NEOGENE STRATIGRAPHIC SUCCESSIONS ALONG A GULF OF MEXICO TRANSECT (MAIN PASS TO GREEN CANYON)

MARIÉ-PIERRE AUBRÝ
Department of Earth and Planetary Sciences, Rutgers University, 610 Taylor Road, Piscataway, New Jersey 08854, USA
e-mail: aubry@eps.rutgers.edu

WILLIAM A. BERGGREN
Department of Earth and Planetary Sciences, Rutgers University, 610 Taylor Road, Piscataway, New Jersey 08854, USA; and Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02536, USA

AND

JAMES V. BROWNING
Department of Earth and Planetary Sciences, Rutgers University, 610 Taylor Road, Piscataway, New Jersey 08854, USA

WITH THE COLLABORATION OF

TAREK ABDELKADER
Geology Department, Faculty of Science, Tanta University, 31527, Tanta, Egypt

AND

JIJUN ZHANG
Imprimia Biostrat Services Limited, 28 Ann Louise Crescent, Markham, ON L3S 0A8, Canada

ABSTRACT: We have examined the Neogene stratigraphic successions recovered from six wells located along a present-day middle neritic (current depositional depth 92 m) to upper bathyal depth (current depositional depth 482 m) transect oblique to the shelf/slope margin in the northern Gulf of Mexico (GOM) using calcareous plankton biostratigraphy. The latter were used to conduct stratigraphic interpretation of the sections and to determine their completeness. We establish that all sections vary considerably in thickness and completeness, depending on depth of deposition, as estimated from benthic foraminiferal analysis, which shows that depositional depth at the six sites changed little through the Neogene. The shallowest section (~90-m estimated depositional depth through the Neogene) is the thinnest with the most complete Upper Miocene–Pleistocene record, whereas the deepest section (~600–800-m estimated depositional depth) is the thickest but also contains the least complete Pliocene–Pleistocene record. The Upper Miocene to Pleistocene sediments deposited between ~200- and 500-m estimated depositional depth exhibit a characteristic allostratigraphic architecture, with sedimentary units bounded by unconformities associated with 1- to 2-Myr hiatuses that vary little along the transect. We integrate the stratigraphic architecture along our local transect in the regional Cenozoic depositional framework in the GOM of Galloway and coauthors and establish that the allostratigraphic units (AUs) correspond well with several of the genetic and seismic sequences delineated. We interpret the depth-related increase in thickness of the Upper Miocene–Pleistocene AUs in light of the sedimentary processes discussed by these authors. However, our interpretation differs considerably from theirs based on our documentation of temporally incomplete sections in the wells. The sedimentary pattern in Well-3 (~200-m estimated depositional depth) is quite different from that at nearby Well-1 (~100–600-m estimated depositional depth), although very similar to the wells further west, even though the distance between Well-3 and Well-1 is about four times that between Well-3 and Well-1. We note also that the stratigraphic pattern in Well-1 changed ~8 Ma, from highly discontinuous before to remarkably continuous after. We have found no clear evidence that glacio-eustasy shaped the Neogene stratigraphic record in the study area. Therefore, we question whether glacio-eustasy was the primary forcing mechanism on stratigraphic architecture in the GOM beyond the shallow part of shelves and propose that salt tectonics may have been a more prominent factor in controlling accommodation. An allostratigraphic architecture was described earlier from the De Soto Canyon northeast of the GOM transect, where the AUs and their boundaries were shown to match, respectively, the seismic sequences and surfaces on the nearby Florida margin. We therefore consider the AUs along the GOM transect as corresponding as well to seismic sequences and therefore to parts of depositional sequences. Based on this, we review notable difficulties in characterizing seismic features (sequences and surfaces) in concrete stratigraphic records and recommend a greater awareness of the temporal significance of unconformities, many of which are associated with multmillion-year hiatuses.

KEY WORDS: conformity, glacio-eustasy, hiatuses, Neogene, sequence boundaries
INTRODUCTION

Developed in earnest four decades ago, sequence stratigraphy has acquired a prominent place in stratigraphic analysis. This is well reflected in the multiple comprehensive overviews on its concepts, methods, and practices (e.g., Gradstein et al. 1998, Coe 2003, Catuneau 2008, Emby 2009) and by the support of the Ocean Drilling Program for shallow drilling on passive margins (New Jersey Margin: e.g., Browning et al. 2008, Miller et al. 2013; Australian Margin: e.g., John et al. 2004, 2011; Bahamas: e.g., Betzler et al. 2000). The Exxon depositional sequence model has been broadly accepted and, aside from its industrial success (de Graciansky et al. 1998), has allowed unprecedented insights into the question of eustasy, culminating with a reconstruction of glacio-eustasy for the last 180 Myr (Miller et al. 2011). However, beyond the reality of depositional sequences with their system tracts and characteristic surfaces, a broader stratigraphic pattern has been described. Allostratigraphy was comprehensively illustrated for the Paleogene of the New Jersey margin (Poggi 1987) and subsequently documented for the Neogene of the eastern Gulf of Mexico (GOM) and Jamaica (Aubry 1993a, 1993b). Allostratigraphic units are unconformity-bounded and separated by long hiatuses that remain essentially constant over long distances (see NACSN 2005). The seismic sequences delineated on the West Florida margin by Mitchum (1978) were identified in cores from the De Soto Canyon, and the bounding seismic boundaries were shown to correspond to unconformities associated with >1-Myr hiatuses (Aubry 1993a). However, the De Soto Canyon sections, at estimated depositional depths ranging from neritic to bathyal (Katz and Miller 1993), were investigated without concern for their relative locations, which possibly explains the long hiatuses. In the course of an integrated biostratigraphic and paleobathymetric study of six nearby sections located along a depth transect west of the De Soto Canyon, extending broadly parallel to the shoreline from Main Pass (offshore Alabama) to Green Canyon (offshore Louisiana) in present-day depositional depths ranging from 92 to 482 m, an allostratigraphic pattern was recovered as well. In this study we analyze the completeness of the six sections and proceed with their temporal interpretation based on calcareous microplankton stratigraphy. This allows us to describe the lateral extent of the allostratigraphic units (AUs) in relation to depositional depth and to speculate on the processes that may be involved in the development of an allostratigraphic pattern.

MATERIALS AND METHODS

Material

The six Neogene successions compared here are from wells located along an ~600-km-long, northeast–southwest depth transect in the northern GOM (Fig. 1; Tables 1, 2). The shallowest succession, off Alabama, was drilled at 92-m water depth; the deepest one, off Louisiana, was drilled at 482-m water depth. The wells were selected specifically for their depth distribution along a transect oriented subparallel to the coastline, but lithologic descriptions, lithostratigraphic frameworks, and seismic data were not made available to us by the oil companies with whom we collaborated on this project. A recent effort to obtain these data in support of the present contribution proved unsuccessful. Seismic lines from offshore Alabama through the Main Pass area and their chronostratigraphic interpretations are, however, available (Greenlee and Moore 1988). The full names of the wells are given in Figure 1 and Table 1. They are numbered Well-1 (shallowest) to Well-6 (deepest) in the text, tables, and figures for easier reading.

Benthic foraminiferal data indicate that the relative depositional depths along the transect were generally maintained throughout the Neogene, but environments were generally deeper (from neritic [Well-1] to middle bathyal [Well-6]; Van Morkhoven et al. 1986). The shallowest wells were at middle neritic to upper bathyal depositional depths (estimated at ~100–200 m), the deepest being at upper middle bathyal depths (estimated at 800–1000 m). Average Neogene depositional depths of each well, as estimated from benthic foraminiferal assemblages, are given in Table 1 (Katz et al., in press).

Samples

Over 1500 samples have been analyzed. With a few exceptions, the samples used for planktonic foraminifera and calcareous nannofossil biostratigraphy originated from the same levels/intervals in the wells. Details concerning sample resolution are given in Table 3. The companies provided washed residues for planktonic foraminiferal analysis. They made available side-wall core samples, ditch cutting samples, or smear slides for calcareous nannofossil study. Smear slides were prepared from unprocessed samples. A discrete cutting sample was used per slide. In an attempt to improve calcareous nannofossil recovery, several (up to eight) smear slides were prepared from as many ditch cutting samples because ditch cutting samples from a given 30-ft (~10-m) interval yielded assemblages of markedly different richness and with variable preservation. The smear slides with the richest and best-preserved material were selected for analysis. No attempt was made to identify the reasons for variable richness (from barren to abundant) and preservation (from poor to good) of the calcareous nannofossils in ditch cuttings recovered from a 30-ft (~10-m) interval. Rapid alteration during drilling and/or cleaning of the cuttings from the embedding drilling mud or, more simply, dissolution during the drying process associated with storage (Self-Trail and Seefelt 2005) cannot be ruled out, but variable input of detrital material is a likely cause.

No samples were provided from the youngest Pleistocene sediments in the wells, and we assume that these constituted normal, undisturbed (e.g., without slump) sections.

Biozonal and Biochronological Framework

This study relies on the taxonomic frameworks in Aubry (1993a, 1993b) and Berggren (1993a, 1993b); on the biozonal schemes of Martini (1971) for the calcareous nannofossils; and on Blow (1969, 1979), Berggren (1977), Berggren et al. (1983, 1995a), and Wade et al. (2011) for the planktonic foraminifera (Table 4). We use the M (Miocene), Pl (Pliocene), and Pt (Pleistocene) zonation of Berggren et al. (1995a) for the Neogene zonation scheme. This zonation has been partly modified by Wade et al. (2011). We have updated the time scale of Berggren et al. (1995a) using the recalibrated (foraminiferal) M-zones (Wade et al. 2011) and by calibrating the (coccolith) NP-zones to the Geomagnetic Polarity Time Scale (Cande and Kent 1995). For the latter purpose we have relied on the calibration of Neogene nannoplankton events to the geomagnetic polarity time scale and their age determination based on astrochronology (Lourens et al. 2004, Raffi et al. 2006). For a few datums we have referred to earlier calibrations in Berggren et al. (1995b). We proceeded with a qualitative analysis of assemblages, placing emphasis on the integration of occurrence data in two independent groups of microfossils. This method proved successful in an earlier study in a nearby area (De Soto Canyon; Aubry 1993a), with strontium isotope stratigraphy (Miller et al. 1993) supporting the biostratigraphically based delineation of unconformities.

The calcareous nannofossils exhibit highly variable preservation in the wells. Their scarcity at some levels is clearly related to poor preservation and diagenesis. Diversity also varies with preservation. Preservation of the planktonic foraminifera is also variable, primarily
good in the Pliocene and Pleistocene, whereas it deteriorates in Miocene (and older) material at greater depths (~15,000–18,000 ft; ~5000–6000 m), owing to the effects of overpressure and resulting in test deformation and distortion. Because preservation and abundance determine the reliability of biozonal control, the quality of the calcareous nannofossil assemblages is discussed for each well in Appendix A. Downhole contamination was pervasive at some levels. Reworking was also encountered at a few levels. Neither hampered stratigraphic interpretation.

Chronostratigraphy

We conduct the discussion below at the chronostratigraphic (subseries) level. This is for convenience, but also because this is the preferred level in sequence stratigraphic analysis. Subseries are de facto chronostratigraphic units, and we use them as formally defined (Aubry 2016). We use dual terminology for rock and time, as argued in Aubry (2007, and references therein) and more recently encouraged by Zalasiewicz et al. (2013). The placement of chronostratigraphic

<table>
<thead>
<tr>
<th>Section</th>
<th>Well-1</th>
<th>Well-2</th>
<th>Well-3</th>
<th>Well-4</th>
<th>Well-5</th>
<th>Well-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude (N)</td>
<td>29.3478</td>
<td>29.2599</td>
<td>29.1903</td>
<td>28.5122</td>
<td>28.1952</td>
<td>27.8092</td>
</tr>
<tr>
<td>Longitude (W)</td>
<td>87.7902</td>
<td>88.0731</td>
<td>88.4507</td>
<td>89.2268</td>
<td>90.0645</td>
<td>90.9283</td>
</tr>
<tr>
<td>Water depth (ft)</td>
<td>303</td>
<td>642.88</td>
<td>656</td>
<td>1397.28</td>
<td>611</td>
<td>1580.96</td>
</tr>
<tr>
<td>Water depth (m)</td>
<td>92</td>
<td>196</td>
<td>200</td>
<td>426</td>
<td>215</td>
<td>482</td>
</tr>
<tr>
<td>KB elevation (ft)</td>
<td>60</td>
<td>84</td>
<td>73</td>
<td>83</td>
<td>77</td>
<td>37</td>
</tr>
<tr>
<td>KB elevation (m)</td>
<td>18.29</td>
<td>25.61</td>
<td>22.26</td>
<td>42.26</td>
<td>21.5</td>
<td>48.2</td>
</tr>
<tr>
<td>Neogene paleodepth (m)</td>
<td>100–600</td>
<td>~600</td>
<td>~500</td>
<td>~600</td>
<td>~800</td>
<td>600–1000</td>
</tr>
</tbody>
</table>

Table 2.—Interval studied in each well, and stratigraphic age of youngest and oldest sediments. The thickness of the Neogene section and oldest sediments studied is also given.

<table>
<thead>
<tr>
<th>Sections</th>
<th>Calcareous top (ft)</th>
<th>Nannofossils bottom (ft)</th>
<th>Planktonic top (ft)</th>
<th>Foraminifera bottom (ft)</th>
<th>Thickness in feet (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well-1</td>
<td>992</td>
<td>7759</td>
<td>992</td>
<td>7600</td>
<td>6767 [~2060]</td>
</tr>
<tr>
<td></td>
<td>Lower Pleistocene</td>
<td>Oligocene</td>
<td>Pleistocene</td>
<td>Eocene</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NN20</td>
<td>NP23</td>
<td>7020</td>
<td>14,430</td>
<td>7140 [~2030]</td>
</tr>
<tr>
<td></td>
<td>Upper Miocene</td>
<td>barren</td>
<td>Upper Miocene</td>
<td>Lower Eocene</td>
<td>7410 [~2245]</td>
</tr>
<tr>
<td></td>
<td>NN11</td>
<td>N17</td>
<td>7020</td>
<td>N17</td>
<td></td>
</tr>
<tr>
<td>Well-2</td>
<td>1700</td>
<td>12,080</td>
<td>1700</td>
<td>12,080</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pleistocene</td>
<td></td>
<td>Pleistocene</td>
<td>Middle Miocene</td>
<td>10,380 [3745]</td>
</tr>
<tr>
<td></td>
<td>NN19</td>
<td>N12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well-3</td>
<td>5010</td>
<td>18,750</td>
<td>5010</td>
<td>18,750</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pleistocene</td>
<td>Miocene</td>
<td>Pleistocene</td>
<td>Middle Miocene</td>
<td>13,740 [~4165]</td>
</tr>
<tr>
<td></td>
<td>NN19</td>
<td>N14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well-4</td>
<td>1740</td>
<td>13,170</td>
<td>1740</td>
<td>13,170</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pleistocene</td>
<td>Upper Miocene</td>
<td>Pleistocene</td>
<td>Miocene</td>
<td>11,430 [3465]</td>
</tr>
<tr>
<td></td>
<td>NN20</td>
<td>N17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well-5</td>
<td>4590</td>
<td>18,780</td>
<td>2860</td>
<td>18,810</td>
<td>14,190 (4300)</td>
</tr>
<tr>
<td></td>
<td>Pleistocene</td>
<td>indeterminate</td>
<td>Pleistocene</td>
<td>Pliocene</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NN20</td>
<td>?</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 samples were examined down to 9144 ft (2787 m). The succession is greatly disturbed between 7759 and 9144 ft (2365 and 2456 m); it is not discussed here. Whereas the upper 7759 ft (2365 m) of the well represent a discontinuous but mostly normal stratigraphic succession, the lower 1385 ft (422 m) are stratigraphically disturbed. Coccoliths characteristic of Cretaceous, Paleocene, Eocene and lower Miocene stratigraphies are mixed at 8059 ft (2456 m). The interval between 8378 and 8595 ft (2554 and 2712 m) is a lower Paleocene to upper Cretaceous succession but levels 8642, 8643, and 8897 ft (2634.1, 2634.4, and 2712 m) yield mixed Paleogene and lower Neogene assemblages with lower Miocene marker species dominant. For the purpose of this study, detailed report on the stratigraphy of the well is limited to the interval between 992 and 7759 ft (302 and 2365 m).

Table 3.—Material studied in each well: sample number, type, resolution, and preparation.

<table>
<thead>
<tr>
<th>Section samples</th>
<th>Well-1</th>
<th>Well-2</th>
<th>Well-3</th>
<th>Well-4</th>
<th>Well-5</th>
<th>Well-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numbers</td>
<td>230</td>
<td>82</td>
<td>400</td>
<td>82</td>
<td>200</td>
<td>87</td>
</tr>
<tr>
<td>Type</td>
<td>sidewall core</td>
<td>ditch cuttings</td>
<td>ditch cuttings</td>
<td>ditch cuttings</td>
<td>ditch cuttings</td>
<td>ditch cuttings</td>
</tr>
<tr>
<td>Interval (ft)</td>
<td>992–9144</td>
<td>7020–14,430</td>
<td>1700–12,080</td>
<td>5010–18,750</td>
<td>1740–13,170</td>
<td>18,740–18,810</td>
</tr>
<tr>
<td>Resolution (ft)</td>
<td>30–100</td>
<td>60</td>
<td>30</td>
<td>60</td>
<td>30</td>
<td>30–100</td>
</tr>
<tr>
<td>Preparation</td>
<td>smear slides from discrete cuttings</td>
<td>smear slides from discrete cuttings</td>
<td>smear slides from discrete cuttings</td>
<td>smear slides from discrete cuttings</td>
<td>smear slides from suspension²</td>
<td>smear slides from discrete cuttings²</td>
</tr>
</tbody>
</table>


2 Prepared smear slides were made available to MPA.
boundaries follows from GSSP definitions (http://www.stratigraphy.org/index.php/ics-gssps). However, we interpret the Neogene System/Period as extending to the Recent and the Pleistocene Series/Epoch as determined by the base of the Calabrian Stage. There has been sufficient documentation in the recent literature (Aubry et al. 2009a, McGowran et al. 2009) to justify this choice that differs from the position of the International Commission on Stratigraphy (ICS) with regard to the insertion of the Quaternary in the chronostratigraphic scale and the redefinition of the Pleistocene, such that the new Lower Pleistocene should be a substitute for the (now nonexistent) Upper Pliocene (Gramling 2009, Van Couvering et al. 2009 [and references therein]).

