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

Overview of the Biostratigraphy and Paleoecology of Sediments from Five Cores from Screven and Burke Counties, Georgia

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ABSTRACT

Five cores from Screven and Burke Counties, Georgia, form the basis for a multifaceted paleontological study of Cretaceous and Tertiary coastal plain sediments. The biostratigraphy and paleoecology of these cores are summarized within the lithostratigraphic framework given in this volume. The basal Cretaceous unit, the Cape Fear Formation, is of probable Coniacian age and is nonmarine. The Middendorf Formation may represent similar lithofacies of different ages, one representing undifferentiated pollen Zone V (late Coniacian and Santonian) and one slightly younger (latest Santonian(?) or early Campanian). The Black Creek Group is Campanian. It is marginal marine to nonmarine in its lower part (subunit 1). In all but the most updip core, subunit 2 of the Black Creek contains Campanian marine sediments. Subunit 3 of the Black Creek shows a marine influence in the most basinward (downdip) Millhaven core. The Steel Creek Formation is Maastrichtian in the Millhaven core and is nonmarine except for its lowest part.

The basal Tertiary unit, the Ellenton Formation, is of early, early late, and middle late Paleocene age. It is marine throughout the study area. The overlying Snapp Formation yields pollen of late, but not latest, Paleocene age. It is mostly nonmarine but contains rare marginal marine palynomorphs. The Fourmile Branch Formation, present only in the Girard and Thompson Oak cores, is a marine unit of early Eocene age. The Congaree Formation is of early middle Eocene age and is present and contains marine fossils in all five cores. The middle Eocene Warley Hill Formation is present only in the Millhaven core. These sediments probably were deposited in less than 100 ft of water. The Santee Limestone is of late middle Eocene age. Foraminifers indicate inferred water depths of less than 200 ft. The Barnwell unit is difficult to date paleontologically but is late Eocene and questionably early Oligocene and is marine. This chapter contains highlights from the individual chapters in this volume.

INTRODUCTION

At the Savannah River Site (SRS) in Aiken, Barnwell, and Allendale Counties, S.C., various hazardous materials have been manufactured, disposed of, and stored since the early 1950's. Ground-water contamination has been detected on the site, and the potential exists for contamination in areas adjacent to the site. In 1991, the U.S. Department of Energy (DOE) funded a multidisciplinary study by the U.S. Geological Survey (USGS) to determine whether ground water flows from the SRS through aquifers in South Carolina into aquifers in Georgia and to determine under what pumping scenarios such flow could occur in the future. Following the detection of tritium in a public water supply well in Burke County, Ga., additional DOE funding was provided to the Georgia Geologic Survey (GGS) of the Georgia Department of Natural Resources for subsurface investigations (Clarke and others, 1994; Summerour and others, 1994).

Accurate ground-water modeling in the Atlantic Coastal Plain depends on an understanding of the stratigraphy. Numerous investigations of subsurface stratigraphy have been conducted in western South Carolina, from Siple (1967) to Fallaw and Price (1995), but relatively little has been published about the subsurface of eastern Georgia (Prowell and others, 1985; Huddlestun and Summerour, 1996). In order to understand the stratigraphy in eastern Georgia, detailed paleontological investigations were under-taken. In 1991, we began our investigation of the Millers Pond core, which had been drilled recently by the GGS in northern Burke County (fig. 1). The USGS drilled two additional test holes—one in northern Screven County (Millhaven test hole) and one in central Burke County (Girard test hole). The cores from these three test holes were designed to serve as the basis for stratigraphic correlation in the area of Georgia adjacent to the SRS. Two other cores, drilled by the GGS, provide additional biostratigraphic information. This report synthesizes the biostratigraphic and paleoecologic investigation of these five cores collected from Burke and Screven Counties, Ga.

The multidisciplinary paleontologic studies summarized here, and described in more detail in the individual chapters that follow, are based on the microfossils found in the cores. Palynomorphs and calcareous-walled microfossils were studied. Palynomorphs include pollen and spores from terrestrial plants, the cysts of marine dinoflagellates, and probable cysts of uncertain origin (acritarchs). Palynomorphs are described in chapters by Frederiksen and others (this volume, chap. C) for Cretaceous sediments and by Edwards (this volume, chap. G) and Frederiksen (this volume, chap. H) for Tertiary sediments. Calcareous microfossils studied here include calcareous nannofossils (Bukry, this volume, chap. D) and ostracodes (Gohn, this volume, chap. E) for Cretaceous material, and calcareous nannofossils (Bybell, this volume, chap. F) and foraminifers (Gibson, this volume, chap. I) for Tertiary material.

Because few readers are familiar with every fossil group, we include a brief introduction to each. For the purpose of formal names of species and genera, palynomorphs and calcareous nannofossils are classified by using the International Code of Botanical Nomenclature (Greuter and others, 1994); ostracodes and foraminifers are classified by using the International Code of Zoological Nomenclature (Ride and others, 1985). Under the botanical code, names of original authors and transferring authors are part of the formal name of a species; under the zoological code, names of original authors are part of the formal name. Under both codes, the name of the original author is placed in parentheses if the species has been reassigned.

