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Foraminifera from Paleogene Sediments from the Millhaven and Millers Pond Cores, Screven and Burke Counties, Georgia

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GEOLOGY AND PALEONTOLOGY OF FIVE CORES FROM
SCREVEN AND BURKE COUNTIES, EASTERN GEORGIA

Edited by Lucy E. Edwards

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By Thomas G. Gibson[1]

ABSTRACT

Paleocene and Eocene foraminifers were studied for biostratigraphic and paleoenvironmental analysis in cores from two test holes in the eastern Georgia Coastal Plain. The Millhaven test hole, located southeast of the Millers Pond test hole, is in the more downbasin position. In the Millhaven core, foraminifers are present in lower and upper Paleocene strata of the Ellenton Formation, lower middle Eocene strata of the Congaree and Warley Hill Formations, upper middle Eocene strata of the Santee Limestone, and upper Eocene and questionable lower Oligocene strata of the Barnwell unit. Foraminifers were recovered only from upper middle Eocene strata of the Santee Limestone in the Millers Pond core. The Millers Pond site is the more westerly of the two sites and is in a more upbasin position.

Foraminifers are moderately to highly altered diagenetically in many of the sandy or carbonate-rich intervals in these cores, and the alteration makes specific identifications difficult. Diagnostic planktonic species are found only in beds of early Paleocene age. Some benthic foraminiferal species that have restricted regional biostratigraphic ranges are present. These species suggest placements for some strata in the early part of the late Paleocene and in the middle Eocene.

Foraminiferal assemblages suggest that most upper Paleocene and Eocene beds were deposited in shallow-marine environments with water depths of less than 100 ft. Assemblages in a few intervals, however, suggest somewhat deeper inner-middle to middle neritic environments. Foraminiferal assemblages suggest well-oxygenated environments during the deposition of most upper Paleocene and Eocene beds, but an upper Paleocene dark clay interval contains assemblages suggestive of high-productivity and low-oxygen environments.

INTRODUCTION

Paleogene foraminifers from the Millhaven and Millers Pond cores were examined during a study of the hydrogeologic framework of easternmost Georgia across the river from the Savannah River Site in South Carolina (fig. 1). This study examined foraminiferal assemblages both for biostratigraphic placement of the strata and for interpretation of depositional environments. Foraminiferal assemblages are discussed in a sample-by-sample format to provide the maximum amount of information from this area where little foraminiferal information is currently available.

In the more easterly, and thus downbasin, Millhaven core, foraminifers are found both in Paleocene and Eocene strata. The specimens are well preserved in the more clayey strata, but most are highly altered in the more sandy and limy beds. In the more upbasin Millers Pond core, foraminifers are found only in the Santee Limestone of late middle Eocene age. These specimens occur in carbonate-rich, sandy sediments, and their tests are moderately to highly altered diagenetically.

Some common and important stratigraphic marker benthic species and one stratigraphically important planktonic species are illustrated by scanning electron microscope (SEM) photographs (pl. 1). A high degree of recrystallization within many assemblages, however, makes it difficult to obtain satisfactory pictures of many species, particularly those from the middle Eocene.

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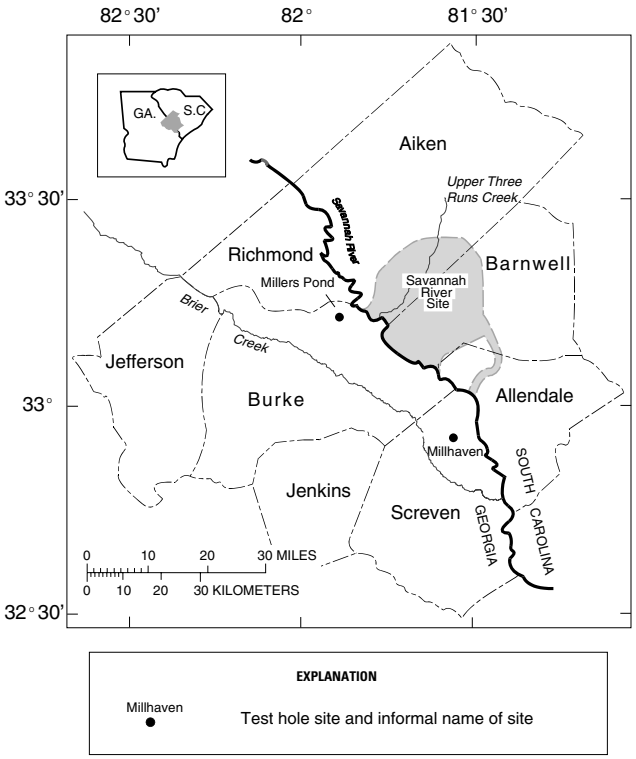

Figure 1. Index map showing the Savannah River Site and the location of the Millhaven and Millers Pond test holes in Screven and Burke Counties, Georgia.

ACKNOWLEDGMENTS

Thomas Servais (U.S. Geological Survey) prepared the foraminiferal samples and aided in the sediment descriptions. Jean M. Self-Trail and Amanda Chapman (U.S. Geological Survey) prepared the illustrations. Raymond A. Christopher (Clemson University) and Harry J. Dowsett (U.S. Geological Survey) made helpful suggestions on the manuscript.

MATERIAL AND METHODS

Foraminifers were prepared from core sections several inches in length. The outside rind of each core segment, which may contain contaminated drilling mud, was removed before processing. Core sections were washed over a 63-micrometer screen that retained all sand-sized and coarser particles.

We then followed two procedures depending upon the state of foraminiferal preservation. In samples containing well-preserved foraminiferal assemblages, the specimens were concentrated from other sand-sized sedimentary particles by soap flotation. However, in many samples, the foraminifers were altered diagenetically and exhibited one or more of the following conditions: extraneous sedimentary particles adhering to the specimens, chamber infillings, calcareous overgrowths, or heavy recrystallization of the test wall. In these samples, the foraminifers were picked from the entire sediment residue that remained after washing.

The degree of diagenetic alteration of the foraminifers in many samples makes it difficult to identify these specimens to the species level. In addition, diagenetic alteration may have selectively removed certain taxa from the original foraminiferal assemblage. Because of these possible biases, samples were studied on a qualitative (species present or absent) basis only.

In the Millhaven core, 23 samples from 5 Paleocene and Eocene units contained foraminifers (fig. 2). In the Millers Pond core, only three samples from the Santee Limestone contained foraminifers (fig. 3). Sample depths are recorded to the nearest 0.5 ft, except in the lower part of the Millhaven core where sample depths are recorded to the nearest 0.1 ft.

Illustrated specimens, other study specimens, faunal slides, and foraminiferal concentrates are deposited in the Cushman Foraminiferal Collection at the U.S. National Museum of Natural History (USNM), Smithsonian Institution, Washington, D.C.