Temporal Interpretation of Sections

The methodology used to conduct the temporal interpretation of the sections is explained in Aubry (1995). It is based on the analysis of sedimentation rate curves leading to the delineation of unconformities, determination of the associated stratigraphic gaps, and estimates of the ages of the unconformable surfaces. The basic concept is that in continuous sections the thicknesses between (bio-, magneto-, isotope) stratigraphic events are proportional to durations between them, whereas the occurrences of events of markedly different ages at the same stratigraphic level are indicative of unconformities. Once unconformities are delineated, the ages of the bounding surfaces of the stratigraphic gaps can be determined, the hiatus measured, and the temporal extent of sections can be mapped against a temporal framework. Since the advent of the Deep Sea Drilling Project, sedimentation rate curves have been routinely established to evaluate the temporal continuity of deep sea sections. "Temporal mapping" was used at coarse scale to determine regional sedimentary history (e.g., Tucholke and Mountain 1986). The methodology used here is an outgrowth of these procedures, conducted at fine scale with the specific objective of resolving the difference between condensed and truncated sections (Aubry 1995, figs. 4, 5). It was used successfully to describe the Neogene stratigraphic record in the nearby De Soto Canyon (Fig. 1; see below).

Locating Unconformities: The occurrence of unconformities in a section is revealed by the sedimentation rate curve. Their precise

This is an author e-print and is distributed freely by the authors of this article. Not for resale.
FIG. 3.—Stratigraphic interpretation of the Oligocene to Pleistocene section in Well-1. Stratigraphic data are given in Figures 2 and 3 and Appendix A. Datums are given in Table 4. See text and Table 5 for further explanation. Note: Contrary to international practices (BIPM 2006), the unit of measurement used here to describe the wells is the foot, which is the unit used by drilling companies. Depositional depth and rates of accumulation are, however, expressed in terms of, respectively, meters and centimeters per thousand years (cm/10³ yr).

This is an author e-print and is distributed freely by the authors of this article. Not for resale.
location (i.e., depth from the top of a well) may then be determined based on evidence such as lithological characters or physical/chemical log data. In the absence of such data we are not able to determine the exact stratigraphic location of the unconformities in the transect wells, and this confers important limitations. The precision achieved in determining the stratigraphic location of inferred unconformities is variable. When data are sufficient, an unconformity (or any specific stratigraphic level, for that matter) can be determined to within 10 m (~30 ft). When sample resolution is low and/or paleontologic data are few, the uncertainty on the location of unconformities may be as much as ~50 m (150 ft). In the former case the hiatus is confidently known and the bounding surfaces of the stratigraphic gap precisely dated. In the latter case, unconformities were arbitrarily positioned and the hiatuses and ages of the unconformable surfaces broadly estimated.

On occasion there were several possible locations for a given hiatus (see Table 5). This was resolved by adopting the simplest solution and minimizing rather than maximizing the hiatus. In brief, we acknowledge that there is some uncertainty as to the overlap between the hiatuses in the six wells, and it is important to recognize that the overlap may be lesser than shown here. There may be additional unconformities in the wells, as suggested by our data, but the hiatuses would be short (<0.5 Myr) and their delineation beyond the limits of resolution in this study based on well cuttings. With the caveats explained above that are inherent to the studied material, we view our temporal interpretation as the best possible based on the current data. It is important to recognize here that our reliance on sedimentation rate curves for the stratigraphic interpretations of the GOM wells is justified by the results obtained from two previous analyses with a

FIG. 4.—Calcareous microfossil distribution in Well-1. See discussion in Appendix A. A) Part 1 (Pleistocene–Pliocene) and part 2 (Miocene). B) Ranges of selected planktonic foraminiferal species. An expanded version of this figure is available in the digital version and at the SEPM Supplemental Data site, https://www.sepm.org/supplemental-materials

This is an author e-print and is distributed freely by the authors of this article. Not for resale.
similar objective that were based on the study of rock samples with precisely known stratigraphic location in the sections (De Soto Canyon and Jamaica, Aubry 1993a and Aubry 1993b, respectively).

**Congruence of Data:** The biostratigraphic data from the two microfossil groups used here were generally congruent in the sections analyzed. In several cases, however, there was a slight discrepancy in the location of unconformities, as determined from concurrent but somewhat offset calcareous nannofossil and planktonic foraminiferal datums. We attribute this discrepancy in part to the difference in the nature of the samples analyzed. Obtained from a mixture of ditch cuttings recovered from a given interval in the well, the planktonic foraminiferal assemblage in each sample represents a mixture of assemblages from different horizons within the interval. In contrast, the calcareous nannofossil assemblage examined in each smear slide is that from a single stratigraphic horizon (single ditch cutting), albeit of unknown position in the sampled interval. In most instances the differences had relatively little impact on the overall stratigraphic interpretation of the sections. However, in some instances, it rendered difficult precise determination of the location/level of the unconformities. Otherwise conflicts were logically resolved by relying on the youngest/highest stratigraphic evidence. Preference was generally given to the coccolith data representing a single horizon rather than a mixed assemblage from numerous horizons.

**Reproducibility:** An important consideration is that the delineation of unconformities in this work is independent of the time scale of reference. These unconformities are associated with hiatuses of >1 Myr, whereas fine tuning of Neogene biochronology since 1985 has involved short durations of <0.5 Myr. A case in point is our recalibration of the temporal history of the Neogene successions from the De Soto Canyon for comparison with the GOM transect. The earlier...
stratigraphic interpretation of the Eureka cores (Aubry 1993a) relied on estimated ages outlined in Berggren et al. (1985). With the recalibrated biochronology used here the ages of the unconformable surfaces and the durations of the hiatuses have changed slightly, but the overall interpretation of a highly discontinuous record remains unchanged.

Accumulation Rates: Accumulation rates were calculated for intervals with good biostratigraphic controls, using the datums considered most reliable in these intervals. The rates proposed here are of uneven reliability, varying from high in temporally well-constrained intervals (e.g., Well 1: Upper Miocene–Pliocene interval [6724–1004 ft; 2050–306 m]; Well 2: Upper Miocene–Lower Pliocene interval [12,180–7890 ft; 3712–2405 m]) to moderate in less well-constrained intervals (e.g., Well 3: Upper Miocene interval [7070–4430 ft; 2155–1350 m]) to approximate in others (e.g., Well 4: lower Upper Miocene interval [18,500–17,400 ft; 5640–5300 m]). There were insufficient data points to calculate accumulation rates in several intervals (e.g., Well 4: Pleistocene interval above 6000 ft [1830 m]; Well 5: Pleistocene interval above 7890 ft [2400 m]).

Terminology: The abbreviations LO and HO (lowest and highest occurrence, respectively) and FAD and LAD (First and Last

Fig. 5.—Stratigraphic interpretation of the Middle and Upper Miocene section in Well-2. Datums are given in Table 4. See text and Table 5 for further explanation.
Appearance Datum, respectively) are used to express the conceptual differences between "stratigraphic occurrence" and "global age of specific evolutionary events," as explained in Aubry (1995; see also Aubry 2009 for the meaning of "datum"). The abbreviations Ma and Myr are used to specify dates (commonly "numerical ages") and durations, respectively, following the recent recommendations by the North American Commission on Stratigraphic Nomenclature (Aubry et al. 2009b).

We use the term stratigraphic gap to designate a missing sedimentary interval (of unknown thickness) and the term hiatus for the corresponding duration (in Myr). An "unconformity" is the physical expression. Presence or absence of overlap between hiatuses,

### Table 4.—Datum levels (FADs and LADs in Ma, from Berggren et al. [1995a, 1995b]) and corresponding lowest and highest occurrences (LOs and HOs) in the wells. 1,2

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LAD Globorotalia tosaensis</td>
<td>0.61</td>
<td>4000</td>
<td>4000</td>
<td>4000</td>
<td>4000</td>
<td>4000</td>
</tr>
<tr>
<td>LAD Pseudoemiliania lacunosa</td>
<td>0.43</td>
<td>992</td>
<td>2360</td>
<td>4680</td>
<td>6490</td>
<td>6490</td>
</tr>
<tr>
<td>LAD Helicosphaera selli</td>
<td>1.37</td>
<td>1004</td>
<td>2420</td>
<td>5870</td>
<td>7620–6420</td>
<td>9460</td>
</tr>
<tr>
<td>LAD Calcidicus macintyrei</td>
<td>1.6</td>
<td>1004</td>
<td>2750</td>
<td>5960</td>
<td>7740</td>
<td>9460</td>
</tr>
<tr>
<td>FAD Gephyrocapsa oceanica</td>
<td>1.71</td>
<td>1108</td>
<td>5930</td>
<td>10,810</td>
<td>10,810</td>
<td>10,810</td>
</tr>
<tr>
<td>LAD Globigerinoides extremus</td>
<td>1.8</td>
<td>1154–1214</td>
<td>6060</td>
<td>7920</td>
<td>10,870</td>
<td></td>
</tr>
<tr>
<td>FAD Globorotalia truncatulinoides</td>
<td>1.93</td>
<td>3020</td>
<td>5870</td>
<td>7740</td>
<td>9460</td>
<td>9460</td>
</tr>
<tr>
<td>LAD Globorotalia miocenica</td>
<td>1.93</td>
<td>3020</td>
<td>5870</td>
<td>7740</td>
<td>9460</td>
<td>9460</td>
</tr>
<tr>
<td>LAD Dentoglobigerina altispira</td>
<td>2.39</td>
<td>4198</td>
<td>7500</td>
<td>13,750</td>
<td>13,750</td>
<td>13,750</td>
</tr>
<tr>
<td>LAD Sphaerodinellopsis seminulina</td>
<td>2.39</td>
<td>4198</td>
<td>7500</td>
<td>13,750</td>
<td>13,750</td>
<td>13,750</td>
</tr>
<tr>
<td>LAD Eudiscoaster quinqueramus</td>
<td>4.81</td>
<td>8490</td>
<td>9120</td>
<td>14,890</td>
<td>14,890</td>
<td>14,890</td>
</tr>
<tr>
<td>LAD Amaurolithus tricorniculatus</td>
<td>4.6–4.8</td>
<td>8640</td>
<td>8730</td>
<td>13,740</td>
<td>13,740</td>
<td>13,740</td>
</tr>
<tr>
<td>LAD Ceratolithus rugosus</td>
<td>5.07</td>
<td>10,110</td>
<td>10,110</td>
<td>10,110</td>
<td>10,110</td>
<td>10,110</td>
</tr>
<tr>
<td>LAD Globorotalia tumida</td>
<td>5.63</td>
<td>4643</td>
<td>4643</td>
<td>4643</td>
<td>4643</td>
<td>4643</td>
</tr>
<tr>
<td>LAD Eudiscoaster quinqueramus</td>
<td>5.48</td>
<td>4467–5203</td>
<td>4580</td>
<td>10,560</td>
<td>11,220</td>
<td>11,220</td>
</tr>
<tr>
<td>LAD Goboquadrina dehiscens</td>
<td>5.80</td>
<td>9360</td>
<td>9360</td>
<td>9360</td>
<td>9360</td>
<td>9360</td>
</tr>
<tr>
<td>LAD Globorotalia lenguensis</td>
<td>6.0</td>
<td>6638</td>
<td>6638</td>
<td>9000</td>
<td>9000</td>
<td>9000</td>
</tr>
<tr>
<td>FAD Amaurolithus primus</td>
<td>7.28</td>
<td>7050–7500</td>
<td>7040</td>
<td>17,400</td>
<td>17,400</td>
<td>17,400</td>
</tr>
<tr>
<td>LAD Eudiscoaster neohamatus</td>
<td>7.3</td>
<td>6210</td>
<td>8010–7560</td>
<td>7040</td>
<td>12,180</td>
<td>12,180</td>
</tr>
<tr>
<td>LAD Goboquadrina acostaensis</td>
<td>8.17</td>
<td>6705</td>
<td>8490</td>
<td>11,280</td>
<td>11,280</td>
<td>11,280</td>
</tr>
<tr>
<td>LAD E. hamatus</td>
<td>9.57</td>
<td>9540</td>
<td>9770</td>
<td>17,400</td>
<td>17,400</td>
<td>17,400</td>
</tr>
<tr>
<td>FAD E. hamatus</td>
<td>10.7</td>
<td>10,620</td>
<td>10,620</td>
<td>10,620</td>
<td>10,620</td>
<td>10,620</td>
</tr>
<tr>
<td>FAD Neogloboquadrina acostaeensis</td>
<td>10.7</td>
<td>6691</td>
<td>6691</td>
<td>6691</td>
<td>6691</td>
<td>6691</td>
</tr>
<tr>
<td>LAD Neogloboquadrina mayeri</td>
<td>10.53</td>
<td>6743</td>
<td>9740</td>
<td>9740</td>
<td>9740</td>
<td>9740</td>
</tr>
<tr>
<td>FAD G. nepenthesis</td>
<td>11.55</td>
<td>6743</td>
<td>6743</td>
<td>6743</td>
<td>6743</td>
<td>6743</td>
</tr>
<tr>
<td>LAD Globorotalia fohsi robusta</td>
<td>11.9</td>
<td>11,990</td>
<td>11,990</td>
<td>11,990</td>
<td>11,990</td>
<td>11,990</td>
</tr>
<tr>
<td>LAD Globorotalia fohsi lobata</td>
<td>12.1</td>
<td>10,980</td>
<td>10,980</td>
<td>10,980</td>
<td>10,980</td>
<td>10,980</td>
</tr>
<tr>
<td>LAD Sphenolithus heteromorphus</td>
<td>13.49</td>
<td>7030</td>
<td>13,590</td>
<td>13,590</td>
<td>13,590</td>
<td>13,590</td>
</tr>
<tr>
<td>LAD Globorotalia peripheroronda</td>
<td>13.99</td>
<td>7143</td>
<td>7143</td>
<td>7143</td>
<td>7143</td>
<td>7143</td>
</tr>
<tr>
<td>LAD Praeorbulina sicana</td>
<td>14.56</td>
<td>13,400</td>
<td>13,400</td>
<td>13,400</td>
<td>13,400</td>
<td>13,400</td>
</tr>
<tr>
<td>LAD Praeorbulina glomerosa glomerosa</td>
<td>14.8</td>
<td>13,860</td>
<td>13,860</td>
<td>13,860</td>
<td>13,860</td>
<td>13,860</td>
</tr>
<tr>
<td>FAD Globorotalia peripheroacuta</td>
<td>14.8</td>
<td>6820</td>
<td>6820</td>
<td>6820</td>
<td>6820</td>
<td>6820</td>
</tr>
<tr>
<td>FAD Orbulina suturalis</td>
<td>15.1</td>
<td>7143</td>
<td>7143</td>
<td>7143</td>
<td>7143</td>
<td>7143</td>
</tr>
<tr>
<td>LAD Helicosphaera ampliaperta</td>
<td>14.87</td>
<td>7256</td>
<td>14,130</td>
<td>14,130</td>
<td>14,130</td>
<td>14,130</td>
</tr>
</tbody>
</table>


2 Denotes planktonic foraminiferal events.

Note: The table entries represent the occurrences of specific evolutionary events recorded in the wells specified in the footnote. The ages are given in Ma (百万年) and Myr (百万年). The abbreviations LAD and FAD indicate the lowest and first appearances of these events, respectively. The numbers in parentheses represent the corresponding wells and locations. The table is a compilation of data from Berggren et al. (1995a, 1995b) and includes both numerical ages and durations for the occurrence of these events.

This is an author e-print and is distributed freely by the authors of this article. Not for resale.
FIG. 6.—Calcareous microfossil distribution in Well-2. See discussion in Appendix A. A) Calcareous nannofossils. B) Ranges of selected planktonic foraminiferal species.
as represented in the temporal maps of stratigraphic successions, allows determination of whether widespread unconformities of similar ages may yield a chronostratigraphic significance (see Aubry 1991).

We have advocated elsewhere the use of the term allostratigraphic unit (AU) to avoid confusion between the sequences of sequence stratigraphy (with their correlative conformity) and the unconformable units of considerable lateral extent documented in several areas (see Donovan 2010). Although the allostratigraphic pattern described in the northeastern GOM (Aubry 1993a, see below) matches the seismic sequences independently described (Mitchum 1978), we continue to refer to AUs until their relation to depositional sequences has been understood.

RESULTS

Although the Neogene sections studied here differ considerably between wells in terms of both the thicknesses of chronostratigraphic units and the ages of the oldest Neogene sediments studied in each (see below), their chronostratigraphic and biozonal contents are comparable (Fig. 2). In addition, all series are represented in normal succession in most wells, and with few exceptions this is true also for the (calcareous and planktonic foraminiferal) biozones. This would suggest, a priori, that the six stratigraphic sections are essentially temporally complete (i.e., contain no stratigraphic gaps), implying that differences in thickness of a given biozone among the wells (e.g., Zones NN20, N22) or between successive biozones in a well (e.g., in Well-2) result from sharp changes in sedimentation rates. However, a stratigraphic gap encompassing the Upper Pliocene and upper Lower Pliocene is clearly present in Well-3, and the Upper Pliocene interval is notably thin in Well-5 compared to the Lower Pliocene one. Thus, the question arises of whether differences in sedimentation rates alone can account for the observed pattern of thicknesses (Fig. 2). We resolve this by applying the methodology of Aubry (1995; see above). We examine below the stratigraphic completeness of the six sections and then proceed to their temporal interpretation.