POLLEN

Pollen grains are the sperm-carrying reproductive bodies of higher plants; that is, gymnosperms (such as conifers and cycads) and angiosperms (the flowering plants). Pollen grains are very small, typically between 0.01 and 0.1 millimeter (mm) in size.

Pollen grains are produced mostly by plants living in land areas. The first gymnosperms evolved in the Devonian Period (about 385 million years ago), and the first angiosperms evolved from gymnosperms early in the Cretaceous Period (about 140 million years ago). Pollen grains are some of the most abundant fossils to be found in sediments that were deposited on land (terrestrial sediments); however, pollen grains are easily transported by wind and streams to the sea. Therefore, pollen grains are very useful for correlating terrestrial sediments and sedimentary rocks from one place to another, but they are also important for correlating sequences of terrestrial sediments with sequences of marine sediments.

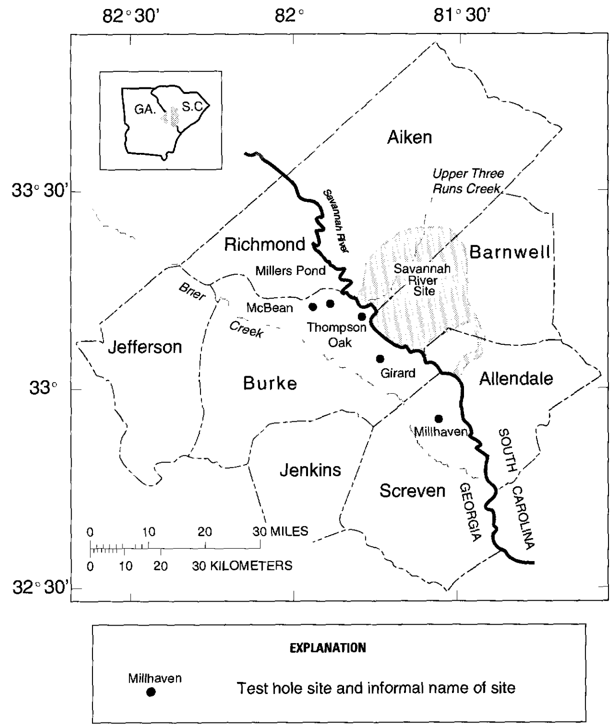

Figure 1. Index map showing the Savannah River Site and the location of test holes in the study area.

The standard pollen zonation for the Upper Cretaceous of the Gulf and Atlantic Coastal Plains was developed in a series of abstracts and papers by various authors and summarized by Christopher (1982a). This zonation was based on material mainly from the Middle Atlantic States. The only pollen zonation for the lower Tertiary of eastern North America was proposed by Frederiksen (1991, 1998) for the Paleocene. This zonation was based on material from the eastern Gulf Coast, but it has also been applied to sections on the Atlantic Coastal Plain (Frederiksen, 1991, 1998). No pollen zonation has been proposed for the Eocene and Oligocene of eastern North America, but chronostratigraphic ranges of the main pollen taxa in the Eocene and Oligocene of this region were displayed by Frederiksen (1979, 1980, 1988).

DINOFLAGELLATES AND ACRITARCHS

Dinoflagellates are single-celled organisms that live in oceans, estuaries, lakes, and ponds. Here, they are considered to be plants because many of them are photosynthetic. Some dinoflagellates are herbivores, carnivores, parasites, or symbionts.

Many dinoflagellates have a complex life cycle that includes a resting stage. During this stage, the organism may live in a very durable capsule called a dinocyst. Nearly all fossil dinoflagellates studied by paleontologists are cysts; however, the genera *Alisogymnium* and *Dinogymnium* in the Cretaceous may be the covering from the motile stage. Nearly all dinocysts that are preserved in the fossil record are from marine dinoflagellates.

Dinoflagellates form distinctive and rapidly evolving fossils that may be found in marine rocks wherever a silt-sized component is present. There is, as yet, no widely accepted standard zonation for them. Important lowest and highest occurrence datums are used to correlate locally and intercontinentally. The presence of fossil dinoflagellates can generally be used to infer marine deposition, and the abundance of dinoflagellates from major taxonomic categories, typically families such as the Peridiniaceae and Areoligeraceae, may be used to infer additional paleoenvironmental conditions.

Acritarchs are, by definition, palynomorphs of uncertain origin. Two distinctive acritarchs are included with the dinoflagellates in the Tertiary study (Edwards, this volume, chap. G).

CALCAREOUS NANNOFOSSILS

Calcareous nannofossils are fossil remains of golden-brown, single-celled algae that live only in the oceans. They are one of the primary organisms at the base of the food chain. These algae make tiny calcite platelets inside their cells. These platelets are the calcareous nannofossils that fall to the ocean bottom and become part of the clay-sized fraction in the sediment. Most calcareous nannofossils are formed by coccolithophorid algae and can also be called coccoliths.