BIOSTRATIGRAPHY

Gohn (1988) summarized the early Cenozoic geology of the southern Atlantic Coastal Plain. This work contains numerous references to the lithostratigraphy of Paleogene deposits in Georgia and South Carolina. Relatively few publications, however, exist on the biostratigraphy of Paleogene Foraminifera in Georgia and South Carolina, and even fewer contain illustrations of the species. Herrick (1961) summarized the occurrence of many benthic species in subsurface samples from Paleogene formations of Georgia, but the species were not illustrated.

Biostratigraphic ranges of many benthic foraminiferal taxa occurring in Georgia and South Carolina deposits largely are undocumented, both in terms of their ranges in Paleogene deposits of the Southeastern United States and in terms of the intercontinental biostratigraphic zonations. I compared the benthic species, when possible, with their biostratigraphic distribution in neighboring areas to the north in North Carolina (Copeland, 1964; Jones, 1983) and Virginia and Maryland (Nogan, 1964; Gibson and others, 1980; Poag, 1989), and to the southwest in Alabama (Bandy, 1949), where more detailed studies of these faunas have been made. Even in these areas, however, the ranges of benthic species in terms of intercontinental biostratigraphic zonations are largely unknown at the present time.

Planktonic foraminifers can be widely distributed in the oceans and, therefore, are widely used in intercontinental correlation and zonations. Unfortunately, they are quite rare in Paleogene strata in the two studied

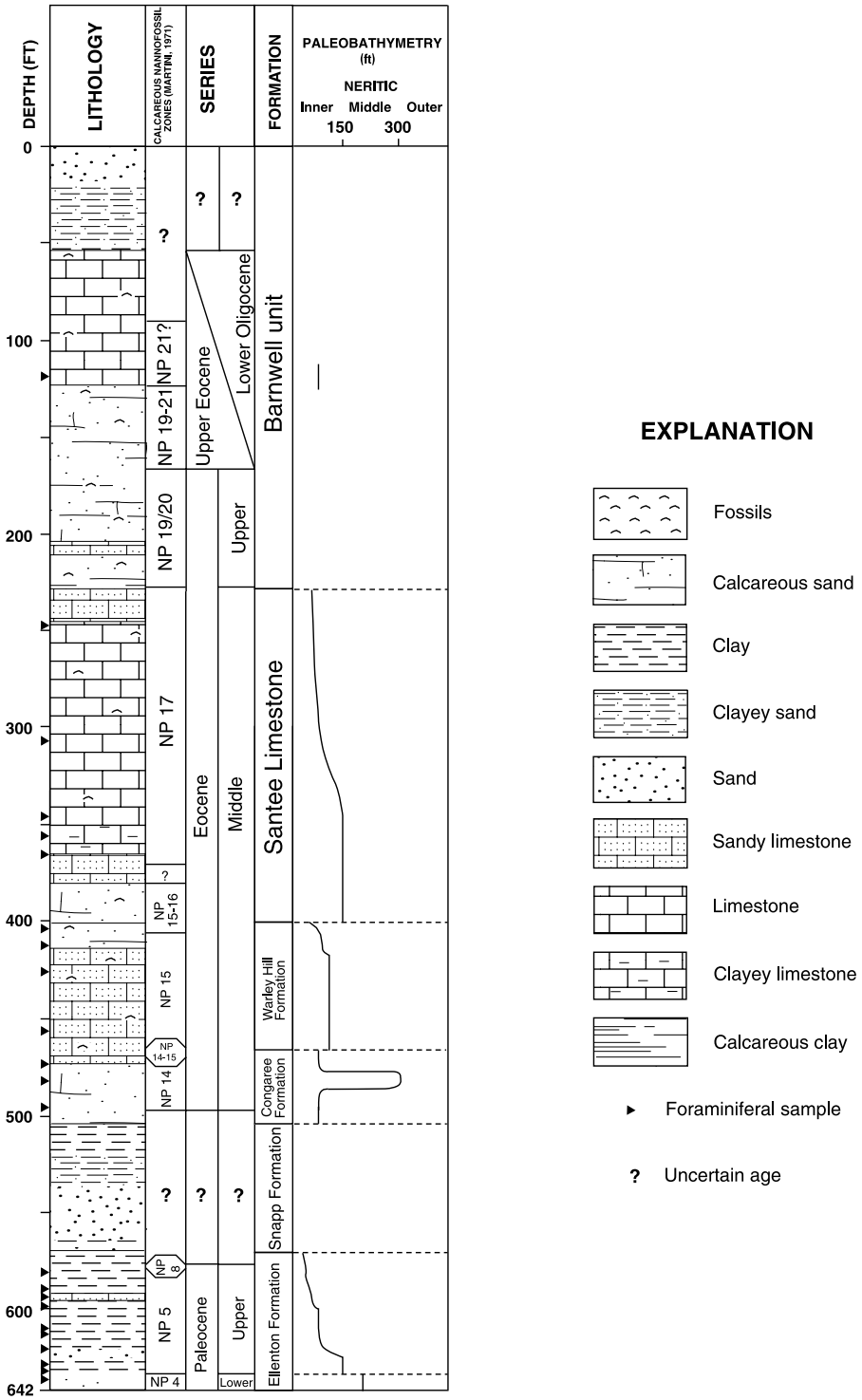

Figure 2. A lithologic log and paleobathymetry of the Millhaven core. The solid triangles indicate the locations of the productive foraminiferal samples. A nonproductive sample from 219 ft is not shown. The calcareous nannofossil zones are from Bybell (this volume, chap. F).

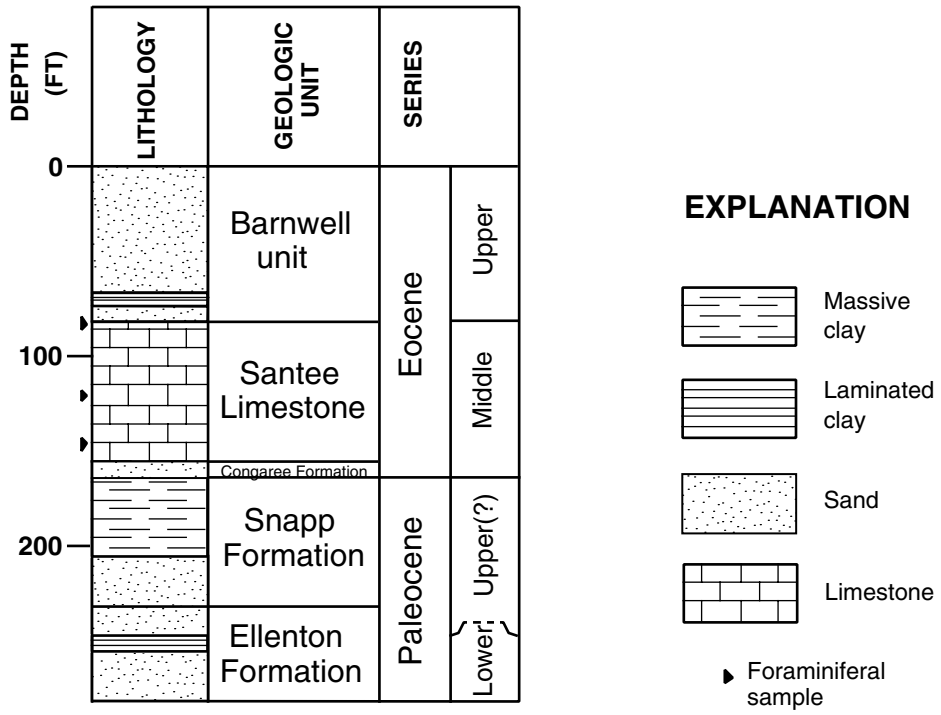

Figure 3. A lithologic log of the Millers Pond core. The solid triangles indicate the locations of the foraminiferal samples. The lithology is from Clarke and others (1994) and the lithostratigraphy is from Falls and Prowell (this volume, chap. A).