Stratigraphic Completeness of Well-1 (Fig. 3)

Despite difficulties related to preservation and inconsistent occurrences (Fig. 4A, B; Appendix A), a firm stratigraphic interpretation of the well is possible through the integration of foraminiferal and nannofossil stratographies, which are in agreement as to the location of the chronostratigraphic boundaries (Figs. 2, 3). The upper 7637 ft (2328 m) of the well represents a discontinuous upper Lower Oligocene to Pleistocene section. The reduced thicknesses of the Oligocene to Middle Miocene and the lowermost Pleistocene intervals contrast with the expanded Upper Miocene and Pliocene intervals. Several stratigraphic gaps are clearly delineated (from younger to older):

1. An intra-Pleistocene unconformity occurs between 992 and 1004 ft (302 and 306 m);
2. An unconformity occurs at the Middle–Upper Miocene contact (NN8/NN11 and M11/M13a zonal contacts) between 6705 and 6743 ft (2044 and 2055 m);
3. A lower Middle Miocene unconformity occurs at 7143 ft (2177 m);
4. The Lower Miocene is unconformable with the upper Lower Oligocene at ~7474 ft (2278 m); and
5. The Oligocene is unconformable with the Lower Eocene at ~7637 ft (2328 m).

Stratigraphic Completeness of Well-2 (Fig. 5)

The biostratigraphic control (Fig. 6A, B; Appendix A) of this well is rather limited, and there are notable discrepancies between the planktonic foraminiferal and calcareous nannoplankton datums. However the Middle to Upper Miocene interval is considered reliably interpretable (Fig. 5). At least three unconformities can be delineated:

1. A Middle–Upper Miocene unconformity, poorly constrained between 10,980 and 10,620 ft (3347 and 3237 m);
2. An unconformity occurs at the Middle–Upper Miocene contact (NN8/NN11 and M11/M13a zonal contacts) between 6705 and 6743 ft (2044 and 2055 m);
3. A lower Middle Miocene unconformity occurs at 7143 ft (2177 m);
4. The Lower Miocene is unconformable with the upper Upper Oligocene at ~7474 ft (2278 m); and
5. The Oligocene is unconformable with the Lower Eocene at ~7637 ft (2328 m).

Stratigraphic Completeness of Well-3 (Fig. 7)

This 10,000-ft- (3050-m-) thick stratigraphic section spans the Pleistocene to upper Middle Miocene (Zone N22 to Zone N12; Zone NN19 to Zone >NN9) (Fig. 2). The two groups of calcareous microfossils complement each other and provide a comprehensive stratigraphic interpretation of the well (Figs. 7, 8).

A prominent stratigraphic gap occurs in this well at 3020 ft (976 m; Fig. 7), separating Pleistocene (Zone Pt1-2; Subzone NN19a) from Upper Pliocene (~Zone P12/P13; NN14–NN18 zonal interval). (It is...
Table 5.—Evidence used to infer the occurrence of unconformities, to determine the associated hiatuses, and the age of the bounding surfaces.

<table>
<thead>
<tr>
<th>Well-1</th>
<th>Lowermost Pleistocene unconformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location: between 992 ft and 1004 ft; approximated at 998 ft</td>
<td></td>
</tr>
<tr>
<td>Stratigraphic gap: Subzone NN19b; upper part NN19a, lower part NN19c</td>
<td></td>
</tr>
<tr>
<td>Constraints on hiatus:</td>
<td></td>
</tr>
<tr>
<td>Upper surface: &gt;LAD Pseudoemiliania lacunosa (0.43 Ma)</td>
<td></td>
</tr>
<tr>
<td>Lower surface: &gt;LAD Helicosphaera sellii (1.37 Ma); &lt;LAD Calcidiscus macintyrei (1.6 Ma)</td>
<td></td>
</tr>
<tr>
<td>Duration hiatus: ≤0.94 Myr</td>
<td></td>
</tr>
<tr>
<td>Arbitrary duration: 1.1 Myr</td>
<td></td>
</tr>
<tr>
<td>Upper surface: 0.5 Ma (approximated)</td>
<td></td>
</tr>
<tr>
<td>Lower surface: 1.6 Ma (calculated from accumulation rates of 28 cm/10^3 yr; in remarkable agreement with the age of the LAD C. macintyrei)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Upper Miocene/Middle Miocene unconformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location: between 6705 ft and 6743 ft; approximated at 6724 ft</td>
</tr>
<tr>
<td>Stratigraphic gap: Subzone NN11a (partim), Zones NN10–NN9, N14 (partim)–N17(partim)</td>
</tr>
<tr>
<td>Constraints on hiatus:</td>
</tr>
<tr>
<td>Upper surface: &gt;LAD Eudiscoaster neohamatus (7.3 Ma)</td>
</tr>
<tr>
<td>Lower surface: &lt;FAD Globotruncanita nepenthes (11.55 Ma); &gt;LAD Neogloboquadrina mayeri (10.53 Ma)</td>
</tr>
<tr>
<td>Duration hiatus: &lt;4.25 Myr</td>
</tr>
<tr>
<td>Arbitrary duration: 5.3 Myr</td>
</tr>
<tr>
<td>Upper surface: 7.9 Ma (estimated from accumulation rates of 28 cm/10^3 yr); in agreement with the FAD Eudiscoaster quinqueramus</td>
</tr>
<tr>
<td>Lower surface: 13.2 Ma (approximated)</td>
</tr>
<tr>
<td>Remark: Age of lower surface determined by applying accumulation rates of 28 cm/10^3 yr for the 306-ft thick interval between 6724 ft (unconformity) and 7030 ft (FAD Sphenolithus heteromorphus).</td>
</tr>
<tr>
<td>Note: In sections where the thicknesses of intervals between HOs and LOs of taxa are proportional to the durations between the datum events based on these taxa, HOs and LOs represent the LADs and FADs of species.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lower Miocene/Middle Miocene unconformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location: 7143 ft</td>
</tr>
<tr>
<td>Stratigraphic gap: Upper Zone NN5; M6 (partim)–M8 (partim)</td>
</tr>
<tr>
<td>Constraints on hiatus:</td>
</tr>
<tr>
<td>Upper surface: &gt;LAD S. heteromorphus (13.49 Ma); &gt;LAD Globorotalia peripheroronda (13.99 Ma)</td>
</tr>
<tr>
<td>Lower surface: &lt;FAD Orbulina suturalis (15.1 Ma)</td>
</tr>
<tr>
<td>Duration hiatus: 1.11 Myr</td>
</tr>
<tr>
<td>Arbitrary duration: 1.2 Myr</td>
</tr>
<tr>
<td>Upper surface: 13.6 Ma (approximated)</td>
</tr>
<tr>
<td>Lower surface: 14.8 Ma (approximated)</td>
</tr>
<tr>
<td>Remark: Ages of upper surface determined by applying accumulation rates of 28 cm/10^3 yr for the 113-ft-thick interval between 7030 ft (FAD S. heteromorphus) and 7143 ft (unconformity).</td>
</tr>
<tr>
<td>Age of lower surface determined by applying accumulation rates of 28 cm/10^3 yr for the 113-ft-thick interval between 7143 ft (unconformity) and 7256 ft (LAD Helicosphaera ampliaperta).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lower Miocene/Middle Miocene unconformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location: 7474 ft</td>
</tr>
<tr>
<td>Stratigraphic gap:</td>
</tr>
<tr>
<td>Constraints on hiatus:</td>
</tr>
<tr>
<td>Upper surface: &gt;LAD H. ampliaperta (14.87 Ma)</td>
</tr>
<tr>
<td>Lower surface: unconstrained</td>
</tr>
<tr>
<td>Duration hiatus: unknown</td>
</tr>
<tr>
<td>Arbitrary duration: 1 Myr</td>
</tr>
<tr>
<td>Upper surface: 15.1 Ma (approximated)</td>
</tr>
<tr>
<td>Lower surface: indeterminate</td>
</tr>
<tr>
<td>Remark: Age of upper surface determined by applying accumulation rates of 28 cm/10^3 yr for the 218-ft-thick interval between 7256 ft (LAD H. ampliaperta) and 7474 ft (unconformity).</td>
</tr>
</tbody>
</table>

Older unconformities: see Appendix A
### Table 5.—Continued.

#### Well-2

**Middle Miocene/Upper Miocene unconformity**
- Location: between 10,620 ft and 10,980 ft; approximated at 10,800 ft
- Stratigraphic gap: Zones NN6 (partim), NN7
- Constraints on hiatus:
  - Upper surface: >FAD *Catinaster coalitus* (10.7 Ma)
  - Lower surface: <LAD *Globorotalia foshi lobata* (12.1 Ma)
- Duration hiatus: <1.4 Myr
- Arbitrary duration: 1.1 Myr
- Upper surface: 10.9 Ma (calculated from accumulation rates of 26 cm/10^3 yr for the interval between the FAD of *C. coalitus* and the FAD of *Eudiscoaster quinqueramus* for the 180 ft between 10,800 ft [the unconformity] and 10,620 ft [FAD *C. coalitus]*)
- Lower surface: 12.0 Ma (calculated from applying accumulation rates of 57 cm/10^3 yr for the 180 ft between 10,800 ft [the unconformity] and 10,980 ft [LAD *G. foshi lobata*)]

#### Intra–Middle Miocene unconformity
- Location: between 13,590 ft and 13,860 ft; approximated at 13,725 ft
- Stratigraphic gap:
- Constraints on hiatus:
  - Upper surface: >LAD *Sphenolithus heteromorphus* (13.49 Ma)
  - Lower surface: <LAD *Helicosphaera ampliaperta* (14.87 Ma)
- Duration hiatus: <1.3 Myr
- Arbitrary duration: 1.2 Myr
- Upper surface: 13.6 Ma (age determined by applying accumulation rate of 57 cm/10^3 yr for the 135-ft-thick interval between 13,725 ft [unconformity] and 13,590 ft [LAD *S. heteromorphus*)]
- Lower surface: 14.8 Ma (age determined by applying accumulation rate of 118 cm/10^3 yr for the 405-ft-thick interval between 13,725 ft [unconformity] and 14,130 ft [LAD *H. ampliaperta*)]

#### Lower Miocene unconformity
- Location: between 14,340 ft and 14,400 ft; approximated at 14,370 ft
- Stratigraphic gap: Lower Zone NN4 to Lower Eocene zones
- Constraints on hiatus:
  - Upper surface: >LAD *H. ampliaperta* (14.87 Ma)
  - Lower surface: unconstrained
- Duration hiatus: indeterminate
- Arbitrary duration: indeterminate
- Upper surface: 14.9 Ma (age calculated from applying accumulation rates of 118 cm/10^3 yr for the 240 ft between 14,370 ft [the unconformity] and 14,130 ft [LAD *H. ampliaperta*)]
- Lower surface: indeterminate

#### Well-3

**Intra–Pleistocene unconformity**
- Location: ~2400 ft
- Stratigraphic gap: Subzones NN19b (partim); NN19c (partim)
- Constraints on hiatus:
  - Upper surface: ≤LAD *Pseudoemiliania lacunosa* (0.43 Ma)
  - Lower surface: <LAD *Calciscus macintyrei* (1.6 Ma); >LAD *Helicosphaera sellii* (1.37 Ma)
- Maximum duration hiatus: ≤0. Myr
- Arbitrary duration: 0.9 Myr
- Upper surface: 0.5 Ma (arbitrary)
- Lower surface: 1.4 Ma (approximated)

#### Lower Pliocene/Lower Pleistocene unconformity
- Location: at 3020 ft
- Stratigraphic gap: Zones NN18, NN17, NN16, ?NN15; Subzone NN19a (partim)
- Constraints on hiatus:
  - Upper surface: <FAD *Globorotalia truncatulinoides* (1.93 Ma); >LAD *C. macintyrei* (1.6 Ma)
  - Lower surface: >LAD *Globorotalia miocenica* (2.39 Ma)
- Minimum duration hiatus: 0.8 Myr
- Arbitrary duration: 0.7 Myr
- Upper surface: 1.7 Ma (approximated)
- Lower surface: 2.4 Ma (arbitrary)
Remarks: The age of the lower surface is given an age of 2.4 Ma (LAD *Globorotalia miocenica*) to allow calculation of accumulation rates (50 cm/10^3 yr) for the interval between 3020 ft (LAD *G. miocenica*) and 4280 ft (LAD *Sphaerodinellopsis seminulina* at 3.16 Ma), which in turn are tentatively used to determine the ages of older unconformities in the well.

The HO of *Reticulofenestra pseudoumbilicus* at 2960 ft does not correspond to the LAD of the species but is best interpreted as a result of reworking above the unconformity.

**Upper Miocene/Lower Pliocene unconformity**

Location: between 4280 ft and 4580 ft (approximated at 4430 ft)

Stratigraphic gap: Subzone NN11a (partim)

Constraints on hiatus:
- Upper surface: \( \geq \text{LAD } S. \text{ seminulina} \ (3.16 \text{ Ma}) \)
- Lower surface: approximated by LAD *Eudiscoaster quinqueramus* (5.48 Ma)

Maximum duration hiatus: 2.32 Myr

Arbitrary duration: 2 Myr

Upper surface: 3.4 Ma (calculated)

Lower surface: 5.4 Ma (approximated)

Remarks: Upper surface at 4430 ft dated through extrapolation of accumulation rates of 50 cm/10^3 yr in the 1410-ft-thick interval between 3020 ft (LAD *S. seminulina*) and 4430 ft (the unconformity). Lower surface dated through extrapolation of accumulation rates of 41 cm/10^3 yr in the 150-ft interval between 4430 ft and 4580 ft (LAD *E. quinqueramus*). Accumulation rates of 41 cm/10^3 yr calculated assuming that the HOs of *E. quinqueramus* at 4580 ft and *Eudiscoaster neohamatus* at 7040 ft represent the LAD of the species.

**Intra–Upper Miocene unconformity**

Location: ~7070 ft (precise location determined by biofacies change)

Stratigraphic gap: Zone NN11a

Constraints on hiatus:
- Upper surface: \( \geq \text{LAD } E. \text{ neohamatus} \ (7.3 \text{ Ma}) \)
- Lower surface: \( < \text{FAD } E. \text{ quinqueramus} \ (8.17 \text{ Ma}) \)

Duration hiatus: <0.87 Myr

Arbitrary duration: 0.4 Myr

Upper surface: 7.4 Ma (approximated)

Lower surface: 7.8 Ma (approximated)

Remarks: Upper surface at 7070 ft dated through extrapolation of accumulation rates of 41 cm/10^3 yr (see above). Lower surface at 7070 ft dated through extrapolation of the accumulation rates of 50 cm/10^3 yr calculated between the HO of *Eudiscoaster hamatus* at 9680 ft and the LO of *E. quinqueramus* at 7370 ft, assuming that these represent the LAD and FAD of the species, respectively.

**Middle Miocene/Upper Miocene unconformity**

Location: ~9740 ft

Stratigraphic gap: Zone NN9 (partim)

Constraints on hiatus:
- Upper surface: \( \geq \text{LAD } E. \text{ hamatus} \ (9.57 \text{ Ma}) \)
- Lower surface: \( \leq \text{FAD } E. \text{ hamatus} (10.41 \text{ Ma}); < \text{LAD } N. \text{ mayeri} (10.53 \text{ Ma}) \)

Maximum duration hiatus: <0.84 Myr

Arbitrary duration: 0.7 Myr

Upper surface: 9.6 Ma (arbitrary)

Lower surface: 10.3 Ma (approximated)

Remarks: Upper surface at 9740 ft dated through extrapolation of accumulation of 50 cm/10^3 yr (see above) in the 200-ft interval between 9540 ft (HO *E. hamatus*) and 9740 ft (unconformity). Lower surface dated through applying tentative accumulation rates of 45 cm/10^3 yr to the 1240-ft interval between 10,980 ft (LAD of *Globorotalia fohsi lobata*) and 9740 ft (unconformity).

**Well-4**

**Lower Pliocene/Lower Pleistocene unconformity**

Location: between 5960 ft and 6030 ft; approximately at 6000 ft

Stratigraphic gap:

Constraints on hiatus:
- Upper surface: \( \geq \text{LAD } \text{Calcicidiscus macintyrei} \ (1.6 \text{ Ma}) \)
- Lower surface: \( \geq \text{LAD } \text{Dentoglobigerina altispira} \ (3.13 \text{ Ma}) \)

Duration hiatus: >1.53 Myr

Arbitrary duration: 1.9 Myr

Upper surface: 1.7 Ma (approximated)

Lower surface: 3.6 Ma (calculated from accumulation rates)
Remarks: Lower surface dated through extrapolation of accumulation rates of 98 cm/10^3 yr in the 720-ft-thick interval between 6720 ft (FAD *Reticulofenestra pseudoumbilicus*) and 6000 ft (unconformity). Accumulation rates of 98 cm/10^3 yr calculated between the LAD of *R. pseudoumbilicus* at 6720 ft and that of *Globoturborotalita nepenthes* at 8490 ft.

