warm subtropical species (Kennett and Srinivasan 1983). Thunell (1984) suggested that the FO of *Gt. truncatulinoides* can be used to identify the boundary in the Gulf of Mexico and to correlate it with the open ocean. In this paper, we use *Gt. truncatulinoides* to separate the Pliocene from the Pleistocene. However, it must be noted that this might not be equivalent to the Pliocene/Pleistocene boundary because it is potentially about 0.5 m.y. older than the Vrica stratotype.

**Diachrony**

Diachrony of fossil taxa is a potential problem in biostratigraphic correlations. In classic biostratigraphic studies, first and last occurrences of fossils are assumed to be synchronous, even in different latitudinal areas. We know that this is not always true. Detailed investigations have revealed that some low-latitude planktonic foraminiferal taxa displayed latitudinal diachronous first and last appearances during the late Neogene (Johnson and Nigrini 1985; Weaver and Clement 1986; Dowsett 1988, 1989). More recently, the diachrony of Oligocene-Miocene planktonic foraminifera has received increasing attention (Miller et al. 1985, 1991; Hess et al. 1989).

Comparison of Miocene planktonic foraminifera in the Eureka boreholes with those at Atlantic DSDP Sites 516, 558, 563, and 608 that have good magnetostratigraphic control (Berggren et al. 1983; Miller et al. 1985; and Miller et al. 1991) shows that some ranges are diachronous.

1. *Catapsydrax dissimilis* - The last occurrence of *Catapsydrax dissimilis* has been extensively used as a marker for the base Zone N7 by various authors (Banner and Blow 1965; Blow 1969; Berggren et al. 1983; Kennett and Srinivasan 1983). At Rio Grande Rise Site 516 (western South Atlantic), this species last occurs at the top of Magnetochronzone C5Dn (~ 17.6 Ma; Berggren et al. 1983, 1985). At Site 558, it last occurs near the top of Chronzone C5Dn (~ 17.6 Ma; Miller et al. 1985); at Site 608, it disappears at the top of Chronzone C5Dr (ca. 18.1 Ma), correlating with the LOs at Sites 516 and 558 within the 0.5 m.y. sample resolution (Miller et al. 1991). In contrast, Keller (1981a) reported that the last occurrence of the species was between 19.6 and 20.0 Ma at DSDP Sites 71 and 77 in Equatorial Pacific. At E68-136, our age-depth plot and Sr-isotope data (text-figs. 3, 4) show that *C. dissimilis* last occurred at 21.0 Ma (middle Biochron N5, Chron C6n, 3.4 m.y. older than the age estimate of Berggren et al. 1985). This premature LO at E68-136 is supported by the depth-depth diagrams (text-figs. 6, 7) that indicate that this LO is far below the LOC. At E68-151A, our Sr-isotope data (text-fig. 12) also show that *C. dissimilis* disappeared prematurely at ~19.0 Ma. However, this apparent premature LO may be partly an artifact of the long hiatus (19-14 Ma) at this site. Thus, we find that although the LO of this taxon was premature at E68-136, its age elsewhere in the northeast Gulf of Mexico is indeterminate. In general, we have found that this taxon provides a good datum level, the exceptions being E68-136 and the sites examined by Keller (1981a).

2. The FO of *Globigerinatella insueta* was delayed at Site 563 relative to E68-136 (text-fig. 6). Latitudinal diachrony is supported by the absence of this tropical species except from one sample at the higher latitude Site 608 (Miller et al. 1991). It is for this reason that we avoid using this taxon in our zonations, and instead use the FO of *Globorotalia praeasciulia* to mark the base of Zone N6 (Miller et al. 1991, and see discussion above).

3. The FO of either *Gt. dehiscens* (premature at E68-136) or *Gt. kugleri* (delayed at E68-136) may be diachronous. However, we have attributed the FO of these taxa at the same level not to diachrony but to an unconformity (U6; text-figs. 2, 3).