cores. The few planktonic specimens recovered from most samples consist mainly of juvenile individuals, which are difficult to place in a specific taxon. The rarity of adult planktonic specimens in the deposits is due primarily to the shallow-water depositional environments of the preserved Paleogene strata in this area. The natural rarity of planktonic specimens in these environments may be augmented by the extensive diagenetic history of many of the samples. Tests of planktonic species are more vulnerable to dissolution during diagenesis than are tests of most benthic species (Murray, 1991). Much less is known biostratigraphically about benthic foraminifers, and they are more closely subjected to environmental controls. Yet, benthic foraminifers compose more than 95 percent of most assemblages.

Most age assignments of strata used in this paper result from the calcareous nannofossil study of these cores by Bybell (this volume, chap. F). Bybell and I have found in studies of Paleogene strata in other parts of the Eastern and Southeastern United States that diagnostic calcareous nannofossil species are much more common in shallow-water deposits than are diagnostic planktonic foraminiferal species (Gibson and Bybell, 1995). In the Millhaven core, planktonic foraminifers, in conjunction with calcareous nannofossils, were valuable in a more accurate placement of the upper lower Paleocene strata.

PALEOENVIRONMENTAL ANALYSIS

The paleoenvironmental analysis is largely based on two approaches: (1) the specific and generic composition of the benthic foraminiferal assemblage and (2) the population characteristics of the entire foraminiferal assemblage. Most benthic species occurring in Paleogene assemblages became extinct during the early and middle Cenozoic. Therefore, for Paleogene species, data on environmental tolerances and distribution in modern environments usually is not possible. However, general paleoenvironmental limits on some extinct species were suggested in studies of Paleogene assemblages in adjacent areas such as those of Olsson and Wise (1987) in New Jersey and Poag (1989) in Virginia.

Numerous benthic genera, however, range from the Paleogene into modern faunas. Although benthic foraminiferal genera usually have wider environmental tolerances than any single contained species, some benthic genera have relatively restricted environmental tolerances for all their modern species. The occurrences of fossil species within these genera also seem to mirror similar environmental controls. Generalized environmental interpretations regarding depth, productivity, and oxidation levels were reconstructed from these genera wherever possible.

Population characteristics of the entire foraminiferal assemblage that can be used for paleoenvironmental analysis include benthic species diversity and the planktonic/

benthic ratio. Gibson and Buzas (1973) conducted studies on species diversity, and Gibson (1988, 1989) studied planktonic/benthic ratios. Both sets of studies show that patterns of these assemblage characteristics found with increasing water depth are similar between the early and middle Cenozoic faunas of the Atlantic and eastern Gulf Coastal Plains and the modern faunas of the western Atlantic Ocean and the Gulf of Mexico.

MILLHAVEN CORE

The Millhaven test hole (33X048) site, lat 32°53'25" N., long 81°35'43" W., is located in Screven County, Ga. (fig. 1). Land surface elevation of the drill site is 110 ft. Twenty-four samples between the depths of 637 and 118 ft were examined for foraminifers (table 1, fig. 2). Foraminifers are present in both lower and upper Paleocene strata of the Ellenton Formation, lower middle Eocene strata of the Congaree and Warley Hill Formations, upper middle Eocene strata of the Santee Limestone, and upper Eocene and possibly lower Oligocene strata of the Barnwell unit in the Millhaven core.

ELLENTON FORMATION

The lower beds of the Ellenton Formation in the Millhaven core, as seen in the lowest foraminiferal sample studied at 636.8 ft, contain a more highly altered and a lower diversity benthic assemblage than the nine samples studied from the middle and upper parts of the formation (631.3 to 581 ft). The lowest sample is of early Paleocene age (lower part of calcareous nannofossil Zone NP 4) as discussed below, and the nine higher samples are of early late Paleocene age (calcareous nannofossil Zone NP 5) (Bybell, this volume, chap. F).

Lower Paleocene beds in the Millhaven core have a thickness of approximately 10 ft or less. These beds apparently represent a relatively thin remnant of a formerly much thicker lower Paleocene deposit in this area that underwent significant erosional removal during the latest early and earliest late Paleocene. Several of the highest Cenozoic sea levels occurred in the early Paleocene (Haq and others, 1987), and deposits representing these extensive seas are found in many areas in the Atlantic Coastal Plain. Studies on Paleogene deposits of western Georgia and eastern Alabama (Gibson, 1992) and Maryland (Gibson and Bybell, 1994) found that these lower Paleocene deposits represented the deepest water deposition and the highest sea levels of any Paleogene unit that is found in those areas. However, the lower Paleocene middle to outer neritic deposits are very patchy in their present-day occurrence in the Atlantic Coastal Plain, which suggests that widespread erosion of these deposits occurred during latest early Paleocene, late Paleocene, and younger times.

The nine samples examined from the higher part of the Ellenton Formation (631.3–581 ft) are of early late Paleocene age (calcareous nannofossil Zone NP 5) according to Bybell (this volume, chap. F). Some benthic foraminiferal species, such as *Cibicides compressus* Olsson, that occur in these samples have their highest occurrences in Virginia and Maryland in strata placed in Zone NP 5 (Nogan, 1964; Bybell and Gibson, 1991), which supports this age assignment.

Five intervals with differing foraminiferal assemblages are present in the formation: (1) a highly altered, low-diversity assemblage of early Paleocene age at 636.8 ft; (2) an assemblage containing apparent mixing of specimens from lower Paleocene beds with early late Paleocene specimens at 631.3 ft; (3) an assemblage suggesting normal productivity and oxygen levels with a probable water depth range of 100 to 200 ft, which occurs at 628.7 ft in clayey glauconitic sand; (4) an assemblage suggestive of water depths of less than 100 ft but having high-productivity and (or) low-oxygen conditions, which occurs in dark clay samples from 621.2 to 599.1 ft; and (5) an assemblage suggestive of water depths of less than 100 ft with normal marine oxygen conditions in samples from 593.7 to 581 ft, which occurs in calcareous and clayey sand beds.