### Intra–Upper Miocene unconformity

**Location:** ~10,560 ft  
**Stratigraphic gap:** Subzone NN11b (partim)  
**Constraints on hiatus:**  
- **Upper surface:** <LAD *Eudiscoaster quinqueramus* (5.48 Ma)  
- **Lower surface:** <FAD *Amaurolithus primus* (7.28 Ma)  
**Duration hiatus:** ≥1.8 Myr  
**Arbitrary duration:** 1.9 Myr  
**Upper surface:** 5.0 Ma (calculated from accumulation rates)  
**Lower surface:** 7.1 Ma (calculated from accumulation rates)

Remarks: Upper surface dated through extrapolation of accumulation rates of 98 cm/10^3 yr (see above) for the 2070-ft-thick interval between 8490 ft (LAD *G. nepenthes*) and 10,560 ft (unconformity). Lower surface dated by applying accumulation rates of 116 cm/10^3 yr for the 720-ft-thick interval between 11,280 ft (FAD *A. primus*) and 10,560 ft (unconformity).

### Middle Miocene/Upper Miocene unconformity

**Location:** ~17,400 ft  
**Stratigraphic gap:** Zone NN9 (partim); Zone NN10 (partim)  
**Constraints on hiatus:**  
- **Upper surface:** >C21 LAD *Eudiscoaster brouweri* (1.93 Ma) and >C21 LAD *Calcidiscus macintyrei* (1.6 Ma)  
- **Lower surface:** ≤LAD *Reticulofenestra pseudoumbilicus* (3.81 Ma)  
**Duration hiatus:** >1.53 Myr; <2.2 Myr  
**Arbitrary duration:** 2.0 Myr  
**Upper surface:** 1.7 Ma (approximated)  
**Lower surface:** 3.7 Ma (calculated from accumulation rates)

Remarks: Upper surface dated by applying accumulation rates of 116 cm/10^3 yr to the 2730-ft-thick interval between 14,670 ft (FAD *E. quinqueramus*) and 17,400 ft (unconformity). Lower surface dated by applying a tentative accumulation rate of 38 cm/10^3 yr for the 990-ft interval between 18,390 ft (FAD *E. hamatus*) and 17,400 ft (unconformity). Accumulation rate of 38 cm/10^3 yr calculated between the LAD *N. mayeri* and FAD *E. hamatus*.

### Well-5

**Upper Pliocene/Lower Pleistocene unconformity**  
**Location:** between 7800 ft and 7920 ft; ~7890 ft  
**Stratigraphic gap:** Subzone NN19a (partim), NN16b, NN16a (partim); Zones NN18, 17  
**Constraints on hiatus:**  
- **Upper surface:** ≤LAD *Eudiscoaster quinqueramus* (1.93 Ma) and ≥LAD *Calcidiscus macintyrei* (1.6 Ma)  
- **Lower surface:** ≤LAD *Reticulofenestra pseudoumbilicus* (3.81 Ma)  
**Duration hiatus:** >1.53 Myr; <2.2 Myr  
**Arbitrary duration:** 2.0 Myr  
**Upper surface:** 1.7 Ma (approximated)  
**Lower surface:** 3.7 Ma (calculated from accumulation rates)

Remarks: Upper surface dated by applying accumulations rates of 80 cm 10^3/yr for the 150-ft-thick interval between 7740 ft (LAD *C. macintyrei*) and 7890 ft (unconformity). Lower surface dated by applying accumulations rates of 57 cm 10^3/yr for the 210-ft-thick interval between 8100 ft (LAD *R. pseudoumbilicus*) and 7890 ft (unconformity). Note the excellent constraint on the accumulation rates in this part of the well, validating both the methodology and the interpretation of discontinuous stratigraphic records.

### Intra–Upper Miocene unconformity

**Location:** ~12,180 ft (arbitrary)  
**Stratigraphic gap:** Subzone NN11b (partim); Subzone NN11a (partim)  
**Constraints on hiatus:**  
- **Upper surface:** ≥LAD *Eudiscoaster quinqueramus* (5.6 Ma)  
- **Below:** ≥LAD *Eudiscoaster neohamatus* (7.3 Ma); <FAD *E. quinqueramus* (8.17 Ma)  
**Maximum duration hiatus:** >0.87 Myr  
**Arbitrary duration:** 1.6 Myr  
**Upper surface:** 6 Ma (calculated from accumulation rates; see above)  
**Lower surface:** 7.6 Ma (calculated using the same accumulation rates as above the surface; however, poorly constrained)
not clear whether a thin sliver of uppermost Pliocene [Zone NN18] is present; see Appendix A.) The Middle Miocene to Lower Pliocene succession is difficult to interpret because of the inconsistencies between datum occurrences (Fig. 7). However, two stratigraphic gaps are likely present:

1. An unconformity is inferred between 7040 and 7370 ft (2146–2246 m) based on the proximity of the HO of *Eudiscoaster neohamatus* and the LO of *E. quinqueramus*. The abrupt disappearance of the agglutinated benthic fauna Agua Salada (agglutinated benthic fauna) Biofacies at 7070 ft (2155 m; together with the closely conjunct HO of *Dentoglobigerina altispira*, *D. venezuelana*, *Globoturborotalita nepenthes*—forms whose LADs occur in the Early to Late Pliocene; Fig. 8) supports this interpretation.

2. An unconformity is inferred at 9740 ft (2670 m) from the stratigraphic proximity of the HO of *Eudiscoaster hamatus* and LO *Neogloboquadrina mayeri* and LO *E. hamatus* (resulting in a very thin Zone NN9).

Finally, Subzone NN19c is extremely thin, suggesting a (younger) unconformity around 2400 ft (732 m) (between 2360 and 2390 ft [719 and 728 m], or 2390 and 2420 ft [728 and 738 m]) (biozonal subdivision is difficult, but the data are compatible with a discontinuous record).

### Stratigraphic Completeness of Well-4 (Fig. 9)

Despite difficulties related to variation in abundance and preservation, the calcareous microfossil datums complement each other for a comprehensive stratigraphic interpretation of the Neogene succession.
Table 6.—Geographic location and present depositional depth (DD) of seven Eureka cores. The thickness of the Neogene section and the age of the oldest sediments (BS) recovered is also given (from Aubry 1993a; Table 1).

<table>
<thead>
<tr>
<th>Corehole</th>
<th>Latitude (N)</th>
<th>Longitude (W)</th>
<th>WD (ft)</th>
<th>P (ft)</th>
<th>R (%)</th>
<th>Age BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>E68-136</td>
<td>29.2833</td>
<td>18.4333</td>
<td>1826</td>
<td>1000</td>
<td>?</td>
<td>Upper Oligocene</td>
</tr>
<tr>
<td>E67-134</td>
<td>29.2500</td>
<td>16.4333</td>
<td>1955</td>
<td>1000</td>
<td>91</td>
<td>Upper Miocene</td>
</tr>
<tr>
<td>E67-135</td>
<td>29.3000</td>
<td>19.4500</td>
<td>2466</td>
<td>1000</td>
<td>84</td>
<td>Upper Miocene</td>
</tr>
<tr>
<td>E66-73A</td>
<td>29.2833</td>
<td>18.4333</td>
<td>2521</td>
<td>1000</td>
<td>76</td>
<td>Middle Miocene</td>
</tr>
<tr>
<td>E66-73</td>
<td>29.2667</td>
<td>17.4333</td>
<td>2810</td>
<td>1000</td>
<td>78</td>
<td>Middle Miocene</td>
</tr>
<tr>
<td>E68-151A</td>
<td>28.0333</td>
<td>3.4333</td>
<td>4349</td>
<td>785</td>
<td>78</td>
<td>Upper Miocene</td>
</tr>
<tr>
<td>E68-139</td>
<td>28.9333</td>
<td>57.4500</td>
<td>6077</td>
<td>1000</td>
<td>61</td>
<td>Upper Cretaceous</td>
</tr>
</tbody>
</table>

1 Calcareous nannofossil biostratigraphy from Gartner et al. (1983). 

between 5010 and 18,390 ft (1527 and 5910 m), which extends from Middle Pleistocene (Zone Pt1a, b; Subzone NN19b) to lower Upper Miocene (Zone M12, >Zone NN9) and is clearly discontinuous (Figs. 9, 10A, 10B).

Three stratigraphic gaps are conspicuous.

1. The Pleistocene interval is unconformable with the Upper Pliocene unit; the unconformity lies at about 6000 ft (1830 m; Zone NN16a/NN19a; Zone PL3/PL1a, b).
2. Subzone NN11b is represented by a thin interval. An unconformity can be confidently delineated at ~10,560 ft (3220 m; Fig. 9).
3. An unconformity is located at 17,400 ft (5304 m; marked by an [apparent] change in sedimentation rates [98 cm/10^3 yr for the NN9 zonal interval vs. ~116 cm/10^3 yr for the Upper Miocene–Pliocene]). The unconformity truncates the upper part of Zone NN9, which is anomalously thin compared to the overlying zones.

Finally, the reduced thickness of Subzones NN19a and NN19b compared with that of Subzone NN19c suggests one or more unconformities in the lower part of Zone NN19 (~5800 ft; 1768 m).

Stratigraphic Completeness of Well-5 (Fig. 11)

Good agreement between the calcareous nannofossil and planktonic foraminiferal datums (Figs. 11, 12) allows a firm interpretation of the succession in the well.

1. An unconformity clearly occurs between 7860 ft (2396 m; Zones Pt1a, b; Subzone NN19c) and 7920 ft (2414 m; Zones PL3–5; Subzone NN16a), separating mid–Upper Pliocene from Lower Pleistocene.
2. Stratigraphic datums are few below 11,000 ft (3353 m). However, an Upper Miocene unconformity clearly occurs in Zone NN11. It is arbitrarily located at 12,180 ft (3712 m).

Stratigraphic Completeness of Well-6 (Fig. 13)

Despite difficulties owing to scarcity of the marker species and the scatter of stratigraphic markers, particularly in the Pliocene interval, we determine the presence of three unconformities in this section (Figs. 13, 14A, 14B).

1. An unconformity is inferred between 9443 and 9460 ft (2878 and 2883 m) from the absence of Subzone NN19b.
2. An unconformity may mark the Pliocene–Pleistocene contact at ~10,840 ft (3304 m).

3. An intra-Pliocene unconformity is clearly marked by the juxtaposed HOs of Eudiscoaster surculus and E. tamalis at 12,550 ft (3825 m) and those of Gt. multicamerata, Gt. Miocenica, and Gq. altispira at 12,160 ft (3706 m). The offset in the determination of the stratigraphic location of this unconformity, depending on the microfossil group considered, is attributed to the displacement of the ditch cuttings in the hole. It is placed at the youngest stratigraphic level (12,160 ft; 3706 m).
4. A third unconformity at 14,890 ft (4538 m) is marked by the juxtaposition of the HOs of G. nepenthes and Gt. margaritae. This unconformity corresponds to the absence of Subzone NN15a, on the basis of which it would be placed slightly higher in the section.

Stratigraphic Correlations Between and Temporal Interpretation of the Neogene Successions Along Transect

Stratigraphic correlations show that the Neogene successions along the GOM transect comprise several AUs traceable from Well-3 to Well-6, each essentially corresponding to a subseries (Fig. 15A). They are, in reverse stratigraphic order, Pleistocene (NN19–NN21), Upper Pliocene (NN17–NN18), Lower Pliocene (NN13–NN16a), and Upper Miocene (NN9–NN11) AUs (note that the Lower–Upper Pliocene boundary falls in Zone NN16 and that the subdivision in AUs only approximates chronostratigraphic subdivisions). In addition, Middle Miocene, lower Middle, and upper Lower and Lower Miocene unconformable sedimentary units are delineated in Well-1. Some of the AUs (Lower Pliocene AU in Well-6) comprise two unconformable units, and it is possible that the lower Middle and upper Lower Miocene unconformable units in Well-1 are part of a single AU.

The stratigraphic gap and hiatus associated with each unconformity in each well and the age of the bounding unconformable surfaces are given in Table 5. Based on these data we have converted the stratigraphic framework along the GOM depth transect (Fig. 15A) into a temporal framework (Fig. 16). The latter (which is independent of thickness) reveals a highly discontinuous sedimentary record. In Well-1 deposition was mostly continuous from Late Miocene through Pliocene (~8.2–1.8 Ma). An ~1-Myr hiatus marks the Pliocene–Pleistocene boundary. Prior to 8.2 Ma the record is highly discontinuous, with sequences representing ±1 Myr separated by a 2- to 4-Myr hiatus. An >6-Myr hiatus separates the Lower Miocene sequence (~20 Ma) from the Oligocene (or older). Well-2 and Well-3 are also highly discontinuous, with prominent >1-Myr hiatuses. In Well-4, Well-5, and Well-6, the hiatuses represent about as much time as the sequences they separate.
Fig. 7.—Stratigraphic interpretation of the Middle Miocene to Pleistocene section in Well-3. Datums are given in Table 4. See text and Table 5 for further explanation.
FIG. 8.—Ranges of selected planktonic foraminiferal and calcareous nannofossil species in Well-3. See discussion in Appendix A.
DISCUSSION

Comparison among the wells is limited by the very nature of their sedimentary successions, and interpretation of the sedimentary patterns along the GOM transect requires caution. The oldest sediments differ greatly among wells (Table 2), being as young as Lower Pliocene in Well-6 to as old as Oligocene in Well-1, and samples from sediments younger than Upper Miocene in Well-3 were not made available to us. In addition to the restricted stratigraphic overlap between wells (with maximal overlap occurring only for the Pliocene interval), the low number of wells along the two-dimensional transect, absence of seismic and log data, and, equally importantly, lack of information on the lithologies recovered in these wells constitute additional limitations. Yet, despite these difficulties, several patterns emerge (Figs. 15, 16) that provide unexpected insights into the sedimentary architecture of the northeast GOM. In an attempt to elucidate the significance of the depositional depth-related patterns described above we first integrate our data in a previous regional study of depositional history in the GOM (Galloway et al. 2000). We then discuss the more general problem of tectonic vs. climatic forcing along the transect. We complete this discussion with a note on the likely nature of the AUs we describe here with regard to seismic stratigraphy and recommend a fresh look at the basic practices of sequence stratigraphy.

Sedimentary Patterns Along the GOM and Regional Depositional History

Several biostratigraphic studies of depositional history in the GOM are available (e.g., Armentrout and Clement 1990, Jiang and Watkins 1992, Armentrout 1996). However, most of them tend to be regional, dealing with one area or another of the GOM, and few are concerned with the northeastern region that is the focus of this study. A synoptic analysis of the distribution of Cenozoic sediments in the GOM as a function of sedimentary regimes and sedimentation dynamics by Galloway et al. (2000) provides a framework with which to examine the AUs described here. One of the limitations for a comprehensive integration of our transect record into this broader Neogene history of the GOM is that the biostratigraphic datums in the study of Galloway et al. are mostly provided by benthic foraminifera (with datums that were not considered in a benthic foraminiferal study of the wells by Katz et al., unpublished data). As a result, the biostratigraphic data in the two studies are not amenable to easy integration, and the delineation of the boundaries between their genetic sequences is not as tightly constrained as are our AUs. This difficulty is somewhat minimized by the fact that the subseries is the basic unit of reference in both studies. However, the time scale in the two studies is different, resulting in a slight offset between chronostratigraphic boundaries. A further limitation is the precise location of our transect on the paleogeographic maps established by these authors for successive depositional episodes. This is due to the difference between the broad (regional) scale of their study and the finer (local) scale in ours. It would seem that the GOM transect is often located in the vicinity of the boundary between the Basin-Margin Sequences that Galloway et al. describe, although we cannot confidently determine which side is relevant in our discussion.

Sedimentation along the transect would have been on the shelf and slope essentially east of the East Mississippi axis of sediment dispersal (see Fig. 1 and Galloway et al. 2000 [their fig. 3]). The early history of deposition, as retraced by Galloway et al. (2000), is remarkably compatible with our temporal interpretation, considering the difficulties in correlating our AUs with their depositional episodes. Of particular interest are the following (Fig. 17):

1. Galloway et al. (2000) remarked that “despite the proximity of the Mississippi system [during the Early Miocene], the northeast Gulf margin remained a site of slow shelf and ramp sedimentation” (op. cit., p. 1758) and established that “a maximum flooding surface separates two Lower Miocene basin-margin sequences, LM1 and LM2” (op. cit., p. 1757). This may be in accord with our record of thin (~218-ft, ~70-m) Lower Miocene sediments in Well-1 and their division into two unconformable sedimentary packages;
FIG. 10.—Calcareous microfossil distribution in Well-4. See discussion in Appendix A. A) Calcareous nannofossil distribution. B) Ranges of selected planktonic foraminiferal species. An expanded version of this figure is available in the digital version and at the SEPM Supplemental Data site, https://www.sepm.org/supplemental-materials.
2. The single “Middle Miocene basin-margin sequence” recording a relatively brief episode (~3 Myr) of deposition (op. cit., p. 1758) possibly corresponds to the interval between 10,800 and 14,370 ft in Well-2 and is generally compatible with Well-1;

3. More difficult is the comparison between the Upper Miocene depositional episode that correlates to seismic sequences J and K and records a long-lived family of sediment dispersal that persisted with little modification for nearly 7 Myr (op. cit., p. 1760) and our temporal interpretation. This is because of the marked variability in the location and extent of the hiatuses in our wells. We note that the lower and upper Upper Miocene are absent in Well-1 and Well-6, respectively, and that the short hiatuses in Well-3 and Well-4 do not overlap;

4. The Mio–Pliocene Genetic Sequence PB1 would seem to be well represented in all wells (no information for Well-2);

5. At least part of the late Early and early Late Pliocene Globobuadrina altispina (PGA) depositional episode is well characterized in the transect. Its upper boundary is marked by an unconformity traceable from Well-3 to Well-6 (at 2945, 7890, 5995, and 12,160 ft, respectively [898, 2405, 1827, and 3706 m, respectively]; see further discussion below).