Lack of recognition of Zone N15 at mid-latitudes may be due to the diachronous ranges of taxa or to unconformities (the "Zone N15 problem" of Berggren, in press). Zone N15 is defined as the interval from the LO of *Paragloborotalia mayeri* (base) to the FO of *Neogloboquadrina acostaensis* (top) (Blow 1969; = the *Globorotalia menardii* Zone of Bolli (1966); see discussion in Berggren, in press). Miller et al. (1985) interpreted the absence of tropical Zone N15 at North Atlantic Sites 558 and 563 to reflect diachronous first and last occurrences rather than hiatuses. Berggren (in press) suggested that the juxtaposition of *P. mayeri* and *N. acostaensis* at these sites may be due to an unconformity. As we have discussed above, the absence of this zone from the tropical Gulf of Mexico E68-136 is clearly due to an unconformity, and our data cannot resolve this controversy.

Our data establish that *D. hamatus* (the criterion for the bases of Zones NN9 and CN7a) first occurs prior to *N. acostaensis* within Zone N15 at E66-73 (text-fig. 8); it first occurs in Zone N14 at Buff Bay, Jamaica (Abry, in press; Berggren, in press), but not until Zone N16 at Site 563 (Miller et al. 1985). As stated above, this either requires a significant unconformity at this level at Site 563, or diachrony between these two taxa.
**TEXT-Figure 13**

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*C. coalitus* (the nominate taxon for the base of Zone NN8) appears prior to the FO of *Globorina nepentes* in Jamaica (in the P. mayeri Zone; = upper Zone N13; Aubry, in press; Berggren, in press). At Sites 558 and 563, this taxon appears in the upper part of Zone N14, well after the FO of *G. nepentes*. At E68-136 and E66-73, this taxon first appears in Zone N11 (text-figs. 2, 8). We have interpreted this anomalous distribution in the Eureka boreholes to reflect downhole contamination of the nannofossils (text-figs. 4, 5, 6, 9, 10). Aubry (this volume) interprets this section as an *in situ* Zone NN8 overlain by downslope transported sediments at both locations. She discusses evidence for mixing of upper middle Miocene sediments throughout the Gulf region and cites Mitchum's (1978) seismic evidence for slumping in the De Soto Canyon region. We concur that stratigraphic mixing is common on continental slopes, and her interpretation is reasonable. However, our data do not support nannofossil evidence for slumping and downslope transport in the middle Miocene section at E68-136 and E66-73 (e.g., the good representation of the *G. foehsi* the evolutionary lineage in this section and the consistent benthic biofacies succession; see above). Nevertheless, it is possible that the foraminifera are part of middle Miocene slump blocks sandwiched between intervals of *in situ* upper Miocene. Two lines of evidence are needed to solve this problem. First, detailed lithologic studies of the upper middle Miocene section are needed; unfortunately, this is not possible for the Eureka boreholes due to core degradation and oversampling. Second, detailed seismic profiles over the boreholes are needed to determine if there is evidence for slumping at the boreholes in question. A solution to this problem awaits examination of seismic data available and future drilling in the De Soto Canyon region.

**Paleoceanography**

It is well documented that Neogene deposition was discontinuous in all the oceans. Unconformities resulted from deep-water circulation, local downslope processes, and carbonate dissolution, among other effects (see Moore et al. 1978 for summary). Although the age of sediments above an unconformity have been used to provide the timing of cessation of erosion (e.g., Moore et al. 1978), we note that deep-water currents may cause non-deposition and diachronous cessation of hiatuses (see example in Christie-Blick et al. 1990). Eustatic change may result in increased downslope erosion and development of deep-water unconformities (Miller et al. 1990; Aubry 1991), although the link between deep-sea hiatuses and global sea level is indirect (Tucholke 1981). As a marginal sea, the Gulf of Mexico may have a more complicated history of paleoceanography and paleoclimates because it is subject to both global oceanographic and local and climatic variations. Also, as noted above, interpretations of boreholes in the ancient sections such as the Eureka boreholes may be complicated by local and regional mass wasting events that can only be recognized with a closely spaced seismic grid and core recovery.

All of the Eureka boreholes examined in this study contain major unconformities. We consider that these may be related to important paleoceanographic changes. For example, a Pliocene unconformity is found at three Eureka boreholes (text-fig. 14), resulting in poor representation of the Pliocene-lower Pleistocene section. This may be causally related to the closure of the Central American Isthmus which could have resulted in intensification of surface water circulation and strong erosion in the Gulf of Mexico. Note that the hiatuses recognized here using planktonic foraminiferal biostratigraphy (text-fig. 14) are...
somewhat shorter than hiatuses inferred from nannoplankton (Aubry, this volume). Oxygen isotope stratigraphy may help to resolve this discrepancy. For example, Miller and J.D. Wright (unpublished data) use oxygen isotope stratigraphy to infer a possible upper lower Miocene unconformity at E68-136, but also to infer that the record is more continuous than indicated by nannoplankton. While we recognize that hiatuses must be delineated by integrating foraminiferal, nannofossil, magneto-, and Sr-isotope, and stable isotope stratigraphy, we present our version of hiatuses based largely on biostratigraphy and Sr-isotope stratigraphy.