636.8 ft (early Paleocene).—The sample from 636.8 ft contains relatively few specimens of a low-diversity assemblage of highly corroded foraminifers, most of which have calcite rhombohedrons attached to their tests. The poor preservation precludes definitive identifications of some specimens beyond the generic level.

Cibicides compressus Olsson, *Bulimina* sp., *Cibicides* sp., and *Gyroidina* sp. are present in the benthic foraminiferal assemblage. *Cibicides compressus* Olsson occurs in both lower and lower upper Paleocene strata in Virginia and Maryland (Nogan, 1964; Thomas Gibson, unpub. data). The highly altered specimens and the few species present in the assemblage suggest that much of the original assemblage was removed during diagenesis. Extensive diagenesis could be expected as this sample is near the top of the lower Paleocene beds. There is a disconformity between lower Paleocene and lower upper Paleocene strata located somewhere between this sample and the overlying sample at 631.3 ft. Subaerial exposure of these beds was likely during the formation of the disconformity.

The foraminiferal assemblage also contains recognizable specimens of the important planktonic species *Globoconusa daubjergensis* (Bronnimann). This planktonic species ranges through much of the early Paleocene (planktonic foraminiferal Zone P1, Danian) but does not range into the latest early Paleocene (Toumarkine and Luterbacher, 1985; Berggren and others, 1995). Bybell (this volume, chap. F), on the basis of the calcareous nannofossils, places this sample interval into calcareous nannofossil Zone NP 4, which is of latest early Paleocene and earliest late Paleocene age (Berggren and others, 1995). The presence of

Table 1. Sedimentary characteristics of foraminiferal samples from the Millhaven core.

Sample depth (ft)	Sedimentary characteristics
	Barnwell unit
118 ----------	Calcareous sand; 71 percent sand size by weight; sand fraction consists of abundant recrystallized shell fragments and bryozoan fragments with about 10 percent quartz; trace of glauconite.
219 ----------	Calcareous quartz silty sand; 87 percent sand size by weight; sand fraction consists of 70 percent quartz, 20 percent calcareous grains, and 10 percent shell fragments.
	Santee Limestone
248 ----------	Calcareous sand; 73 percent sand size by weight; sand fraction consists of 85 percent carbonate and 15 percent glauconite; just traces of shell debris and quartz.
307 ----------	Limestone with some recrystallized shell fragments and a trace of pyrite.
346 ----------	Calcareous unit with trace of glauconite.
355 ----------	Calcareous unit with traces of quartz and glauconite.
365 ----------	Calcareous unit with 15 percent glauconite.
	Warley Hill Formation
404 ----------	Calcareous quartz sand; 85 percent sand size by weight; sand fraction consists of 45 percent carbonate, 30 percent quartz, and 25 percent shell fragments.
413 ----------	Calcareous quartz sand; 84 percent sand size by weight; sand fraction consists of 55 percent quartz, 40 percent carbonate, and 5 percent glauconite.
426.5 --------	Calcareous unit with 10 percent glauconite and 5 percent pyrite, trace of quartz.
456 ----------	Calcareous unit with 20 percent glauconite, 10 percent shell hash, and 5 percent quartz.
	Congaree Formation
473.5 --------	Quartz sand, 88 percent sand size by weight; sand fraction consists of 60 percent quartz and 40 percent glauconite.
481.5 --------	Quartz sand, 90 percent sand size by weight; sand fraction consists of 55 percent quartz and 45 percent glauconite.
495.5 --------	Quartz sand, 95 percent sand size by weight; sand fraction consists of 85 percent quartz and 15 percent glauconite with a trace of phosphate.
	Ellenton Formation[1]
581 ----------	Calcareous unit with 20 percent shell fragments and 10 percent quartz.
589 ----------	Calcareous unit with 15 percent shell fragments.
593.7 --------	Clayey very fine sand, discontinuous clay laminae, very shelly including small oyster.
	[At 595.2 ft, there appears to be burrowed contact of sand into underlying clay]
599.1 --------	Dark clay, thin discontinuous sand lenses, highly bioturbated, small clam shells.
609.8 --------	Dark clay, thin discontinuous sand lenses, highly bioturbated.
613.1 --------	Dark clay, thin discontinuous sand lenses, highly bioturbated.
621.2 --------	Dark clay, thin discontinuous sand lenses, highly bioturbated.
	[At 622.4 ft, there is a rapid downward change with no noticeable break from clay to quite glauconitic medium sand, mostly slightly indurated; this change occurs with a gradual downward decrease in the amount of clay over the upper 2 ft to considerably lower levels]
628.7 --------	Clayey glauconitic fine to medium sand with the more sandy intervals being somewhat indurated.
631.3 --------	Clayey glauconitic fine to medium sand.
636.8 --------	Clayey glauconitic fine to coarse sand.

[1]The Snapp Formation was cored above the Ellenton Formation from 570 to 504 ft in the Millhaven core; no foraminifers were observed and no samples were taken.

G. daubjergensis (Bronnimann) indicates that this interval belongs to the older, or early Paleocene, part of calcareous nannofossil Zone NP 4 (Berggren and others, 1995).

The probable diagenetic removal of much of the assemblage makes a meaningful paleoenvironmental interpretation of the sample difficult. However, the moderate abundance of the more dissolution susceptible planktonic specimens suggests that planktonic specimens were abundant and that this sample reflects a relatively offshore environment.

631.3 ft (late Paleocene with mixing of early Paleocene specimens).—The sample from 631.3 ft contains shallow-marine benthic foraminiferal species that are similar to those found in Paleocene strata to the north. Benthic taxa present include *Lenticulina*, *Hanzawaia*, *Cibicides compressus* Olsson, *Cibicides neelyi* Jennings, *Cibicides* sp., *Pulsiphonina prima* (Plummer), *Gyroidina*, *Alabamina*, and *Nodosaria latejugata carolinensis* Cushman. These taxa occur both in lower and lower upper Paleocene strata in North Carolina, Virginia, and Maryland (Nogan, 1964; Gibson and others, 1980, Thomas Gibson, unpub. data).

The calcareous nannofossil assemblage occurring in this sample suggests placement in Zone NP 5 of the lower upper Paleocene (Bybell, this volume, chap. F). However, this sample also contains moderately abundant lower Paleocene planktonic foraminifers including *Globoconusa daubjergensis* (Bronnimann) and *Morozovella pseudobulloides* (Plummer). The presence of a calcareous nannofossil assemblage that is indicative of an early late Paleocene age suggests that the early Paleocene planktonic foraminifers in this sample have been reworked from underlying lower Paleocene deposits. The reworking of early Paleocene planktonic foraminifers into lower upper Paleocene beds placed in Zone NP 5 is seen in other localities in the Atlantic Coastal Plain (Thomas Gibson, unpub. data). As discussed above, much of the lower Paleocene material appears to have been removed through erosion from the Millhaven test hole site.