Galloway et al. (2000) explain that the Neogene depositional history in the GOM was controlled by redistribution of source areas and drainage patterns leading, among other things, to prograding shorezone/shelf systems, progradational slope apron, and basin floor apron, as well as to shelf or basin starvation. We consider it difficult to interpret the patterns of thickness and temporal incompleteness along the AUs in relation to these processes.

The differences in thickness between AUs along the GOM depth transect are striking (Figs. 2, 15A). The Pleistocene AU is ~330 m (1150 ft) in Well-1, ~2350 m (7920 ft) in Well-5, and 3300 m (10,870 ft) in Well-6. The Lower Pliocene AU is ~600 m (1980 ft) in Well-1 but 900 m (2970 ft) in Well-4 and ~1800 m (5940 ft) in Well-6. The Upper Miocene AU is ~420 m (~1390 ft) thick in Well-1 but ~2500 m (8250 ft) thick in Well-4.

Perhaps even more striking is the difference in cumulative thickness of the AUs among wells. The 2250-m (686-m) stratigraphic succession of Well-1 spans the entire Neogene, whereas the ~5600-m succession of Well-6 is younger than the Miocene–Pliocene boundary. The former section represents 23.5 Myr; the latter represents <5.4 Myr. Should both sections be temporally continuous (i.e., no hiatuses), the accumulation rates would have been >10 times greater at the Well-6 than at the Well-1 location (112 cm/103 yr vs. 9 cm/103 yr). (Note that the latter rate is unexpectedly [suspiciously] low for a siliciclastic shelf.) In fact, the lower part of the Pliocene section in Well-6 was deposited at rates of ~117 cm/103 yr and its upper part at ~374 cm/103 yr, whereas the same interval in Well-1 was deposited at a rate of ~28 cm/103 yr. The accumulation rates in the intermediate wells increase with depth. It is noteworthy that the ranges of microfossils in the Upper Miocene–Pliocene section in Well-1 are orderly, whereas they are remarkably disorderly in the Pliocene section of Well-6 (compare Figs. 3 and 13), which likely indicates that high accumulation rates in this well result from sediment mixing and reworking. (A possible increase in productivity at a more offshore location [Well-6] would be insufficient to account for the high accumulation rates there.)

Although a well-to-well comparison cannot be fully achieved, there is a general trend toward increasing thickness of the AUs with depth. Clearly, the shallower site (Well-1: neritic; <200 m estimated depositional depth) in the transect is also that with the lowest late Neogene rates of accumulation, and the deepest sites (bathyal, estimated depositional depth 600–800 m) are those with the highest late Neogene rates (200–600 m). This may suggest that since the Late Miocene most of the sediments bypassed the shelf (Well-1) and accumulated on the slope, with greater accumulation occurring at greater depth (Well-6). This is in general agreement with the findings of Galloway et al. (2000), who, for instance, describe the formation during the Late Miocene of “thick shelf-margin delta and slope apron successions” (op. cit., p. 1760) and the Early Pliocene location of depocenters “basinward of the predepositional shelf edge” (op. cit. p. 1763; “deposide” is an abbreviated form of the locution “depositional episode”).

The main difference between our study and that of Galloway et al. (2000) concerns, arguably, the recognition of stratigraphic gaps, although we acknowledge again that it is often difficult to precisely project our local transect in the regional description of these authors.

Comparison among the five Upper Miocene to Pleistocene AUs is informative (Fig. 16). First, from Upper Miocene to Recent, the most complete succession is in Well-1. In it a long hiatus separates the Pleistocene AU from the older succession, but no Pliocene and Upper Miocene AU can be delineated based on biostratigraphically inferred unconformities. In contrast, the successions in Wells-3 to -6 are highly discontinuous over the same interval, and the ages of several bounding surfaces are approximately the same (e.g., upper bounding surface of the Lower Pliocene AU, Wells-3 to -5. Levels 2945, 7890, and 5995 ft, respectively [898, 2405, and 1827 m, respectively]). The succession in Well-6 is the least complete (it exhibits the longest cumulative hiatus of all sections).

The implications, for the interval considered, are (1) the shallowest (neritic; depositional depth 100–600 m; current depth 92 m)
FIG. 11.—Stratigraphic interpretation of the Oligocene to Pleistocene section in Well-5. Datums are given in Table 4. The asterisk (*) denotes the presence of a zonal marker. See text and Table 5 for further explanation.
succession is the thinnest (150 ft; 500 m) and the most (temporally) complete; (2) the deepest (middle bathyal; depositional depth 600–800 m; current depth 482 m) succession is the thickest (1500 ft; 5000 m) and the least complete; and (3) there is no progressive decrease of the hiatuses along the inferred depth transect.

Although the stratigraphic overlap between wells is insufficient for a meaningful comparison of older (Middle Miocene and older) patterns, we note the overlap between hiatuses and the close ages of most bounding surfaces. The change from a highly discontinuous record to an essentially continuous one at shallow depth after ~8 Ma suggests a major event in the northern GOM around that time (see below).

An explanation for the change in temporal completeness along the transect is proposed in the next section. Here we examine whether the sedimentary patterns along the GOM transect are strictly local or whether they constitute examples of patterns known elsewhere. If local, they are essentially irrelevant to the discipline of stratigraphy; in

---

Fig. 12.—Ranges of selected planktonic foraminiferal and calcareous nannofossil species in Well-5. See discussion in Appendix A.
contrast, if they are characteristic of sedimentary successions, they must be attentively considered.

A comparison of the sedimentary patterns along the GOM transect with patterns described elsewhere is limited to a few case histories because the methodology applied here has rarely been used in previous studies.

The allostratigraphic architecture described along this depth transect of continuous successions separated by major stratigraphic gaps bounded over long distances by surfaces of similar age has also been described in Neogene records from the nearby De Soto Canyon in the northeastern part of the GOM and from Jamaica (Aubry 1993a, 1993b), as well as from Paleogene records from the central Atlantic Coast (Poag 1993, Miller et al. 2011, Aubry unpublished data). Characteristically, shallower sections are more complete but thinner than sections in deeper settings. Despite the different settings (coastal plain vs. canyon), the same striking differences occur between the shallowest and deepest sections in the GOM transect and the De Soto Canyon (Fig. 18):

1. In the shallower GOM transect Well-1 (92-m water depth), the Oligocene–Miocene boundary (23 Ma) was reached at a depth of ~2700 m, whereas in the deeper Well-6 (482-m water depth), sediments no older than the Pliocene–Miocene (5 Ma) were recovered at 4894 m (1492 ft; see above). Likewise, in the De Soto Canyon, shallower core E68-136 (600 m), the Neogene section was 994 ft (303 m) whereas in the deeper core E68-139 (2000-m water depth) the Plio–Pleistocene section is as much as 610 ft (177 m).

2. Hiatuses associated with AU boundaries along the GOM transect vary between 1 and 2 Myr, and many overlap. Some hiatuses remain essentially constant along AU boundaries as depth increases. The hiatus (~1.8 Myr) is almost the same at 2945 ft (898 m) in Well-3, 7890 ft (2405 m) in Well-5, and 5995 ft (1827 m) in Well-4, with the lower bounding surface of nearly the same age in the three wells. The hiatus is slightly shorter in Well-6, but the lower surface at 2160 ft (658 m) is only slightly younger than in the other wells. We recognize that the ages of these surfaces were approximated, but this approximation was made independently for each well. Moreover, if the age differences between surfaces could be somewhat greater within limits (see Table 5 for maximum and minimum ages of surfaces), the differences could also be smaller. The material studied here does not allow more precise age resolution. Yet similar patterns were identified in the De Soto Canyon, although perhaps with less regularity than in the GOM, possibly as a result of the difference in setting. However, a ~2.6-Ma surface is traceable laterally through most of the canyon, and a 2.6-Ma surface is also prominent.

Bounding surfaces laterally correlatable over long distances have also been identified in the Paleogene of the Western Atlantic Coast (Poag 1993, Aubry unpublished data) and in the deep sea (Aubry 1991, 1995). Without assuming or implying that similarities in regional sedimentary architecture reflect the same forcing mechanism in different marine settings, we stress that this general pattern requires attention. We limit our discussion below on the mechanism that may lead to the allostratigraphic architecture of the GOM transect.

**Tectonic Versus Climatic Forcing on Stratigraphic Architecture**

Being mostly along strike, the GOM transect is not favorable, in principle, to a discussion of sequence formation associated with eustatic sea level change. However, we could have expected to decipher sedimentary patterns indicative of sea level change in this stratigraphic record, in particular a relationship between stratigraphic gaps and
**Fig. 14.**—Calcereous microfossil distribution in Well-6. See discussion in Appendix A. 

**A)** Calcereous nannofossils. **B)** Ranges of selected species of planktonic foraminifera. An expanded version of this figure is available in the digital version and at the SEPM Supplemental Data site, https://www.sepm.org/supplemental-materials.
glacio-eustatic events inferred from oxygen isotope stratigraphy (Fig. 16). Such a relationship has been shown to occur (at least partially) on the New Jersey margin, where hiatuses tend to straddle glacio-eustatic events (Miller et al. 2011, 2013). The GOM transect does not reveal any such relation in the northern GOM off Louisiana. The Late Pliocene hiatus in Wells-3 to -6 may be explained by the combined effects of the 3.3-, 2.5-, 2.2-, and 2.1-Ma glacio-eustatic events (Fig. 16), but, notwithstanding the depth of these wells, this is contradicted by sedimentary continuity over the same duration in Well-1, where shallower deposition would have been more prone to register sea level changes. The ~3-Myr-long Late Miocene hiatus (associated with the unconformity at 6724 ft; 2049 m) in Well-1 could be interpreted as the cumulative result of glacio-eustatic events at 10.3, 8.7, and 8.2 Ma, which would immediately beg an answer to why events at 12.9 and 11.7 Ma did not also leave a similar signature. The absence of a consistent association between hiatus and glacio-eustatic events at a given locality that remained at about the same depositional depth through time indicates that glacio-eustasy is unlikely to have fashioned the sedimentary record along the GOM transect.

An unconformity may result from erosion, nondeposition, or a combination of both (Aubry 1991; Fig. 19). Sustained erosion would result from marine current activity causing the progressive removal of sediments (Fig. 19A). In this case, the lower surface is the active surface that registers the erosional history, while the upper surface is critical for determining the end of this history at a specific location. A special case of progressive erosion is subaerial erosion during a regression–transgression cycle (Fig. 19B). In contrast, "instantaneous" erosion could result from slope failure causing the abrupt removal of large quantities of sediments and their displacement to greater depth either as slumps or as dispersed
particles. In this case, the timing of failure corresponds to the age of the upper surface, whereas the lower, detachment surface has genetic significance (Fig. 19C). Nondeposition could result from starvation, when sediments by-pass a certain area to be deposited at greater depths further offshore. In this case, the two surfaces are time-significant with regard to the process involved, the lower and upper surface dating the beginning and end of sediment starvation, respectively (Fig. 19D).

Galloway et al. (2000) explain the geographic distribution of sediments in the GOM as a function of starvation and slope failure. For instance, they

![Stratigraphic correlations of Neogene sections in the northern GOM.](https://www.sepm.org/supplemental-materials)
FIG. 16.—Temporal correlations of the Neogene sections in the northern GOM. Depositional depth increases from east to west along the transect. Bold characters for depths of surfaces of unconformities denote high confidence in the age of those surfaces (calculated from accumulation rates or approximated; see Table 5). Dotted transversal lines indicate glacio-eustatic events, as inferred from deep sea oxygen isotope records (from Boulila et al. [2011] for the Early and Middle Miocene and from Miller et al. [2011] for the Late Miocene and Early Pliocene events. Late Pliocene–Pleistocene events, at 100-kyr intervals, are not shown). Color pattern as in Figure 15. An expanded version of this figure is available in the digital version and at the SEPM Supplemental Data site, https://www.sepm.org/supplemental-materials

<table>
<thead>
<tr>
<th>TIME (Ma)</th>
<th>Biochrons</th>
<th>Magnetic Polarity</th>
<th>Well-6 (Modern W.D. = 482m)</th>
<th>Well-4 (Modern W.D. = 426m)</th>
<th>Well-5 (Modern W.D. = 215m)</th>
<th>Well-3 (Modern W.D. = 200m)</th>
<th>Well-2 (Modern W.D. = 196m)</th>
<th>Well-1 (Modern W.D. = 92m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Modern W.D. = 482m</td>
<td>Modern W.D. = 426m</td>
<td>Modern W.D. = 215m</td>
<td>Modern W.D. = 200m</td>
<td>Modern W.D. = 196m</td>
<td>Modern W.D. = 92m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>86 cm/kyr</td>
<td>90 cm/kyr</td>
<td>95 cm/kyr</td>
<td>100 cm/kyr</td>
<td>105 cm/kyr</td>
<td>110 cm/kyr</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>120 cm/kyr</td>
<td>125 cm/kyr</td>
<td>130 cm/kyr</td>
<td>135 cm/kyr</td>
<td>140 cm/kyr</td>
<td>145 cm/kyr</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>150 cm/kyr</td>
<td>155 cm/kyr</td>
<td>160 cm/kyr</td>
<td>165 cm/kyr</td>
<td>170 cm/kyr</td>
<td>175 cm/kyr</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>180 cm/kyr</td>
<td>185 cm/kyr</td>
<td>190 cm/kyr</td>
<td>195 cm/kyr</td>
<td>200 cm/kyr</td>
<td>205 cm/kyr</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>210 cm/kyr</td>
<td>215 cm/kyr</td>
<td>220 cm/kyr</td>
<td>225 cm/kyr</td>
<td>230 cm/kyr</td>
<td>235 cm/kyr</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>240 cm/kyr</td>
<td>245 cm/kyr</td>
<td>250 cm/kyr</td>
<td>255 cm/kyr</td>
<td>260 cm/kyr</td>
<td>265 cm/kyr</td>
</tr>
</tbody>
</table>

This is an author e-print and is distributed freely by the authors of this article. Not for resale.
FIG. 17.—Tentative correlation among the six wells along the GOM depth transect and the seismic and genetic sequences delineated in the GOM by Galloway et al. (2000). See text for explanation. An expanded version of this figure is available in the digital version and at the SEPM Supplemental Data site, https://www.sepm.org/supplemental-materials

<table>
<thead>
<tr>
<th>Galloway et al. (2000)</th>
<th>Basin Center Seismic Sequences</th>
<th>Well-6 W.D. = 482m</th>
<th>Well-4 W.D. = 426m</th>
<th>Well-5 W.D. = 215m</th>
<th>Well-3 W.D. = 200m</th>
<th>Well-2 W.D. = 196m</th>
<th>Well-1 W.D. = 92m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>R</strong></td>
<td>Pleistocene - Sang</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Q</strong></td>
<td>Pleistocene - Trim.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>P</strong></td>
<td>Pliocene - Ang. II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>O</strong></td>
<td>Pliocene - Lenti. 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>Pliocene - Gloch. alt</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>M</strong></td>
<td>Pliocene - Bul. 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>K</strong></td>
<td>Upper Miocene</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>J</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>I</strong></td>
<td>Middle Miocene</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>H</strong></td>
<td>Lower Miocene</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>G</strong></td>
<td>Lower Miocene 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This is an author e-print and is distributed freely by the authors of this article. Not for resale.
describe Early Pliocene basin starvation in the eastern Gulf and Middle Miocene megaslides in the Texas–Louisiana shore-zone system. Without lithologic descriptions, logs, or location of the wells on seismic profiles available to us, the cause(s) of widespread unconformities in our two-dimensional transect can only be speculative, although processes associated with subaerial erosion are unlikely at the depths of concern. Starvation over short durations bracketed by episodes of normal deposition would seem unlikely. In addition, interruption of sediment supply in a vast area, for instance encompassing Wells-3 to -6, would seem doubtful considering the location of the transect, not far from the mouth of the Mississippi River. On the other hand, mass wasting of sediment would seem a more likely mechanism for the formation of stratigraphic gaps in a basin where salt tectonics is predominant, particularly on slope. In fact, in a study of the benefit of three-dimensional seismic on exploration on Viosca Knoll, Fingleton and Zinni (1999) accept a depositional model that recognizes the presence of slumps and slump scars on the slope apron beyond the shelf, and Hernandez-Mendozza et al. (2008) emphasize the role of salt diapirs in the Burgos Basin just west of our transect. As explained above, high Pliocene accumulation rates at the deeper Well-6 are characterized by mixing and reworking, which further supports slope transport from shallower sources. The fact that the AUs are not traceable on the shallower shelf Well-1 may also point to a salt tectonics forcing on slope (and basinal) sedimentation.

A period of relative tectonic quiescence would explain the short and local gaps (compare Wells-2, -3, and -4), whereas periods of greater tectonic activity would favor mass displacement over large areas. The Late Miocene–Early Pliocene, when Genetic Sequences PB1 and PGa were being deposited in all wells, may have been such a time of

---

**Fig. 18.**—Correlations among selected Eureka cores in the De Soto Canyon (as in Fig. 15B) (from Aubry [1993a], updated to the numerical chronology used in this article). Dotted transversal lines as in Figure 16; color pattern as in Figure 15. An expanded version of this figure is available in the digital version and at the SEPM Supplemental Data site, https://www.sepm.org/supplemental-materials

---

This is an author e-print and is distributed freely by the authors of this article. Not for resale.
This is an author e-print and is distributed freely by the authors of this article. Not for resale.
If the AUs delineated along the GOM transect correspond to seismic sequences, then, by extension, they must also correspond to parts of the depositional sequences of sequence stratigraphy (Posamentier et al. 1988, Van Wagoner et al. 1988, see also Armentrout 2018 for definition and discussion). We recognize that “genetic” and “depositional” sequences are defined somewhat differently (see Miller et al. [2018] for discussion); as the difference has little impact in the discussion below we refer to either as “sequence” below, whereas we identify “seismic sequence”). We refrain from attempting to locate the GOM AUs in a sequence stratigraphic framework, but we offer a few comments relative to interpretations by Galloway et al. (2000) to show that the architecture of the stratigraphic record is more complex than the sequence model suggests and that identification of specific horizons in a sequence requires detailed stratigraphic analysis, not simply automatic characterization inferred from the model.