Earlier Miocene

As discussed earlier, Zone N4a is missing at E68-136, indicating a possible unconformity U6 at the Oligocene/Miocene boundary. There is a sample gap spanning the Oligocene/Miocene boundary at E68-151. The unconformity at E68-136 may correlate to the PH hiatus of Keller and Barron (1983). The PH hiatus has been attributed to deep-water circulation changes associated with the opening of the Drake Passage (Keller and Barron 1983). However, it should be noted that we have not detected a coeval break in the North Atlantic Ocean (Miller and Tucholke 1983; Miller et al. 1985; Miller et al. 1991). The definition and significance of this break in the Gulf of Mexico remain uncertain, because it appears to have been formed slightly earlier than that of Keller and Barron (1983).

Late Early Miocene

A long hiatus at E68-151A developed from 19.0 to 12.6 Ma, spanning the interval from Biochron N6 through N11 (early to early middle Miocene). At E68-136, a hiatus extends from ~18.0-16.5 Ma (unconformity U5; text-figs. 3, 4, 14). The duration of this gap might be slightly longer than we estimated (~19.0-16.5), because Zone N3 is absent (Aubry, this volume). This gap at E68-136 correlates in part with hiatus NH1 of Keller and Barron (1983; 20-18 Ma, respectively). It correlates well with a pulse of Northern Component Water from 19-16 Ma inferred from carbon isotope reconstructions (Wright et al. 1992). It may correlate with widespread erosion in the northern North Atlantic associated with Reflector R2 (Miller and Tucholke 1983).

Seismic stratigraphic profiles (Line S of Mitchum 1978, fig. 1) indicate that an important lower Miocene seismic unconformity occurs at E66-73 at ~0.5 sec (two-way travel time). This suggests that it correlates with a level ~88m below the lowest sample (i.e., older than 16.2 Ma). The 18.0-16.5 hiatus at E68-136 (unconformity U5) and the seismic unconformity at E66-73 ("F" of Mitchum 1978) may correlate with the 17.5 Ma sequence boundary of Haq et al. (1987a), and may therefore be the product not of current erosion, but of increased downslope erosion. We require detailed seismic stratigraphic coverage and additional drilling to document the cause of this break (i.e., by deep-water currents or by eustatically driven downslope erosion).

Middle Miocene

A short, early middle Miocene hiatus at E68-136 (U5; 16.3-15.2 Ma) correlates well with hiatus NH2 of Keller and Barron (1983), but there is no corresponding gap at E66-73 (text-figs. 9, 14). The corresponding interval at E68-151A is part of a long hiatus. A hiatus (unconformity U4) developed at E68-136 between 14.1-13.6 Ma. This gap apparently correlates with hiatus NH3 of Keller and Barron (1983). However, once again, there is no corresponding gap at E66-73, and a long hiatus at E68-151A, Mullins et al. (1987, 1988) suggested that a major erosional surface resulted from the Loop Current in the eastern Gulf of Mexico during the middle Miocene (~15-12 Ma). Our biostratigraphic results, particularly those from the upper bathyal region (text-fig. 14, E68-136 and E66-73) indicate that the inferred influence of the Loop Current was minimal in the De Soto Canyon area. Our data indicate that the strongest erosion occurred in the De Soto Canyon during the Pliocene. For this reason, we assume that the Loop Current was areally restricted during the middle Miocene, and that closure of the Isthmus of Panama in the "middle" Pliocene (e.g., Coates et al. 1992) may have intensified its effects.