Relatively deep water depositional environments are present during some intervals of Zones NP 3 and NP 4 of the early Paleocene. Foraminiferal assemblages from these intervals in the Atlantic Coastal Plain deposits thus contain abundant planktonic specimens, mostly composed of *G. daubjergensis* (Bronnimann) and *M. pseudobulloides* (Plummer) (Thomas Gibson and Laurel Bybell, unpub. data). The abundant planktonic specimens apparently are reworked from these lower Paleocene deposits and incorporated into the lower part of the strata that formed during the widespread marine transgression of Zone NP 5 in the early late Paleocene. The exact location in the Millhaven core of the disconformable contact between the two different age units within the Ellenton is uncertain, but apparently occurs somewhere between 636.8 and 631.3 ft.

For the Millhaven core, I consider a similar reworking of lower Paleocene planktonic foraminifers into basal transgressive beds of the lower upper Paleocene more likely than either of two other interpretations for the age disparity. These basal transgressive beds contain calcareous nannofossils indicative of Zone NP 5. One other interpretation for the age disparity is downhole contamination of early late Paleocene calcareous nannofossils into lower Paleocene strata. Another is an unrecognized disconformity that could have separated the foraminiferal and nannofossil samples taken from the core segment from 631.3–631.6 ft (whether the two samples were taken from opposite ends of this core segment or both from the same end is unknown and undeterminable).

628.7 ft (late Paleocene).—The sample from 628.7 ft contains a well-preserved and diverse benthic assemblage. Benthic taxa include *Hanzawaia*, *Cibicides compressus* Olsson, *Lenticulina*, *Alabamina*, *Pulsiphonina prima* (Plummer), *Eponides lotus* (Schwager), *Nodosaria latejugata carolinensis* Cushman, *Pseudonodosaria tenuistriata* (Franke), *Spiroplectammina wilcoxensis* Cushman and Ponton, *Loxostomum*, *Nodogenerina plummerae* (Cushman), *Epistominella minuta* (Olsson), *Bolivinopsis emmendorferi* (Jennings), *Pararotalia perclara* (Loeblich and Tappan), and *Pyramidina virginiana* (Cushman). This assemblage is characteristic of the lowermost part of the Aquia Formation in Virginia and Maryland (Nogan, 1964; Thomas Gibson, unpub. data). Some of these species also range into the middle part of the Aquia Formation. The lowermost beds of the Aquia Formation are placed in calcareous nannoplankton Zone NP 5 of the lower upper Paleocene; the middle beds extend from Zone NP 6 to NP 8 (Gibson and others, 1991). Planktonic specimens make up a small proportion of the assemblage. The foraminiferal assemblage suggests shallow-marine environments having water depths less than 200 ft, but possibly in the 100-ft or slightly deeper range. Normal marine productivity and oxygen levels were present.

621.2 ft (late Paleocene).—The sample from 621.2 ft contains a well-preserved and moderately diverse assemblage that differs considerably from the underlying assemblages. Benthic taxa include *Epistominella minuta* (Olsson), *Fursenkoina*, *Pararotalia perclara* (Loeblich and Tappan), *Pulsiphonina prima* (Plummer), and *Pyramidina virginiana* (Cushman). *Pararotalia perclara* (Loeblich and Tappan) is commonly found in Paleocene strata, but it is not found in beds younger than those placed in calcareous nannofossil Zone NP 8 in Virginia and Maryland (Thomas Gibson, unpub. data). The assemblage suggests shallow-marine environments having water depths around 100 ft or shallower. The above-noted species dominate the assemblage. Their abundance suggests high-productivity and (or) low-oxygen depositional environments for the interval containing this sample and the three overlying ones. This is in contrast to the relatively normally oxygenated environments that are characteristic of samples below 621.2 ft. The high-productivity and (or) low-oxygen assemblages occur in a dark clay interval, which contrasts with the underlying

interval of clayey, glauconitic, fine to medium sand. The dark color of the clay also supports the idea that low-oxygen environments were present that would lead to increased preservation of organic matter in the sediments.

613.1 ft (late Paleocene).—The well-preserved assemblage from 613.1 ft contains a relatively low diversity benthic component with few planktonic specimens. The benthic assemblage is dominated by *Pararotalia perclara* (Loeblich and Tappan) and *Fursenkoina*, with lesser proportions of *Epistominella minuta* (Olsson), *Pulsiphonina prima* (Plummer), and *Pyramidina virginiana* (Cushman). This benthic assemblage is similar to that of the underlying sample. These species are either characteristic of, or found in, high-productivity or low-oxygen environments (Poag, 1989; Gibson and others, 1993; Thomas Gibson, unpub. data).

609.8 ft (late Paleocene).—The benthic assemblage from 609.8 ft is well preserved but shows relatively low species diversity. The composition is similar to the two underlying assemblages, with *Pararotalia perclara* (Loeblich and Tappan) and *Fursenkoina* being dominant.

599.1 ft (late Paleocene).—The well-preserved benthic assemblage from 599.1 ft has relatively low species diversity and is highly dominated by *Pararotalia perclara* (Loeblich and Tappan). Other abundant species include *Epistominella minuta* (Olsson), *Fursenkoina*, and *Pyramidina virginiana* (Cushman). The assemblage is similar to those of the underlying three samples and suggests shallow-marine environments of about 100-ft water depth or less with high-productivity and (or) low-oxygen conditions.

Burrowed contact.—At 595.2 ft, there appears to be a burrowed contact of overlying clayey very fine sand into the dark clay unit. The foraminiferal assemblages above and below this surface differ considerably.

593.7 ft (late Paleocene).—The sample from 593.7 ft contains a low-diversity benthic assemblage consisting of moderately well preserved to slightly recrystallized specimens, and it also contains a few planktonic specimens. The assemblage is highly dominated by *Anomalinoides umboniferus* (Schwager) and also contains *Cibicides alleni* (Plummer), *Gyroidinoides*, *Pyramidina virginiana* (Cushman), and *Buliminella elegantissima* (d'Orbigny). These species commonly occur in upper Paleocene deposits, but most of them also occur in lower Eocene and younger strata. The assemblage is characteristic of shallow-marine environments having water depths less than 100 ft. The assemblage differs from those in the underlying four samples by the presence of *A. umboniferus* and *C. alleni*, which are characteristic of more oxygenated waters. This change suggests that the burrowed surface at 595.2 ft separates two differing depositional settings.

589 ft (late Paleocene).—The small benthic assemblage from 589 ft consists of moderately well preserved to partially recrystallized specimens. The low-diversity assemblage is highly dominated by *Anomalinoides umboniferus* (Schwager) with lesser numbers of *Pyramidina virginiana* (Cushman). The assemblage is characteristic of shallow-marine environments of less than 100-ft water depth.