1. These authors identify two Lower Miocene basin-margin sequences, LM1 and LM2, and interpret their contact as a maximum flooding surface (MFS) “that reveal[s] substantial evolution in sediment dispersal and depositional pattern not currently differentiated in the deep basin” (op. cit., p. 1757). The MFS is “a downlap surface that is associated with the condensed section” (Vail 1987, p. 3) or “a surface of deposition at the time … of maximum transgression” (Posamentier and Allen 1999). Well-1 contains two Lower Miocene sedimentary units that can reasonably be identified as LM1 and LM2. Their contact in the well, however, is unlikely to correspond to an MFS because a ~7-Myr hiatus separates the two sequences at ~7330 ft (2234 m). What would easily be interpreted as a condensed section (with extremely low sedimentation around 7330 ft) is in fact a stratigraphic gap, and the two units (LM1 = 7474–7330 ft [2278–2234 m]; LM2 = 7330 and 7256 ft [2234 and 2212 m]) may well have been deposited at the high sedimentation rates expected for a siliciclastic margin.

2. Galloway et al. (2000) highlight the fact that during the PQA depositional episode (Seismic Sequences M+N), the “overall rate of sediment supply to the GOM was greatly reduced from Early Pliocene rates. Consequently, depocenters are anomalously thin” (op. cit., p. 1761; emphasis ours). Sequence PQA in our wells is in fact very thin, being 210 ft (64 m) in Well-5, 720 ft (219 m) in Well-4, and 1200 ft (366 m) in Well-6. However, this thinness does not result, a priori, from low sedimentation rates (due to low sediment supply) but rather from the occurrence of extensive stratigraphic gaps (at 7890, 6000, and 12,160 ft [2405, 1829, and 3706 m] in the respective wells) that truncate the upper part of the sequence.

3. Sequence PB1 (= Seismic Sequence L) is conformable with Sequence PQA (= seismic sequences M+N), which implies the absence of a measurable hiatus across the L/M stratigraphic surface along the transect. In contrast, Sequence PQA is unconformable with the overlying sequence. The unconformity is traceable from Well-3 to Well-6 (see depth location in the well above). Its lower surface likely lies in Seismic Sequence M. However, its upper surface does not belong to Seismic Sequence O but rather to undifferentiated Seismic Sequences P and Q (= Sequence PAB). This is because there is no preserved evidence of Late Pliocene deposition along the transect, except in Well-1.

These examples, taken here for the sake of discussion, illuminate some of the difficulties in converting features seen in seismic stratigraphy into concrete stratigraphic features even in areas that are a priori without structural complications (as along the GOM transect). The example immediately above indicates that the unconformity at the top of Sequence PQA represents the concatenation of two or three seismic surfaces and leads us to emphasize that stratal concordance (parallel bedding) is not proof of conformity (absence of hiatus) across prominent seismic surfaces such as sequence boundaries. Although the strata of sequences PQA and PAB (= seismic sequences M and P+Q) are likely concordant along the transect, they are unconformable. The other examples touch on the difference between a true condensed section characterized by low sedimentation rates and a truncated section in which apparent low sedimentation rates result from the occurrence(s) of stratigraphic gaps (compare Aubry 1995, their figs. 4–6). In this respect, it would be interesting to reevaluate the depressed nature of biostratigraphic events in relation to sequence stratigraphy (e.g., Armentrout and Clement 1990). The upper record of *Gg. altispira* is truncated (by unconformities) in Well-3 through Well-6 (Fig. 16). The HO of this species in the GOM wells does not qualify as an ecologically depressed bioevent; rather, it is a non-descriptive feature due to the vagaries of sedimentary processes. It may well be that numerous bioevents used in sequence stratigraphy and thought to be occurring prematurely result in fact from truncation by unconformities (see Aubry 1998). Finally, some sequences (e.g., PB1) are remarkably well represented, both temporally and laterally, their bounding surfaces constituting true chronostratigraphic horizons over distances of several hundreds of kilometers. However, as seen from the GOM record, such remarkable horizons may be the exceptions rather than the rule.

**SUMMARY AND CONCLUSIONS**

Based on an integrated calcareous plankton biostratigraphic study we have conducted a stratigraphic analysis of Neogene successions recovered from six wells located along a near-parallel to the shoreline (or shelf-margin) depth transect in the northern GOM (Main Pass–Green Canyon). We have shown that all successions are discontinuous and may be described in terms of units bounded by unconformities (AUs). We have shown that the shallowest (middle neritic) succession is both the thinnest and the most complete over the Upper Miocene to Pleistocene interval, whereas the deepest (middle bathyal) one was the thickest and most incomplete over the Pliocene–Pleistocene interval. We have also shown that the hiatuses at sequence boundaries do not decrease with paleodepth along the transect but are instead bounded by surfaces of similar ages.

The stratigraphic architecture documented in these wells is similar to that observed elsewhere using the same methodological approach, whether in the De Soto Canyon at the northwestern end of the Florida slope, in Jamaica, or on the New Jersey Margin. This consistent pattern of AUs separated by more or less constant hiatuses over long distances, now documented in basins with different tectonic regimes, should encourage investigations to identify its causes.

We find no evidence of an overprint of eustatic changes on the stratigraphic architecture in the study area. Combined with previous studies, this investigation raises the possibility that glacio-eustasy played a less significant role in shaping the architecture of the stratigraphic record other than in nearshore environments. The origin of the widespread unconformities we describe here in the northern part of the GOM may be related to salt tectonics, which would have led to massive remobilization of sedimentary units producing slumps, slides, or other forms of sedimentary mass wasting. An important event of this nature may have occurred in the latest Pliocene–earliest Pleistocene, resulting in a prominent ~3.6-Ma detachment surface. The biostratigraphic analysis of the deep basins of the GOM would constitute a test of our hypothesis of mass transport of sediments as an explanation of the allostratigraphic pattern described here. It is expected that slumps and slides would have piled up there and also that mixing of sedimentary particles of different ages would have resulted from the avalanches of older, shallower, unconsolidated sediments penetrating the soft in situ basinal deposits.

This is an author e-print and is distributed freely by the authors of this article. Not for resale.
The correspondence of the AUs with seismic sequences, whether along the GOM transect or in the De Soto Canyon to the east, indicates that they are parts of the depositional sequences of sequence stratigraphy. As such, they should receive greater attention than they have until now because their lateral and temporal distribution reflects an active, yet unsuspected, sedimentary dynamic. Unconformities and their associated hiatuses are as essential to stratigraphic interpretation as are sedimentary units, and minimizing their significance contributes to the falsification of depositional history and its processes.

ACKNOWLEDGMENTS

This article is the culmination of a study undertaken at the request of a consortium of oil companies as a contribution to the Deep Water Benthic Foraminiferal Project (DWBFP) funded through the Woods Hole Oceanographic Institution from 1975 to ~1995. The project (one of several) was completed and presented to the companies in 1993, and results were partially described in an abstract/poster session at the annual AAPG/Society for Sedimentary Geology (SEPM) meeting in 1993 (Aubry et al. 1993) in Houston, Texas. Several companies (BP, Chevron, Marathon, UNOCAL) contributed well samples and data (the project was also supported by Texaco). The basic biostratigraphic framework for this investigation (and without which this study could not have been conducted) is based upon two earlier investigations that were also part of the DWBFP Project (q.v.): (1) the Neogene calcareous planktonic biostratigraphy of the Buff Bay section in Jamaica (Aubry 1993b, Berggren 1993a) and (2) a transect on the northeastern GOM slope near the De Soto Canyon based on the Eureka cores taken by a consortium of oil companies (with Shell Oil Company as operator) from 1965 to 1968 (see Aubry 1993a, Berggren 1993b [p. 297–298], Zhang et al. 1993). The composite stratigraphy of these two studies essentially spans the entire Neogene (up to and including the Pleistocene). We are grateful to our colleagues in the petroleum industry for their support and for discussion. We thank Miriam Katz for sharing data on the paleobathymetric history of the wells along the transect and Ken Miller, Don Van Nieuwenhuise, and Peter Sugarman for discussion over the years. We gratefully acknowledge enlightening discussion with John Armentrouth and his thoughtful review of this manuscript as well as the review by Richard Fluegeman and the comments by the Volume Editor Richard Denne.

REFERENCES


**APPENDIX: BIOZONAL SUBDIVISION OF THE SIX WELLS BASED ON CALCAREOUS NANOFOSILS AND PLANKTONIC FORAMINIFERA**

The stratigraphic interpretations of the six Neogene successions examined in this article are given below. The wells are organized in order of increasing depth.

**Well-1 (Chevron Main Pass Block 254, Well OCS-G 1655 #1)**

**Overview:** It was anticipated that, based on the biostratigraphy of sidewall cores, the biostratigraphic subdivision of Well-1 would be straightforward. In fact, it is complicated by a combination of factors related to preservation and inconsistent occurrences. Calcareous nanofossils were poorly preserved above the lower Miocene and below the Oligocene; numerous intervals were barren; discoasters, many species of which are critical for Neogene biozonal stratigraphy, were scarce or, like other markers, exhibited discontinuous occurrences; and reversed stratigraphic successions occurred. In such circumstances, some calcareous nanofossil zonal boundaries could not be precisely delineated (Fig. 4A). Planktonic foraminifera are well preserved in the younger (Plio-Pleistocene) part of the well, but preservation generally deteriorated downhole. A relatively broad biostratigraphic subdivision/zonation was possible in most parts of the well. However, fine-scale zonation was impossible owing to the absence/rarity of stratigraphically definitive taxa (Globorotalia foksi group), apparently anomalous stratigraphic ranges (those of Globorotalia nepenthis, Gt. lenguasensis), and/or the vagaries of stratigraphic distribution and preservation (Fig. 4B).

**Calcareous nanofossil stratigraphy (Figs. 2A, B):**

**Pliocene—** (992 ft to 1108 ft or 992 ft to 1179 ft). Level 992 ft is assigned to mid-Pliocene Zone NN20. The interval between 1004 ft and 1219 ft (or 1331 ft) belongs to Zone NN19a, characterized by the co-occurrence of Pseudoemiliania lacunosa, Helicosphaera sellii, and Calcidiscus mactintyre. The lowest Gephyrocapsa oceanica was encountered at 1108 ft. As level 1170 ft is barren, there is a large uncertainty as to the position of the Pliocene/Pleistocene boundary in the well.

**Pliocene—** (1108 ft or 1170 ft to 24500 ft). Biostratal subdivision of the Pliocene is tentative. First, discoasters are exceedingly rare and poorly preserved, and, as a result, their occurrences are discontinuous. Second, levels with assemblages characteristic of Subzone NN15b (with Reticulofoenestra pseudoumbilicus, Sphenolithus abies, S. neoabies, Eudiscoaster tamalis) alternate with levels best assigned to Zone NN16. Third, ceratoliths are rare in the upper part of the Pliocene interval, possibly because of poor preservation.

The Lower/Upper Pliocene boundary (NN15/NN16 zonal boundary) is located between 2680 ft and 2731 ft based on the consistent occurrence of R. pseudoumbilicus, S. abies, and S. neoabies below 2731 ft. The presence of Eudiscoaster tamalis suggests the upper part of Zone NN15. The lowest occurrence of this discoaster at 4198 ft may serve to delineate the NN15a/b subzonal boundary. Eudiscoaster asymmetricus is present at 4436 ft, which may suggest Zone NN14 or NN15. Amauroolithus tricorniculatus occurs at 4467 ft with Ceratolithus sp. C. acutus. This suggests a level close to the Miocene/Pliocene boundary.

The three samples available between 4467 ft and 5200 ft were barren.

**Upper Miocene—** (5203 ft to 6705 ft). All calcareous nanofossil-bearing Upper Miocene sediments in this well belong to Zone NN11. Subdivision into Subzones NN11a and b is hampered by poor preservation. Amuraolithus delicatus occurs at 5453 ft, indicating Subzone NN11b. M. convallina occurs at 6515 ft, indicating Subzone NN11a.

**Middle Miocene—** (6740 ft to 7202 ft). Catlnaster coiltis (Zones NN8–NN9) is rare at 6743 ft and 6863 ft. Level 6920 ft yields Middle Miocene assemblages with Eudiscoaster exilis, E. nannigulensis, and Coccolithus minutiplicatus. This level may belong to Zone NN6 or NN7. Level 6972 ft is barren. The interval between 7030 ft and 7202 ft belongs to Zone NN5.

**Lower Miocene—** (7256 ft to 7482 ft). Zone NN4 is present between 7256 ft and 7330 ft. Below this latter level, zonal assignment is uncertain because of poor preservation. The interval between 7369 ft and 7482 ft may belong to Zone NN2; alternatively, level 7369 ft belongs to Zone NN3.

**Upper Lower Oligocene—** (7572 ft to 7759 ft). The interval between 7572 ft and 7759 ft belongs to Zone NP23 with Gt. margaritae. The LO of Catenaster coiltis occurs at 8467 ft, which may suggest Zone NN15 or NN16. Amauroolithus tricorniculatus occurs at 4467 ft with Ceratolithus sp. C. acutus. This suggests a level close to the Miocene/Pliocene boundary.

**Planktonic foraminifera (Fig. 3):** Unless otherwise noted, sample depths are those of sidewall cores (SWC); ditch cuttings are referred to as DC, where appropriate.

**Oligocene—** (992 ft–1154 ft). Globorotalia truncatulinoides is present at 992 ft (SWC), suggesting that the section above ~1000 ft to 1200 ft is of Pleistocene age. The Pliocene/Pleistocene boundary is placed between 1154 ft and 1214 ft based on the LAD of G. extremus in the latter sample (SWC).

**Pliocene—** (1214 ft to ~4500 ft). The HOs of Gt. miocenica (1550 ft) and Gt. margaritae (2562 ft) serve to identify the P15/P16 and the P13/P14 boundaries, respectively, of Late Pliocene age. Faunas from 1600 ft to 2562 ft are characterized by i.a., Gt. crassula, miocenica, crassaformis viola, Globigerinoides ruber, G. conglobatus, Neogloboquadrina humerosa-dutertrei.

Early Pliocene faunas are characterized by i.a., Gt. margaritae, tumida, pseudomiocenica, crassaformis, menardii “B” (= limbata), Dentoglobigerina altispina. The LO of Gt. tumida at 4643 ft (SWC) (5.6 Ma) indicates that the Miocene/Pliocene boundary is located near 4500 ft to 6000 ft.

**Miocene—** (4600 ft to >6600 ft). Upper Miocene faunas occur down to at least about 6600 ft and are characterized by Gt. pseudoamiantum, menardii “B” (limbata), Neogloboquadrina acostaen-sis, N. humerosa, Globigerinoides extremus, Gt. obliqua, Sphaero-oidinella seminula.

The Miocene/Pliocene biostratigraphic interval (Zones M5b–M11 [middle part]) is about 400 ft thick. The HO of Neogloboquadrina...
mayeri at 6743 ft, LO Gt. peripheracuta (≈M6/M7) at 6820 ft (DC), and HO Gt. peripheroronda and LO of Orbolina suturalis (the latter = M5b/M6) at 7143 ft were sequentially recorded. Middle Miocene faunas are characterized by, i.a.l., Gt. archeomenardii, N. mayeri, Gt. trilobus, Globorotaloides variabilis. Unfortunately, we have not found representatives of the Gt. foehsi group in this well. However, the notation by Chevron of G. foehsi robusta at 7000 ft (DC) suggests the presence of Zone M9b (probably between 6820 ft and 6743 ft). Note that the name N. mayeri can be used interchangeably here and throughout the article with the name N. siakensis, as the two taxa may, indeed, be synonymous (Zachariasse and Sudjono 2012).

The Lower Miocene extends to about 7474 ft (HO of Gl. angulisuturalis). Paragloborotalia kugleri is recorded at ≈7390 ft (DC) by Chevron and suggests that Zone M1a extends to at least this level in this hole. Within this thin interval faunas are characterized by Catapsydrax dissimilis (HO 7260 ft; = M3/M4), Gt. praescutulata (LO 7256 ft = Zone M3, or younger, equivalent), Dentoglobigerina venezuelana, Dg. praedehiscens, Globoquadrina trilobus, and Neo-globogyra mayeri, but it is not possible to discern a precise sequential biostratigraphy or zonation.

Oligocene—(7474 ft and 7637 ft). This interval contains Oligocene forms such as Paragloborotalia opima (HO 7572 ft; = O5/O6 boundary). Precise biostratigraphic zonation of the Oligocene is not possible, but an approximate twofold subdivision is suggested based on the data summarized above and in Figure 3.

Eocene—(7637 ft and 7655 ft). The lowermost (SW) samples contain a late Eocene fauna with Globigerinatheka semiinvoluta, Gl. truncatulinoides, Gt. archeomenardii, N. mayeri, Gl. fohsi robusta, and a late Eocene fauna with Gt. trilobus, G. fohsi robusta, Globigerinoides trilobus, and Neo-globogyra mayeri, but it is not possible to discern a precise sequential biostratigraphy or zonation.