Late Miocene

At the three major boreholes (E68-136, E66-73, E68-151A), we recognized a late middle to early late Miocene hiatus around 10 Ma (text-fig. 14). This hiatus coincides with hiatus NH5 of Keller and Barron (1983). We speculate that it is mainly associated with the large, rapid sea level drop near the middle/late Miocene boundary (the 10.5 Ma sequence boundary of Haq et al. 1987a). This is also supported by the reworking of middle Miocene taxa, such as Pg. mayeri, Gt. fohsi fohsi, and Gt. peripherorunda at the lower bathyal site E68-141 (text-fig. 13).

The hiatus NH6 of Keller and Barron (1983), which occurred within Biochron N17 (7.5-6.2 Ma), cannot be detected in our boreholes. In contrast, we recorded a relatively complete Zone N17 at E68-136 (text-fig. 14).

Pliocene to Early Pleistocene

This Pliocene-lower Pleistocene section contains a widespread unconformity, which is the most important one in the northeastern Gulf of Mexico region (text-fig. 14). This hiatus may be attributed: 1) to the closing of the Central American Seaway, which may have intensified the Loop Current/Gulf Stream during the Pliocene and early Pleistocene (Mullins et al. 1987); 2) to the growth of Northern Hemisphere ice sheets beginning in the late Pliocene (3 Ma) which may be related to deep-water changes. These long Pliocene-early Pleistocene hiatuses could be attributed to one or more of the inferred eustatic lowerings between 4.5 Ma and 1.6 Ma (Haq et al. 1987). However, the most complete record is at the shallowest borehole (E68-136) where deposition resumed in early Pliocene Biochron N22 (text-fig. 14); longer hiatuses occurred in the deeper boreholes (text-fig. 14), consistent with erosion by deep-water currents. Raymo et al. (1992) document that the most intense production of Northern Component Water (NCW) (analogous to North Atlantic Deep Water, NADW) occurred in the early Pliocene prior to the growth of the ice sheets. Thus, the erosion may be correlated to production of early Pliocene NCW in the North Atlantic. However, given the minimal geological effects of NADW on the De Soto slope today, we relate the erosion to the effects of the Loop Current which reaches the bottom today. We base this speculation on the fact that the timing of the hiatus (5 to 1.9 Ma or younger) corresponds to the beginning of deep-water closure (3.8 Ma according to Gardner et al. (1987); see summary in Coates et al. (1992)). The Pliocene erosion noted here may also explain the poor lower Pleistocene record of the Gulf of Mexico.
CONCLUSIONS

We evaluated planktonic foraminiferal biostratigraphy of several the Gulf of Mexico Eureka boreholes, emphasizing the Miocene depositional history of the De Soto Canyon region.

We recognize six possible unconformities at E68-136:

1) Zone N4a is absent; this may be ascribed to an unconformity (~23.7-23.2 Ma) or the diachronous first occurrence of either *Globorotalia kugleri* or *Globoquadrina dehiscens*.

2) Undifferentiated Zone N6/N7 is concatenated (~18.0-16.5 Ma). This concatenated interval is adjacent to the boundary between calcareous nanoplankton Zones NN2 and NN4, and is consistent with an unconformity at this level.

3) Based on the juxtaposition of the FO of *Praeorbulina glomerosa* (16.3 Ma) and *Orbulina* (15.2 Ma), there may be an unconformity separating Zones N8 partim and N9 partim, although the possible hiatus is short (<1.0 m.y.).

4) An unconformity is identified by the juxtaposition of the FO of *Globorotalia peripherausta* (14.1 Ma) with the LO of *Sphenolithus heteromorphus* (13.6 Ma) and a condensed or absent Zone N11; the associated hiatus is short (<0.5 m.y.).

5) The absence of Zones N15 and lower N16 identifies an unconformity that straddles the middle/upper Miocene boundary. A high percentage of stained foraminifera occur at the level of the inferred unconformity, supporting our interpretation that there is a stratigraphic break here.

6) Zones PL1a partim through PL6 are missing, indicating an unconformity that is associated with a ～3 m.y. hiatus (~5.0-1.9 Ma).

Sr-isotope stratigraphy of E68-136 supports the age estimates developed here using planktonic foraminiferal biostratigraphy, although upper Oligocene Sr-isotope stratigraphy and biostratigraphy remain ambiguous. Based on the relative completeness and stratigraphic integrity of the *Globorotalia foksi* lineage at both E68-136 and E66-73, we find no evidence for downslope transport of sediments that has been inferred from nanofossil biostratigraphy (Aubry, this volume); however, it is possible that the upper middle Miocene section at both boreholes consists of stumped sediments sandwiched between *in situ* upper Miocene sediments.