581 ft (late Paleocene).—The small benthic assemblage from 581 ft consists of moderately well preserved to partially recrystallized specimens. The low-diversity assemblage is dominated by *Anomalinoides umboniferus* (Schwager) with lesser numbers of *Pyramidina virginiana* (Cushman), compositionally similar to the two underlying samples. However, the proportion of *Pararotalia perclara* (Loeblich and Tappan) is considerably higher than found in the underlying samples. The increase in *P. perclara* (Loeblich and Tappan) in this sample possibly signifies that somewhat higher productivity and (or) lower oxygen levels were present.

SNAPP FORMATION

The Snapp Formation was cored above the Ellenton Formation from 570 to 504 ft in the Millhaven test hole. No foraminifers were observed and no samples were taken.

CONGAREE FORMATION

Three samples of the Congaree Formation from the Millhaven test hole were examined; they came from between depths of 495.5 and 473.5 ft. Benthic foraminiferal species characteristic of middle Eocene strata in the Southeastern United States, such as *Cibicides westi* Howe, *Siphonina claibornensis* Cushman, *Cancris involutus* Copeland, and *Guembelitria columbriana* Howe occur in these samples. Bybell (this volume, chap. F) placed these Congaree samples in calcareous nannofossil Zone NP 14 (earliest middle Eocene).

Foraminiferal assemblages in the lower and upper Congaree samples suggest shallow-marine environments with water depths of approximately 100 ft. However, a considerably deeper water pulse with water depths of around 300 ft is suggested by the assemblage in the middle sample at 481.5 ft.

The Congaree samples, which are placed in calcareous nannofossil Zone NP 14 by Bybell (this volume, chap. F), contain much greater amounts of sand-sized particles (mostly very fine to fine grained, with both quartz and glauconite being abundant) (table 1), than do the calcareous samples from the overlying Warley Hill Formation.

495.5 ft (middle Eocene).—The sample from 495.5 ft contains a moderately well preserved, moderately diverse benthic assemblage that contains a few adult planktonic specimens. The most common or diagnostic benthic taxa are *Cibicides westi* Howe, *Cibicides* sp., *Gyroidinoides*, *Siphonina claibornensis* Cushman, *Eponides lotus* (Schwager), and *Anomalinoides umboniferus* (Schwager). *Siphonina claibornensis* Cushman has its initial appearance in the Southeastern United States in strata placed in calcareous

nannofossil Zone NP 13 of the late early Eocene. This species survives into the late Eocene (Thomas Gibson, unpub. data). The joint occurrence of this species and *C. westi* Howe, which is characteristic of the middle Eocene, suggests a middle Eocene age for the sample. The assemblage suggests fairly shallow marine environments having water depths of approximately 100 ft.

481.5 ft (middle Eocene).—The sample from 481.5 ft contains a moderately well preserved and moderately diverse benthic assemblage, and it also contains a moderate number of planktonic specimens. Benthic taxa include *Gyroidina*, *Siphonina claibornensis* Cushman, *Cibicides westi* Howe, *Cibicides alleni* (Plummer), *Cibicidoides* sp., *Cancris involutus* Copeland, *Eponides lotus* (Schwager), *Trifarina*, *Bulimina*, *Bolivina*, and *Guembelitria columbiana* Howe. *Pseudohastigerina micra* (Cole) and *Acarinina* spp. compose the planktonic component. The presence of *Cibicides westi* Howe, *Cancris involutus* Copeland (which occurs in middle Eocene beds in North Carolina, Jones, 1983), and *Guembelitria columbiana* Howe indicates a middle Eocene age. The composition of the benthic assemblage and the relative abundance and diversity of planktonic specimens, including the presence of common adult forms, suggest deposition in middle neritic environments with water depths of approximately 300 ft. This interpreted depth is significantly greater than that proposed for the underlying sample. This projected depth increase is accompanied by an increase in glauconite content to 45 percent of the sand fraction from 15 percent in the lower sample.

473.5 ft (middle Eocene).—Most specimens in the sample from 473.5 ft are recrystallized to a lesser or greater degree. The species diversity of the benthic assemblage is moderately low, and some planktonic specimens are present. Important benthic taxa include *Cibicides westi* Howe, *Eponides lotus* (Schwager), *Eponides carolinensis* Cushman, *Bulimina*, *Bolivina*, *Lenticulina*, and *Valvulineria involuta* Cushman and Dusenbury. The benthic assemblage, plus the occurrence of the planktonic species *Pseudohastigerina micra* (Cole), places this sample in the middle Eocene. The assemblage suggests deposition in water depths of approximately 100 ft or slightly deeper, which represents a considerable shallowing from the underlying sample. Glauconite remains an important constituent in the sample, but it is less abundant than in the underlying sample.

WARLEY HILL FORMATION

Four Warley Hill samples were examined between depths of 456 and 404 ft in the Millhaven core. Benthic foraminiferal species that are characteristic of middle Eocene strata in the Southeastern United States, such as *Cibicides westi* Howe and *Guembelitria columbiana* Howe, occur in these samples. Bybell (this volume, chap. F) placed the Warley Hill in Zone NP 15 (early middle Eocene).

Foraminiferal assemblages in most of these samples suggest shallow-marine environments with water depths of approximately 100 ft with even shallower depths for the uppermost sample.

The Warley Hill samples from 413 and 404 ft are calcareous quartz sands, but they contain much more carbonate matrix and carbonate sand grains, less glauconite and quartz, and somewhat coarser sand grains than do samples in the quartz sand of the Congaree Formation. Shell fragments are present in large amounts in the uppermost sample at 404 ft, which supports the interpretation of very shallow marine environments for this interval.

456 ft (middle Eocene).—The specimens in the sample from 456 ft range from moderately well preserved to slightly recrystallized. Benthic species diversity is moderate, and there are some planktonic specimens. Benthic species found include *Valvulineria involuta* Cushman and Dusenbury, *Eponides carolinensis* Cushman, *Eponides lotus* (Schwager), *Cibicides westi* Howe, *Gyroidinoides octocameratus* (Cushman and Hanna), *Hanzawaia*, and *Caucasina*. These benthic taxa place this sample in the middle Eocene. The depositional environment had water depths around 100 ft or slightly deeper.

426.5 ft (middle Eocene).—The foraminifers in the sample from 426.5 ft are moderately well preserved. The assemblage has a moderately low species diversity and contains a moderately low number of planktonic specimens. Important benthic taxa include *Gyroidinoides octocameratus* (Cushman and Hanna), *Cibicides westi* Howe, *Eponides lotus* (Schwager), *Guembelitria columbiana* Howe, and *Caucasina*. The benthic species suggest a middle Eocene age. The assemblage suggests deposition in water depths of approximately 100 ft or slightly deeper.