Overview: A comprehensive stratigraphic interpretation of this 7480-ft-thick upper Lower Miocene to Upper Miocene section (between 7020 ft and ~14,340 ft) is extremely difficult to achieve. Practically all Miocene NN and M zones were delineated (Fig. 6A, B), but there is little agreement in this well between the locations of calcareous nannofossil and planktonic foraminiferal stratigraphic events (Fig. 6A, B), possibly a combined effect of downhole caving and reworking. The abundance of the calcareous nannofossils varies mostly from common to few; preservation is mostly moderate; and a few levels are barren. However, caving occurs, being pervasive at seven levels, most of them in the Middle Miocene. Samples contain clean and well-preserved as well as, at least, blackened planktonic foraminifera, and it is clear that the state of preservation is not an indicator of stratigraphic level/age. For instance, obviously reworked specimens of the F. foehsi group are scattered sporadically through the interval 9000 ft to 10,000 ft, and Gt. peripheroronda occurs sporadically at least as high as 9360 ft; the preservation of these reworked specimens varies from clean to blackened, as does that of downhole caved Gt. truncatulinoides at 7200 ft to 8300 ft. As a general guide to determining M-zonal boundaries, the uppermost level at which a particular taxon occurs in relatively large numbers was used rather than isolated specimens. This approach results in a biostratigraphy that is consistent with that based upon calcareous nannoplankton.

Calcareous nannofossil stratigraphy (Fig. 4): Upper Miocene—(7020–7050 ft to 10,620–10,650 ft). Zone NN11 extends from 7020–7050 ft to 8460–8490 ft. Amaurolithus delicatus is rare at 7020–7050 ft, indicating Subzone NN11b. The co-occurrence of Eudiscaster neohamatus, E. quinqueramus, and Misonithia convallis between 7560–7590 ft and 8460–8490 ft indicates Subzone NN11a. The NN11a/NN11b subzonal boundary occurs between 7110–7140 ft and 747–7500 ft but cannot be more precisely delineated. The interval between 8550–8580 ft and 9450–9480 ft belongs to Zone NN10. The HO of Eudiscaster hamatus at 9540–9570 ft marks the NN9/NN10 zonal boundary. Zone NN10 is characterized by the occurrences of E. brouweri, E. pentaradiatus/E. misconceptus, E. neohamatus, and E. bollii, the latter species being abundant only at 9180–9210 ft. Zone NN9 extends from 9540–9570 ft to 10,350–10,380 ft, Zone NN8 from 10,440–10,470 ft to 10620–10650 ft. Discoasters are poorly preserved (broken arm tips) and scarce in these two zones. Cathinaster calyculus was not encountered, possibly because of poor preservation and low diversity of assemblages.

Middle Miocene—(10,710–10,740 ft to 14,040–14,070 ft). This interval belongs to Zones NN6–NN7 undifferentiated (10,710–10,740 ft to 13,500–13,530 ft) and Zone NN5 (13,590–13,620 ft to 14,040–14,070 ft). The NN6–NN7 zonal interval stratigraphic resolution is hampered by poor preservation, reflected in the scarcity of discoasters and the very low diversity of the assemblages. Eudiscaster kugleri was not found, but the occurrence of E. challengeri at 10,890–10,920 ft suggests a position within Zone NN7. Good preservation and relatively high diversity in Zone NN5 contrast with poor preservation and low diversity above 13,590–13,620 ft.

Lower Miocene—(14,130–14,160 ft to ~7474 ft). Helicosphaera ampliaperta occurs at 14,130–14,160 ft and 14,220–14,250 ft together with Shonlithus heteromorphus. This indicates Zone NN4. No specimen of H. ampliaperta was found at 14,310–14,340 ft (caving?), and the lowest level in the section (14,400–14,430 ft) is barren.

Planktonic foraminifera (Fig. 5): Miocene—(7020 ft to 14,300 ft). We ascribe the interval from 7020 ft to ~8900 ft to the Upper Miocene. Faunas in this interval are characterized by i.a.l., Sphaeroidinellopsis seminulina, N. acostaensis, D. venezuelana, D. altispira, Gt. nepenthis, Gl. obliquus, extremus and trilobus, and Gt. plesiostomida. The HO of Gt. dehiscens is at 9360 ft, and while the true LAD of this taxon is near the Miocene/Pliocene boundary, its last occurrence in the Gulf Coast is generally found in the late Miocene within Zone M13b, which would be consistent with the calcareous nanoplankton biostratigraphy derived here. The HO of Gt. lenguensis is at 9000 ft, and at 9180 ft this form occurs in large numbers. In the Gulf of Mexico Eureka cores the HO of this form was found to coincide closely with the M13a/b boundary (LO Gt. plesiostomida) within Zone NN10, and this determination/correlation here is consistent with the Eureka core data. The HO of N. mayeri (= M11/M12 boundary) is estimated to occur at 9900 ft; at 10,080 ft this form occurs in high numbers. This level lies in Zone NN9, consistent with our studies on Jamaica and the Eureka cores. The Middle/Upper Miocene boundary, situated at the M12/M13 zonal boundary, is arbitrarily estimated to lie at about 9800 ft. Samples above 9800 ft usually contain common acostaensis, suggesting that the interval from about 9800 ft to 9000 ft spans the M12–M13 zonal interval. Globorotalia foehsi lobata occurs at 10,890 ft, suggesting a level within Zones N11–N12, and the F. foehsi group occurs commonly at 11,000 ft and at levels below. These levels are within (calcareous nanoplankton) Zones NN6–NN7, consistent with records in the Eureka cores and elsewhere. The HOs of the Praeorbulina complex at 13,500 ft (~M6/M7 zonal boundary) and of Pr. glomerosa glomerosa at 13,860 ft (~M5b) suggest that the Lower/Middle Miocene boundary is within (the lower part of) this interval. The lowermost samples (below 14,300 ft) contain typical early Eocene faunas with Monozovella aequa, M. formosa, M. subbotinae, M. aragonensis,
Acarinina wilcoxensis, Ac. angulosa, and Subbotina patagonica, and can be ascribed to Zone P7.

Pleistocene (and probably Pliocene) is present in the upper part of the well (above 7020 ft) because of the downhole (caved) presence of Gt. truncatulinoides consistent to at least 8300 ft (in the Upper Miocene).

Well-3 (SOHIO Viosca Knoll Block 817, Well OCS-4928 #4, P42)

Overview: There are several difficulties with establishing a calcareous nannofossil biozonal framework for this hole. Calcareous nannofossils are scarce at most levels, and preservation is generally poor. As only diagenetically resistant taxa occur at most levels, bizonal subdivision was not possible for the Lower Pliocene in this well, and the Upper Miocene subzonal boundaries could not be precisely delineated, a delineation further hampered by numerous barren intervals (Fig. 8). This resulted also in approximate location of chronostratigraphic boundaries. Finally, because of barren intervals and exceedingly rare nannofossils at some levels, reworking was difficult to determine. Zonal subdivision of the Pleistocene is thus only tentative. In contrast the planktonic foraminifera are relatively difficult to determine. Zonal subdivision of the Pleistocene is thus only tentative. In contrast the planktonic foraminifera are relatively common and well preserved in this well, down to about 7000 ft; below this level and extending to the bottom of the section examined (~12,000 ft) they are sporadic.

Calcareous nannofossil stratigraphy (Fig. 6): Pleistocene—
(1700–1730 ft to ?)[2930–2960 ft]. This interval belongs to Zones NN20 and NN19, the zonal boundary possibly occurring between 2330–2360 ft and 2360–2390 ft. However, calcareous nannofossils are very rare above 2000–2030 ft, and preservation is poor. Also, Pseudoeuglyphaenia lacunosa occurs at 1700–1730 ft and 1930–1960 ft, where it is assumed to be reworked. Helicosphaera sellii occurs at 2390–2420 ft and 2420–2450 ft, suggesting Subzone NN19b. However, this taxon was not encountered below, and, again, reworking cannot be excluded. The HO of Calciscus mcnittitry occurs at the top of Subzone NN19a at 2720–2750 ft. The extent of this subzone is not established. Level 2750–2780 ft belongs to Subzone NN19a, but level 2780–2810 ft yields only small Gephyrocapsa spp. and Coccolithus pelagicus; level 2810–2840 ft yields rare Helicosphaera carteri, and level 2840–2870 ft is barren. Small Gephyrocapsa spp., two arms of a discoaster and Eudiscoaster brouweri, were encountered at 2900–2930 ft. It is not clear whether the interval between 2780–2810 ft and 2900–2930 ft is entirely Pleistocene or if it extends into the Pliocene.

Lower Pliocene—(2930 ft to 4550 ft). Reticulofenestra pseudoumbilicus occurs at 2930–2960 ft, together with Retico- fenestra pseudoumbilicus is the only species occurring consistently down to 4400–4430 ft. Eudiscoaster asymmetricus, present at 2960–2990 ft and 3200–3230 ft, may be used to restrict zonal assignment to Zones NN14–NN15. The occurrence of Pseudoemiliania lacunosa at 3020–3050 ft may suggest Zone NN15 down to this level. Level 4280–4310 ft yields a relatively diverse discoaster assemblage, with E. pentaradiatus, E. surculus, and E. variabilis. The HO of E. quinqueramus is at 4550–4580 ft. Between this level and 4520–4550 ft, calcareous nannofossils are very rare or absent. Thus, the position of the Miocene/Pliocene boundary in this well is uncertain.

Upper Miocene—(4550–4580 ft and 9800–9830 ft). Zone NN11 occurs from 4550–4580 ft to 7340–7370 ft. No ceratoliths were encountered, but based on the HO of E. neohamatus at 7040–7070 ft, the NN11a/NN11b subzonal boundary may be placed between this level and 7010–7040 ft. The sporadic occurrences of E. quinqueramus below 7310–7340 ft are interpreted as caving. Zone NN10 extends from 7340–7370 ft to 9620–9650 ft. In it calcareous nannofossils are more abundant and better preserved (and, thus, assemblages are richer) than in the same zonal interval recovered from the other five wells. A few specimens of E. hamatus were observed scattered through the interval. Because of discontinuous occurrences of this taxon, and of its co-occurrence with E. pentaradiatus and E. misconceptus (with a FAD in Biochron NN10), they are considered reworked. Eudiscoaster sp. occurring between 8050–8740 ft and 8000–8720 ft. The HO of E. bellii is at 9320–9350 ft. Zone NN9 extends from 9650–9680 ft to 9770–9800 ft. It is uncertain which part of Zone NN9 is represented.

Middle Miocene—(9800 ft to 12,080 ft). Calcareous nannofossils are very rare and poorly preserved below 9770–9800 ft. Reticulofenestra pseudoumbilicus is present at most levels, and Eudiscoaster variabilis occurs sporadically. Isolated specimens of E. hamatus occur at 11,390–11,420 ft and 11,720–11,750 ft. Correlation with planktonic foraminiferal zones indicates that these are caved. The only indices of Middle Miocene sediments are at 11,210–11,240 ft (Eudiscoaster sp. cf. E. sanmiguelensis, 11,900±20 ft (D. exilis), and 12,050–1–2,080 ft (E. sanmiguelensis). However, their scarcity precludes a definitive Middle Miocene age assignment. Coccolithus miopelagicus, a diagenesis-resistant taxon that has its HO in Zone NN8, was not encountered.

Planktonic foraminifera (Fig. 6): Pleistocene—(1700 ft to 3020 ft). Pleistocene faunas (with Globigerinoides ruber, Gl. trilobus-sacculifer, Globorotalia manardii, Gt. crassaformis, Gt. inflata, Neogloboquadra gabrielii, Sphaeroindellina dehiscens s.s., Palle- ninia obtusiloba, and the index form Gt. truncatulinoides) occur commonly down to 3020 ft, where the HOs of Gt. miocenica and Gt. pseudomiconicna indicate a Late Pliocene age for this level.

Pliocene—(3020 ft to 6330 ft). Faunas characterized by most of the forms cited above continue downwards below 3020 ft but are considered to be downhole cavings here. The HOs of N. acostaensis (3230 ft), Gt. margaritae (= P12/P13; 3840 ft), and Sphaeroindellina seminulina (4280 ft) and the occurrence below 4700 ft of the N. humerosa–dutertrei complex (generally characteristic of the pre–Late Pliocene) support an age estimate of Early Pliocene for the stratigraphic interval below 3020 ft. The HO of Pulleniata in primas at 6330 ft suggests an Early Pliocene age for this level, but Miocene calcareous nannoplankton occur as high as 4550 ft.

Miocene—(6330 ft to 12,080 ft). Downhole contaminants from the Pleistocene are relatively common over the interval of 5030 ft to 5090 ft. Microfaunas between 5000 ft and 7000 ft are generally characterized by Sphaeroindellina sp. and (presumed) downhole Pleistocene contaminants.

At 7070 ft the (Agua Salada) agglutinated benthic fauna appears suddenly together with the closely conjunct HOs of Dentoglobigerina altispira, D. venezuelana, and Globoturborotalites nepenthe. Faunas below 7300 ft are characterized by i.a. Sph. seminulina, Globorotalia manardii “B” (limbus), Gt. manardii s.l., Gt. nepenthis, D. altispira, D. venezuelana, Gl. trilobus, Gl. obliquus, and Globigerinella praestompona and siphonifera—faunas with a distinct mid–Late Miocene character but which do not provide a definitive biostratigraphic discrimination. The HO of Neogloboquadra mayeri at about 9740 ft, which is closely associated with the HO of the benthic foraminifera Cibicidoides crebri (whose LAD has been associated with Zone N15 [= M11] by Van Morkhoven et al. 1986), over the interval of 9560–9740 ft suggests a level close to the M11/M12 zonal boundary and the Middle/Upper Miocene boundary (but see Katz and
Miller [1993], who record C. crebbsi extending in low numbers into Lower Pliocene levels.

The HO of Globorotalia fohsi lobata-robusta (= M9b/M10) has been observed at 11,990 ft, and faunas here and below are characterized by Sphaeroidinellopsis multiola, which is typically and commonly developed over the M8–M9 zonal interval. Small forms referable to Gt. archeomenardii and Gt. praeomenardii in the lower part of the well associated with the fohsi complex support a middle Middle Miocene age assignment for the lowest part of the well examined in this study (~12,080 ft).

Well-4 (UNOCAL Mississippi Canyon Block 455, Well OCS-G 6953 #1)

Overview: Calcareous nannofossil abundance and preservation varied greatly from level to level in Well-4, so that several zonal and subzonal boundaries could not be delineated confidently. Likewise, even though downhole caving did not appear to be a major factor, the absence of (some) biostratigraphic markers, particularly in the extensive (~7000–8000 ft) Upper Miocene section between ~10,000 ft and >18,000 ft, rendered age estimates and biostratigraphic subdivision difficult (Fig. 10A, B).

Calcareous nannofossil stratigraphy (Fig. 7): Pleistocene—(5010–5040 ft to 5930–5960 ft). This interval is assigned to Zone NN19 and subdivided into Subzones NN19a to NN19c based on the HOs of Helicosphaera sellii at 5841–5870 ft and Calcidiscus mcintyrei at 5930–5960 ft. A few specimens of E. brouweri occur at 5930–5960 ft. As Gephyrocapsa oceanica is also present at this level, they are regarded as reworked.

The Pliocene/Pleistocene boundary occurs between 5930–5960 ft and 6030–6060 ft.

Upper Pliocene—(6030–6060 ft to 6630–6660 ft). This is a lower Upper Pliocene interval that belongs to Zone NN16a, as indicated by the co-occurrence of Eudiscoaster surculus and E. tamalus. The Upper/Lower Pliocene boundary is located between 6630–6660 ft and 6720–6750 ft.

Lower Pliocene—(6630–6660 ft to ~10,320 ft). Calcaceous nannofossils are scarce at many levels in this interval, and preservation is very poor. This hampers somewhat confident delineation of the zonal boundaries. The frequency of discoasters and ceratoliths, both groups critical to the zonal subdivision of the Lower Pliocene, clearly reflects preservation. Ceratoliths occur only in intervals with good preservation, and discoasters are more frequent when preservation is good. Although ceratoliths are common in intervals with good preservation, Ceratolithus rugosus is rare in this well. Specimens that may represent C. cristatus or C. armatus (the latter sometimes regarded as a junior synonym of C. acutus) co-occur with C. acutus (common in the well), which leads to uncertain delineation of Zone NN13.

The HO of (scarce) Reticulofenestra pseudomamillicus is placed at 6720–6750 ft, slightly above the HO of Sphenolithus abies and S. neoables. The interval between 6720–6750 ft to 8490–8420 ft is assigned to Zone NN15 and tentatively subdivided into Subzones NN15a and NN15b based on the LO of E. tamalus at 7500–7530 ft. This is tentative because of the discontinuous occurrence of E. tamalus below 6720–6750 ft and the possibility that the sample from 7500–7530 ft represents caving, in which case only Zone NN15a would be represented (which is not supported by the sedimentation rate curve; see below). Level 8610–8860 ft yields both E. asymmetricus (common) and Amaurolithus tricorniculatus. It is confidently assigned to Zone NN14. The interval from 8700–8730 ft to 10,290–10,310 ft may belong to Zone NN13 (and perhaps Subzone NN12a) or to Zone NN13 and Subzones NN12b and NN12a (see above). No ceratoliths were encountered at 10,200–10,230 ft and 10,290–10,310 ft. Their absence (or extreme scarcity) is attributed to poor preservation. The biozonal and chronostratigraphic position of these levels is indeterminate. If older than the LO of C. acutus, they are Upper Miocene.

Upper Miocene—(10,530–10,560 ft to ~18,360–18,390 ft). Calcareous nannofossil preservation (and abundance) also varies greatly in this interval, hampering the confident delineation of subzonal boundaries. Eudiscoaster quinqueraeus occurs between 10,530–10,560 ft and 14,670–14,700 ft. The interval between 10,530–10,560 ft and 11,250–11,280 ft is assigned to Subzone NN11b based on the occurrence of Amaurolithus spp. The interval between 14,310–14,340 ft and 14,670–14,700 ft is assigned to Subzone NN11a based on the occurrence of E. neohamatus and Myniliitha convallis. There is a sampling gap between 11,550–11,580 ft and 14,310–14,330 ft. The absence of ceratoliths at 11,340–11,370 ft to 11,550–11,580 ft is attributable to poor preservation.