Three unconformities occur at E66-73:

1) One or more unconformities may separate Zone N12 (top recognized by the LO of *G. foksi* spp.) from Zone N14. Intense dissolution occurs near this level, obscuring biostratigraphic relationships.

2) An unconformity may separate Zones N15 from N16 partim; this may correlate with an unconformity at E68-136.

3) An unconformity separates upper Miocene Zone N17b from Pleistocene Zone N23.

Zone N4 partim and Zone N5 are represented at E68-151 (~23-19 Ma). A thin section of middle Miocene at this borehole is separated from lower Miocene strata by an unconformity. Another unconformity separates middle Miocene from upper Miocene strata.

Some of these unconformities correlate with those noted in other ocean basins (e.g., Keller and Barron 1983; Miller and Tucholke 1983), although the current unconformities (i.e., whether due to sea-level or deep-water effects) remains uncertain. The most distinct unconformity developed in the Pliocene, with erosion or nondeposition continuing into the early Pleistocene at two boreholes. We relate this event to closure of the Isthmus of Panama, which may have intensified the Loop Current. Middle Miocene erosion by the Loop Current noted on the West Florida shelf (Mullins et al. 1987) was minimal in the De Soto Canyon region.

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Plate 1

All scale bars are 100µm.

1, 2 Globorotalia foehsi lobata, ventral view. 1, E66-73, 3478'; 2, ventral view, E66-73, 3438'.

3 Globorotalia foehsi robusta, ventral view, E66-73, 3478'.

4-7 Globorotalia praefohsi sensu Blow and Banner, ventral views; 4-6, E66-73, 3558'; 5, E69-136, 2457'; 7, E66-73, 3478'.

8, 9 Globorotalia praefohsi sensu Kennett and Srivisvan, ventral views, E48-136, 2466' (first occurrence).

10 Globorotalia foehsi, ventral view, E68-136, 2457'.

11, 12 Globorotalia peripheroronda, 11, ventral view, E68-136, 2586'; 12, axial view, E66-73, 3661'.

13 Globorotalia peripheroronda-peripheroacuta transition, ventral view, E68-136, 2466'.

14, 15 Globorotalia peripheroacuta, 14, axial view, E66-73, 3598'; 15, ventral view, E69-136, 2486'.

16 Globorotalia archeomenadii, ventral view, E68-136, 2546'.

17 Globorotalia plesionumida, ventral view, E66-73, 3158'.

18 Globorotalia praemenadii, ventral view, E68-136, 2466'.
Plate 2
All scale bars are 100μm.

1, 2  *Globorotalia praeascita*. 1, ventral view, E68-136, 2627° (first occurrence); 2, dorsal view, E68-136, 2627° (first occurrence).


5  *Globorotalia paralanguenensis*, ventral view, E68-136, 2336°.

6  *Neogloboquadrina praeascervata*, ventral view, E68-136, 2246°.

7  *Globigerina nepentes*, ventral view, E68-136, 2270°.

8–10  *Neogloboquadrina acostaensis*, ventral views. 8, E66-73, 3258° (first occurrence); 9, E68-136, 2246°; 10, E68-136, 2226°.

11  *Sphaeroidinellopsis kochii*, ventral view, E68-136, 2394°.


14  *Globigerinoidea vicamus* s.s., ventral view, E68-136, 2586° (first occurrence).

15–17  *Orbulina suturalis*. 15, showing areal pores, E68-136, 2535° (first occurrence); 16, dorsal view, E68-136, 2526°; 17, ventral view, E68-136, 2457°.

18  *Praeorbulina glomerosa glomerosa*, ventral view, E68-136, 2546° (first occurrence).


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Plate 3
All scale bars are 100µm

2. Pohyberibola christiani, side view, E68-136, 2276'.
3. Cassigerinella chupolensis, apertural view, E68-136, 2535'.
4-6. Globorotalia kugleri s.s., 4, ventral view, E68-136, 2753' (first occurrence); 5, dorsal view, E68-136, 2755' (first occurrence); 6, axial view, E68-136, 2711'.
7, 8. Globorotalia mendacis, 7, dorsal view, E68-136, 2734'; 8, ventral view, E68-136, 2734'.


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