413 ft (middle Eocene).—The sample from 413 ft contains a moderately diverse benthic assemblage in which most specimens are slightly recrystallized. A few planktonic specimens are present. Important benthic taxa present in the sample include *Gyroidinoides octocameratus* (Cushman and Hanna), *Cancris involutus* Copeland, *Cibicides westi* Howe, *Valvulineria involuta* Cushman and Dusenbury, *Eponides lotus* (Schwager), and *Guembelitria columbiana* Howe. These benthic species indicate a middle Eocene age for the sample. The assemblage suggests a depositional environment with water depths of approximately 100 ft.

404 ft (middle Eocene).—Most foraminifers in the sample from 404 ft are slightly recrystallized. The species diversity is moderately low. The benthic assemblage contains *Cibicides westi* Howe, *Cibicides* sp., *Gyroidinoides octocamerata* (Cushman and Hanna), *Valvulineria involuta* Cushman and Dusenbury, *Eponides carolinensis* Cushman, *Eponides ouachitaensis* Howe and Wallace, and *Textularia*. There are only a few planktonic specimens. The presence of *C. westi* Howe and other benthic species indicates a middle

Eocene age. The assemblage suggests warm, shallow-marine waters, probably within the shallower part of a 0- to 100-ft depth range.

SANTEE LIMESTONE

Five samples were examined from the Santee Limestone, between the depths of 365 and 248 ft in the Millhaven core; all samples are placed by Bybell (this volume, chap. F) in calcareous nannofossil Zone NP 17 (upper middle Eocene). Most of these samples contain *Cibicides westi* Howe and *Siphonina claibornensis* Cushman; the co-occurrence of these benthic species is characteristic of middle Eocene strata in the Southeastern United States.

The lower three samples are from soft calcareous beds and contain a slightly recrystallized but diverse foraminiferal fauna that suggests water depths of 100 to 200 ft. Foraminifers in the upper two samples (limestone and calcareous sand) are highly recrystallized; the relatively few recognizable specimens suggest possibly slightly shallower water depths of 100 ft or less.

365 ft (late middle Eocene).—Most foraminifers in the sample from 365 ft are slightly recrystallized. A diverse benthic assemblage is present, including *Pseudononion*, *Cibicides westi* Howe, *Cibicides* sp., *Siphonina claibornensis* Cushman, *Gyroidinoides octocameratus* (Cushman and Hanna), *Bolivina*, *Lagena*, *Textularia*, *Pyramidina*, *Trifarina*, and *Uvigerina*. A moderate number of planktonic specimens are present, including *Pseudohastigerina micra* (Cole) and *Cheiloguembelina*. The foraminiferal assemblage suggests water depths of 100 to 200 ft. This assemblage is similar to those found in the two overlying samples of the Santee Limestone. These assemblages suggest slightly deeper water environments than those found in the underlying sample from the upper part of the Warley Hill Formation.

355 ft (late middle Eocene).—The foraminifers in the sample from 355 ft are slightly to moderately recrystallized. A diverse benthic assemblage similar to that of the underlying sample is present, along with a small to moderate proportion of planktonic specimens. *Cibicides westi* Howe, *Pseudononion*, *Siphonina claibornensis* Cushman, *Gyroidinoides octocameratus* (Cushman and Hanna), *Pyramidina*, and *Lagena*, are present among other benthic taxa. The assemblage suggests water depths of 100 to 200 ft.

346 ft (late middle Eocene).—The foraminifers in the sample from 346 ft range from moderately well preserved to slightly recrystallized. A diverse benthic assemblage includes *Pseudononion*, *Cibicides westi* Howe, *Gyroidinoides octocameratus* (Cushman and Hanna), *Siphonina claibornensis* Cushman, *Valvulineria*, *Nonionella*, *Anomalinoides*, *Hanzawaia*, *Bolivina*, *Pararotalia*, *Trifarina*, *Textularia*, *Spiroplectammina*, *Guembelitria columbiana* Howe, and *Lagena*. A small proportion of planktonic specimens is present. This assemblage, as well as the underlying two, suggests water depths between 100 to 200 ft, which are slightly deeper than any interpreted for age-equivalent strata in the limited number of samples from the Millers Pond core.

307 ft (late middle Eocene).—Only a few highly recrystallized foraminifers are present in the sample from 307 ft. Identifiable benthic taxa include *Cibicides westi*, *Cibicides* sp., *Cibicidoides* sp., *Elphidium*, and *Nonion*. The identifiable assemblage suggests shallow waters with depths of 0 to 100 ft.

248 ft (late middle Eocene).—A few highly recrystallized foraminifer specimens are present in the sample from 248 ft. *Cibicides* and *Quinqueloculina* are the most abundant genera. No planktonic specimens or any age-diagnostic benthic taxa were recognized. The preserved assemblage suggests warm-water environments with depths of probably less than 100 ft.

BARNWELL UNIT

The lower sample examined from the Barnwell unit at 219 ft in the Millhaven core did not contain foraminifers. The upper sample examined from the Barnwell unit is considered either latest Eocene or earliest Oligocene in age (Bybell, this volume, chap. F).

118 ft (latest Eocene or earliest Oligocene).—The foraminifers in the sample from 118 ft are moderately to highly recrystallized. *Cibicides* is the most abundant benthic taxon, and lesser numbers of *Siphonina*, *Gyroidinoides*, and *Eponides* are present. A small proportion of adult planktonic foraminifers is present. No age-diagnostic taxa were noted. The assemblage suggests shallow-marine environments, probably in the deeper portion of the 0- to 100-ft depth interval.

MILLERS POND CORE

The continuously cored Millers Pond test hole (GGS–3758, Burke 2) in Burke County, Ga. (fig. 1), penetrated Upper Cretaceous through upper Eocene deposits. The land surface elevation is 245 ft at the drill site. The site is located at lat 33°13'48" N., long 81°52'44" W. This test hole is in a more upbasin location than is the Millhaven test hole, and beds containing calcareous microfossils are much less numerous. Only three Cenozoic samples, between a depth of 148 and 82 ft, yielded foraminifers (table 2, fig. 3). Foraminifers in all three assemblages are moderately to highly recrystallized. The three samples are from strata placed in the Santee Limestone of middle Eocene age (Falls and Prowell, this volume, chap. A). The uppermost sample at 82–83 ft is in carbonate-rich quartzose sand of the upper Three Runs Aquifer of Clarke and others (1994). The underlying samples from 148 ft and 120 ft are in carbonate-rich

Table 2. Sedimentary characteristics of foraminiferal samples from the Millers Pond core.