The NN9/NN10 zonal boundary occurs between 17,010–17,040 ft and 17,370–17,400 ft. Eudiscoaster hamatus is abundant at this latter level. It is absent at 17,280–17,310 ft, in a sample believed to reflect caving. It is rare at 17,190–17,220 ft, 17,100–17,130 ft, and 17,010–17,040 ft. It occurs discontinuously above. At 17,010–17,040 ft, E. hamatus occurs with E. miconceptus/E. pentaradiatus, which indicates Zone NN10 (and the reworking of E. hamatus). Surprisingly, E. bollii occurs discontinuously in the interval assigned to Zone NN10. Calcidiscus calyculus occurs with E. hamatus at 17,378–17,400 ft, which is indicative of the upper part of Zone NN9 (Subzone NN9b). Its absence lower in the well may reflect poor preservation.

Zone NN9 extends down to at least 18,360–18,390 ft. No zonal assignment is possible between 18,450–18,480 ft and 18,720–18,750 ft, the assemblages containing only long-ranging species and no dominants. Cretaceous taxa are dominant at 18,630–18,660 ft and 18,720–18,750 ft.

Planktonic foraminifera (Fig. 8): Pleistocene—(5000 ft to 5800 ft). Planktonic foraminiferal assemblages from 5000 ft to about 5800 ft are characterized by mixed assemblages of warm (menardii, ruber, sacculifer, pulleniatinids, sphaerodinellids), and cool (inflata, cressafornis, truncatulinoides-tosaensis) water taxa, reflecting alternating glacial-interglacial cycles that cannot be distinguished in ditch cuttings. The common occurrence of truncatulinoides down to 5800 ft suggests that the Pliocene/Pleistocene boundary lies at or below this level.

Pliocene—(~5800 ft to ~10,000 ft). The essentially coterminous HOs of mioecina, multiformata, altispira, and extremus at 6030 ft suggest a level within Zones P13–4. The HO of Sphaeroidinellopsis group at 6540 ft indicates the P13/P14 boundary, that of nepentes at 8490 ft indicates the P11/P12 boundary. There are no biostratigraphic markers/information allowing an approximate, let alone a precise, determination of the level of the Miocene/Pliocene boundary in this well. Faunas from 6500–8500 ft are characterized by common henegro-seminulina and from 8500 ft to 15,600 ft by common nepentes and seminulina. Globorotalia cressafornis and G. margaritae are relatively common down to about 10,000 ft, suggesting that the Miocene/Pliocene boundary is somewhat near? slightly below this level.

Miocene—(10,000 ft to 18,750 ft). The HO of Globigerinoides segelii, a generally rare but characteristic Late Miocene taxon, occurs at ~11,000 ft (within Upper Miocene Subzone M13b and M14; see above). No samples were available from ~11,750 ft to ~14,250 ft.

Faunas from 15,000 ft to 17,700 ft are characterized by common nepentes, acostaensis, venezuelana, and G. dehiscens, whereas
between 17,700 ft and 18,500 ft *nepentes* is less common in faunas dominated by the other three forms. While it occurs (sporadically) more rarely than *Gq. dehiscens* at 15,590 ft suggests a level equivalent to/within Zone M13. The HO of *N. mayeri* at 18,540 ft (M11/M12 boundary) supports this estimate. The Middle/Upper Miocene (Tortonian/Serravallian) boundary would then be located somewhat above 18,540 ft. Between 18,540 ft and 18,750 ft faunas are characterized by *mayeri* and *menardii* “A” forms, typical of upper Middle Miocene (Zone M11).

**Well-5 (BP Ewing Bank Block 788, Well OCS-G 5796 #1)**

**Overview:** The stratigraphic succession in this well spans the Pleistocene to Upper Miocene (Zones NN20 to NN11a), as determined from calcareous nannofossils; Fig. 2). Tenuous planktonic foraminiferal evidence indicates, however, a Pliocene age (Zone P11a) at 12,450 ft. The age discrepancies between the two groups of microfossils (Fig. 12) may reflect caving (planktonic foraminifera) or reworking (calcareous nannofossils) but due to the scarcity of calcareous nannofossils at most levels, it was difficult to assess caving and reworking. Biozonal subdivision of the Pleistocene interval is thus uncertain, but the proximity of the HOs of *Calcisudis macintyrei* and *Helicosphaera sellii* suggests that the NN19a/b or the NN19b/c subzonal contact is unconformable. Calcareous nannofossils were common in the Lower Pleistocene interval, but only diagenesis-resistant taxa occurred. The ceratoliths being exceedingly rare, biozonal subdivision of the Lower Pleistocene was not possible.

**Calcareous nannofossil stratigraphy (Fig. 9):** Pleistocene—(1740 ft to 7860 ft). Calcareous nannofossils are few to very rare in the Pleistocene, and many levels are barren. Reworked (mostly Cretaceous), (rare) Paleogene, and (occasional) Neogene taxa were encountered. Rare specimens of *Pseudoellenthia lacunosus* occur at 4680 ft. This species is, however, very rare in the well, so that the delineation of the NN19/NN20 zonal boundary between 4620 ft and 4640 ft is tentative. The HOs of *H. sellii* lies at 7620 ft, that of *C. macintyrei* at 7740 ft. These distributions indicate Subzones NN19b and NN19a, respectively. However, as the interval between 6420 ft and 7560 ft is mostly barren, it is not possible to locate the NN19b/c subzonal boundary. Very rare *Eudiscoaster brouweri* at 7800 ft and 7860 ft and *E. sp. cf. E. pentaradiatus* at this latter level are considered reworked.

Pliocene—(7920 ft to >13,170 ft). There is a sharp contrast in calcareous nannofossil abundance and preservation between levels 7860 ft and 7920 ft. Assemblages are rich at 7920 ft, and they yield *Eudiscoaster brouwerii*, *E. misconceptus*, *E. surculus*, and *E. tamalis*. This indicates the lower Upper Pliocene Subzone NN16a. Small morphotypes of *Reticulofenestra pseudoumbilicus* occur at 8100 ft. This indicates that the NN15/NN16 zonal boundary occurs between 8040 ft and 8100 ft. Below 8100 ft, biozonal assignment is uncertain. Level 8730 ft, with *Amauroolithus delicatus*, *Ceratolithus cristatus*, *Eudiscoaster asymmetricus*, *H. challengeri*, *E. surculus*, *Reticulofenestra pseudoumbilicus*, and *Sphenolithus abies* is assigned to Zone NN14. Level 10,430 ft, with *Ceratolithus rugosus*, *E. surculus*, and rare *E. asymmetricus* is assignable to Zone NN14 or NN13. *Ceratolithus sp. cf. C. acuta* was encountered at 10,560 ft. This suggests a level close to the Miocene/Pliocene boundary.

Upper Miocene—(11,220 ft to 13,170 ft). *Eudiscoaster* sp. cf. *E. quinqueramus* are infrequent in the interval between 10,680 ft and 11,160 ft. The HO of rare but typical morphotypes of *E. quinqueramus* is at 11,220 ft. No ceratoliths were encountered in the upper range of *E. quinqueramus*, but *E. neohamatus* occurs below 12,180 ft, indicating Subzone NN11a. The interval between 11,220 ft and 12,120 ft may belong to Subzone NN11b. Common *Eudiscoaster loeblichii* were encountered at 12,420 ft, and *Catinaster* sp. cf. *C. coalius* occurs between 12,360 ft and 12,840 ft.

**Planktonic foraminifera (Fig. 9):** Pleistocene—(1740 ft to <7920 ft). Planktonic foraminiferan faunas from 1740 ft to about 4000 ft contain generally persistent and well-preserved faunas characterized by *Globorotalia inflata*, *G. menardii-tumida* complex, *Globigerinoides ruber*, *G. scuclifer*, *Neogloboquadrina dutertrei*, and the Pliocene index form *G. truncatulinoides*. The latter form is persistent and generally well preserved down to 3700 ft and generally sporadic down to 7140 ft, although relatively common at some levels (e.g., 5220 ft). Below this 7140 ft, *G. truncatulinoides* occurs as single specimens in only a few samples, and below 9720 ft it is obviously caved, inasmuch as evidence indicates a major break at 9720 ft (see below). The presence of the Early to Middle Pleistocene *Gt. crassaformis* subspecies (morphotype) *hessi* at 4620 ft and 4680 ft suggests that this part of the stratigraphic section is near, but above, the Pliocene/Pleistocene boundary. The HO of *G. punctulata*, generally considered to be restricted to the Pliocene, occurs at 4710 ft. However, one of us (W.A.B.) has observed this taxon in the Pleistocene in high southern latitudes (Kerguelen Plateau) in the Subantarctic region.

Pliocene—(7920 ft to >13,170 ft). The HOs of *Globorotalia miocenica* and *Gt. multicamerata* are juxtaposed at 7920 ft. A normal stratigraphic succession is present below 7920 ft, with the HOs of *Dentoglobigerina altispira* (8100 ft), *Gt. margaritae* (=P12/P13; 8070 ft), *Gp. pseudomiocenica* (8760 ft), and *G. nepentes* (P11/P12; 9120 ft) occurring in sequential order downhole. Mid-early Pliocene faunas are characterized by *Sphaeroindelopsis seminulina*, *Rhombus*, *N. humerosa–dutertrei* complex, *Gt. nepentes*, *G. crassaformis*, and *G. extremus*.

The age of the bottom of the section studied in this hole is difficult to determine owing to the monotony of Lower Pliocene faunas and the absence of any unequivocal Upper Miocene markers as well as sinistrally coiled *Globorotalia menardii* “B” (*littorata* group (observed also in the Marathon Green Canyon, Block 152 well), which would indicate an age of >5 Ma). However, the HO of a form assigned here to *Globorotalia aff. Gt. cibaeensis* (which is the nominate form for the P11a/b boundary of Berggren et al. [1995]) and whose LAD has an age estimated at 4.6 Ma) at 12,450 ft suggests that the base of the section studied here (at 13,170 ft) is in Zone P11a and the Lower Pliocene.

**Well-6 (Marathon Green Canyon Block 152, Well OCS-G 7022 #1)**

**Overview:** The interval between 5590 ft and 14,740 ft constitutes a discontinuous Middle Pleistocene to Lower Pliocene section (Zones NN22 to P11; Zones NN20 to NN14–NN13 undifferentiated; Fig. 2). The scarcity of the microfossils hampers a refined biozonal subdivision of the section (Fig. 14A, B). Calcareous nannofossils are mostly rare, and preservation is poor to moderate. Few and moderately preserved from 10,750 ft to 10,990 ft and from 17,920 to 18,780, they are common to abundant and moderately well preserved from 12,550 ft to 13,480 ft. No anomalous stratigraphic succession resulting from caving was noted, except at 14,770 ft, where an assemblage characteristic of Subzone NN15b occurs below the NN14/NN15 zonal boundary. No biozonal assignment is possible below 14,740 ft. The interval between 15,010 ft and 17,500 ft is mostly barren and with exceedingly scarce calcareous nannofossils. Calcareous nannofossils are few to common between 17,920 ft and 18,780 ft, but the assemblages consist of long-ranging taxa without zonal markers (noteably the absence of discoasters). Likewise,
planktonic foraminiferal faunas are sporadically distributed, and preservation varies from good to poor. There are large stratigraphic intervals of up to 500 ft, over which planktonic foraminifera are rare or absent, rendering biostratigraphic interpretation tenuous/hazardous. Analysis of the faunal associations in the cutting samples suggests that caving may not be a significant factor in the distribution over most (but not all) of the stratigraphic section studied here.

Calcareous nannofossil stratigraphy (Fig. 10): Pleistocene—(5590 ft to 10,810 ft). The highest occurrence of Pseudomelitiana lacunosa at 6490 ft delineates the NN20/NN19 zonal boundary. However, the position of this boundary is tentative. The six samples analyzed between 5590 ft and 6280 ft yield only Cretaceous taxa, except for level 6190 ft that yielded Gephyrocapsa oceanica. The absence of P. lacunosa at 7000 ft, 7420 ft, and 7510 ft may be explained by the scarcity of coccoliths at these levels. Zone NN19 extends down to 10,810 ft and is subdivided into Subzones NN19a and NN19c, as delineated by the simultaneous HO's of Helicosphaera selli and Calcidiscus macintyrei at 9460 ft. The single specimens of E. brouweri and E. triradiatus (likely a variant of the former species) at 10,810 ft are considered reworked. Gephyrocapsa spp. are common at this level, and few specimens of G. oceanica were observed, which indicates a Pleistocene level.

Pliocene—(10,870 ft to 14,740 ft). The sequential HO's of Eudiscoaster brouweri at 10,870 ft, of E. misconceptus (a variant of E. pentaradiatus) at 12,520 ft, E. surculus at 12,580 ft, R. pseudoumbilicus at 13,360 ft, and Amaurolisthus tricorinulatus at 13,740 ft, mark, respectively, the NN19/NN18, NN18/NN17, NN17/NN16, NN16/NN15, and NN15/NN14 zonal boundaries. The biozonal age of level 13,740 ft that yields both A. tricorinulatus and Ceratolithus rugosus but not Eudiscoaster asymmetricus is uncertain. Although this would suggest Zone NN13, E. asymmetricus was not encountered below 14,080 ft (in Subzone NN13a). A conservative assignment to the NN13–NN14 zonal interval is given. Alternatively, the LO of D. asymmetricus is at 14,080 ft and species of Amaurolisthus is exceedingly rare at 14,110 ft and 14,230 ft. The co-occurrence of E. surculus and E. tamalis between 12,550 ft and 13,330 ft indicates Subzone NN16a, and that of this latter species with R. pseudoumbilicus between 13,360 ft and 13,750 ft indicates Subzone NN15b.

Planktonic foraminifera (Fig. 11) Zonal assignment: Pleistocene—(5590 ft to 10,000 ft). Faunas characterized by i.a., Globorotalia truncatulinoides, Gt. menardii, Gt. inflata, Neogloborotalia quadrata duturetii, Sphaeroidinellina dehiscens, Globigerinoides ruber, and Gl. trilobus-sacculifer characterize the stratigraphic section down to about 8940 ft. Gt. tosaensis is present up to about 4000 ft, suggesting that the section above this level is middle Upper Pleistocene (<0.61 Ma). From 8940 ft to ~9400 ft planktonic forms are sporadically found (rare of absent) in cutting samples, making stratigraphic interpretation impossible. Samples from about 10,000 ft to 12,000 ft are characterized by Globigerinoides conglobatus, Gl. extremus, Sphaeroidinellina dehiscens, and Gl. crassaformis and cannot be assigned to a specific stratigraphic interval. At 12,160 ft definitive Late Pliocene events are recorded, which indicates that the Pliocene/Pleistocene boundary lies somewhere between 8940 ft and 12,160 ft, probably in the vicinity of 10,000 ft, if one interpolates between the two levels.

Pliocene—(10,800 ft to <17,950 ft). The HO's of Globorotalia multicamerata, Gt. pseudomioconica, Gt. miocenica, and Dentoglobigerina altispira occur at 12,160 ft. We interpret the HO's of altispira and multicamerata at 12,160 ft as indicative of (approximately) the P13/P14 boundary (~3 Ma). This is corroborated by the observation that "assemblages" of typical Sphaerodinellina dehiscens s.s. (<3 Ma) occur at and above 12,580 ft, while the distinctive early Pliocene forms S. dehiscens immatura (with diminutive supplementary aperture on the spiral side) occur below this level. Faunas down to about 13,000 ft are characterized by menardine globorotaliids (menardii, pseudomiocenica, miocenica, multicamerata), Gt. praekirbyi (not to be confused with Gt. margaritae, which has its HO below at 14,890 ft), D. altispira, and the supernova-dutertrei complex. Dentoglobigerina venezuelana has its HO at 13,060 ft, supporting a general Middle Pliocene determination of this part of the stratigraphic record in this well. The HO's of Gt. margaritae and Gl. nepenthes have been recorded at 14,890 ft. We take the HO of nepenthes as definitive and assign an age of ~3.46 Ma to this level (= P11/P12 boundary). We note in passing that keeled menardine globorotaliids are characteristic of this level and above; below this level they are rare down to 17,950 ft.

The stratigraphic section from 14,800 ft to the bottom of the section examined (18,810 ft) is characterized by S. seminulina, Neogloborotalia acostaensis, the N. hemerosa-dutertrei complex, Gl. nepenthes, and D. altispira, not unlike the assemblages observed below 8500 ft in the Soho (BP) 455 Well. Biostratigraphic subdivision and/or age determination of the lower fourth of this well is virtually impossible owing to the relative uniformity/monotony of the faunal "assemblages." The only possible clue to an approximate age estimate may be the occurrence of common sinistrally coiled forms of the Gt. pseudomiocenica-Gt. menardii "B" (= limitata) complex at 17,950 ft. Our studies (W.A. Berggren, unpublished data) on DSDP Site 502 (Colombian Basin) have shown that this complex is uniformly dextrally coiled for about 2 Myr, from mid-Subchron C3.4n (~Thvera Subchron; ~5.1 Ma) to the Mammoth Reversed (Chron C2A.2r ~3.25 Ma), at which level it evolves into the plano-convex Gt. miocenica. Below this the Gt. pseudomiocenica-menardii "B" (limitata) group is sinistrally coiled from ~C3A.2n (~6.5 Ma) to mid-Chron C3.4n (Thvera; 5.1 Ma). If we assume that the sinistrally coiled specimens at 17,950 ft represent the first downhole reflection of this event in deep sea cores, then this level would be between 6.5 and 5.1 Ma and close to the Miocene/Pliocene boundary, currently estimated at 5.32 Ma in both the magnetobiostatigraphic and astronomical time scales.