Sample depth (ft)	Sedimentary characteristics
	Santee Limestone
82–83	Carbonate-rich quartzose sand; 59 percent sand size by weight; quartz composes 75 percent of the sand-sized material with carbonate as the remainder; quartz is very angular to angular; echinoid spines present; no glauconite present, but there are trace amounts of red jasper and obsidian.
120	Carbonate sand; 77 percent sand size by weight, and all is carbonate; echinoid spines present; no glauconite present.
148	Calcareous silty sand; 93 percent sand size by weight; sand fraction mostly carbonate with only 5 percent angular to subangular quartz; no glauconite present, but there are trace amounts of obsidian and chalcopyrite.

and quartz-poor sediments of the lower confining unit of this aquifer system. The general lithologic nature of each sample and the most important foraminiferal components of each sample are given below. More detailed sedimentologic information is in table 2.

SANTEE LIMESTONE

Most foraminifers from the Santee Limestone in the Millers Pond core are moderately to highly recrystallized. The identifiable taxa suggest shallow-marine environments with water depths of 100 ft or shallower for the calcareous sediments of the three samples from the Santee Limestone. There is considerable variability in the proportion of quartz grains in these sands.

148 ft (middle Eocene).—The sample from 148 ft is a calcareous, slightly silty sand that contains a small amount (5 percent) of quartz. Few foraminifers are present, and most of these are poorly preserved. The specimens mainly belong to several species of *Cibicides* (but *C. westi* Howe is not present) with a few poorly preserved miliolid specimens probably belonging to *Quinqueloculina*. No species known to be significant biostratigraphically were recognized in the assemblage.

Because of the poor state of preservation and the likely removal of some or many species of the original foraminiferal assemblage, little definitive interpretation of the paleoenvironments is possible. The species found in the sample are in keeping with a warm marine environment with water depths of less than 100 ft as found for the overlying two samples discussed below.

120 ft (middle Eocene).—The sample from 120 ft is a carbonate sand that does not contain quartz grains. Foraminiferal specimen preservation ranges from moderately to highly recrystallized. This assemblage contains more genera than noted in the overlying sample at 82–83 ft, but this higher diversity may reflect only the better preservation that is present in this sample. The dominant benthic forms belong to *Hanzawaia* and *Cibicides*, but the sample also contains *Nonion*, *Elphidium*, *Bolivina*, *Lenticulina*, *Globocassidulina*, *Gyroidina*, and *Cibicides westi* Howe. *Pseudohastigerina micra* (Cole) is the only planktonic species noted. *Cibicides westi* Howe is characteristic of middle Eocene strata in the Southeastern United States, being found in the Lisbon and Gosport Formations in Alabama (Bandy, 1949), other middle Eocene strata in Georgia (Herrick, 1961), and middle Eocene strata in North Carolina (Jones, 1983). The presence of this species suggests a middle Eocene age for this sample.

The generic composition of the benthic foraminiferal assemblage and the presence of only a few planktonic specimens suggests shallow-marine, probably well-oxygenated depositional environments having water depths less than 100 ft. The faunal similarity to Alabama middle Eocene faunas and the carbonate substrate suggest warm temperate to subtropical paleotemperatures. The abundance of *Cibicides* and *Hanzawaia* specimens and the presence of echinoid spines in the sample suggest a relatively firm substrate during deposition. The absence of glauconite in the sample may suggest moderately high sedimentation rates, as the apparently open marine conditions would not preclude glauconite formation, which was common in this time interval in other areas in the Southeastern United States.

82–83 ft (middle Eocene).—The sample from 82–83 ft is a carbonate-rich quartzose sand. The benthic assemblage is moderately to highly recrystallized, which makes it difficult to identify specimens to the species level. The benthic assemblage is dominated by taxa of *Discorbis*, *Hanzawaia*, *Elphidium*, *Nonion*, *Cibicides*, *Cancris*, and *Textularia*. The sample contains common specimens of *Cibicides westi* Howe, which is characteristic of middle Eocene strata, and *Cancris involutus* Copeland, which is found in middle Eocene beds in North Carolina (Jones, 1983). No planktonic specimens were noted.

The generic composition of the foraminiferal assemblage suggests a shallow-marine, probably well-oxygenated depositional environment having water depths less than 100 ft, similar to that proposed for the underlying sample. A significant quartzose sand component is present in this sample in contrast with its absence in the underlying two samples. Its presence suggests possible shallowing of the marine

environment or a change in the sediment source, transportation system, or energy level in the depositional regime of this interval.

CONCLUSIONS

Foraminiferal assemblages indicative of late early and early late Paleocene and middle Eocene ages are present in the more downbasin Millhaven test hole. A late early Paleocene age assignment for the lowest beds of the Ellenton Formation is based on the co-occurrence of planktonic foraminiferal taxa and calcareous nannofossil taxa. Early late Paleocene and middle Eocene age assignments are based on the ranges of benthic foraminiferal taxa in the Southeastern United States. More detailed age assignments of the strata on the basis of the foraminifers are not possible. This is because the ranges of most benthic taxa in terms of the intercontinental zonations, which are largely based upon planktonic microfossils, are not yet known, and diagnostic planktonic foraminiferal species are not present in most beds. Detailed age assignments of most foraminifer-bearing beds were possible, however, on the basis of the calcareous nannofossils (Bybell, this volume, chap. F).

In the Millhaven core, one sample from the Ellenton Formation contains both early Paleocene planktonic foraminiferal specimens and calcareous nannofossils diagnostic of the lower part of the upper Paleocene. The planktonic foraminifers apparently were derived during erosional removal of lower Paleocene strata in this area and reworked into the basal part of the lower upper Paleocene transgressive sequence. Lower Paleocene strata that are now eroded from this area apparently represent middle to outer neritic environments because the reworked assemblages are dominated by planktonic specimens. Similar situations of abundant deeper water lower Paleocene specimens being reworked into shallow-water lower upper Paleocene beds are also present in Atlantic Coastal Plain deposits in North Carolina and Virginia.

In the more upbasin Millers Pond core, foraminiferal assemblages were obtained only from the Santee Limestone. The assemblages contain benthic species characteristic of a middle Eocene age.

Most foraminifer-bearing beds examined in the two cores were deposited in inner neritic (0- to 100-ft water depth) to inner-middle neritic (100- to 200-ft water depth) environments. One interval in the Congaree Formation, in the early middle Eocene, at 481.5 ft, contains assemblages suggestive of deeper water environments with depths around 300 ft. Some intervals in the upper middle Eocene strata of the Santee Limestone in the more southeasterly, more downbasin Millhaven core suggest slightly deeper water environments (inner-middle neritic) than presumably coeval inner neritic strata of the Santee Limestone, which is found in the more northwesterly, more upbasin Millers Pond core. This paleobathymetric interpretation suggests that the upbasin-downbasin relationship now present in these two cores is similar to that present during the middle Eocene.

Depositional environments generally had near-normal to normal oxygenation levels except for an interval in early late Paleocene time. This interval is represented by beds of the Ellenton Formation where high-nutrient and (or) low-oxygen environments were present as reflected by the benthic foraminiferal assemblage. The sediments in this interval, however, are bioturbated and contain some small clam shells, so oxidation levels were not so low as to preclude some bottom organic activity.

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