Calcareous nannofossils have been living in the world's oceans from the Triassic Period, and they have evolved and changed rapidly and constantly over time. They are extremely useful for dating marine sediments because existing zonations have a precision of 1 million to 4 million years or even less.

In the last three decades, relatively stable standard biostratigraphic zonations have been developed for calcareous nannofossils. A lowest or highest stratigraphic occurrence (FAD, first appearance datum; LAD, last appearance datum) is used to define the base and top of each zone. For the Cretaceous, we use the biostratigraphic zonation of Perch-Nielsen (1985), modified from Sissingh (1977), in which each zone has a formal name and an informal abbreviation ("CC" followed by a number). For the Cenozoic, we use the zonation of Martini (1971) in which each nannoplankton zone is designated by "NP" followed by a number. Calibration to the Cenozoic zonation of Bukry (1973, 1978) and Okada and Bukry (1980) also is provided.

OSTRACODES

Ostracodes are a group of fossil and modern, small, bivalved crustaceans; modern species inhabit a wide variety of aquatic environments. They are well represented in the fossil record primarily by their hinged, smooth or ornamented, calcified-chitinous valves and are common in marine deposits of the Atlantic Coastal Plain. Typical Cretaceous and Cenozoic forms in the coastal plain range in size from 0.6 mm to 1.1 mm.

Ostracodes are mostly a benthic group. Accordingly, the compositions of ostracode assemblages, and the distributions and morphologies of individual taxa, are strongly influenced by environmental factors, including water depth, turbidity, salinity, oxygen content, and food supply. As a result, ostracode assemblages tend to be useful in the paleoenvironmental analysis of sedimentary sections. They also are useful biostratigraphic indicators in local and regional studies where the effects of paleoenvironmental conditions on species distributions are reasonably well known. The ostracode interval zones of Hazel and Brouwers (1982; modified by Pitakpaivan and Hazel, 1994) are frequently used in biostratigraphic studies of ostracodes from Upper Cretaceous sediments in the Atlantic Coastal Plain.

FORAMINIFERS

Foraminifers are similar to amoeboid organisms in cell structure but differ in having granular rhizopodia and elongate pseudopodia that emerge from the cell body. Foraminifers are covered with an organic test and typically have a wall composed of calcite or an agglomeration of mineral grains embedded in the organic test. Foraminifers are composed of two primary groups: planktonic foraminifers (marine floaters), and benthic foraminifers (sea-floor dwellers). Fossils of both groups are included here.

Benthic foraminiferal morphologies are very diverse, from simple single-chambered to multichambered, complex forms with tests composed of calcite or mineral grains. Benthic foraminifers occupy a wide range of marine environments, from brackish estuaries to the deep ocean basins, and occur at all latitudes. They can be used to infer the salinity and water depths for sedimentary deposits and to recognize oxygen and productivity levels of environments. Planktonic foraminifers, which typically provide more precise age control than benthic species, occur in low numbers in the cores examined in this study; however, they are valuable in the recognition of the upper lower Paleocene strata in the Millhaven core. As is typical in shallow-water deposits, the few planktonic specimens recovered from the remaining samples consist mainly of juvenile individuals.

ACKNOWLEDGMENTS

We thank U.S. Geological Survey colleagues John S. Clarke, W. Fred Falls, R. Farley Fleming, and David C. Prowell, as well as Paul F. Huddlestun (Georgia Geologic Survey, Atlanta) and palynological consultant Joyce Lucas-Clark (Fremont, Calif.) for the sharing of data and ideas and the sometimes lively discussions that helped shape the ideas in this paper. Jonathan R. Bryan (Okaloosa-Walton Community College, Niceville, Fla.) kindly looked at the larger foraminifers from the Millhaven core. We owe many thanks to Raymond A. Christopher (Clemson University) for his willingness to review the entire volume.

MATERIAL AND METHODS

This study is based on the paleontology in five cores in east-central Georgia (fig. 1). They are listed here in order from the most basinward to the most onshore (updip).

- The Millhaven test hole (33X048) was drilled by the U.S. Geological Survey (USGS) in 1991–92 in northern Screven County on the Millhaven Plantation, 2 miles (mi) northeast of Brier Creek and about 7 mi west of the Savannah River at lat 32°53'25" N., long 81°35'43" W. Surface elevation is 110 feet (ft) above sea level. This hole was cored to a depth of 1,452 ft and bottomed in the Upper Cretaceous Cape Fear Formation.
- The Girard test hole (32Y020) was drilled by the USGS in 1992 in southern Burke County at the lookout tower on Griffins Landing Road, 2 mi north of the town of Girard at lat 33°03'54" N., long 81°43'13" W. Surface elevation is 250 ft above sea level. This hole was cored to a depth of 1,385 ft and bottomed in pre-Cretaceous red beds.
- The Thompson Oak test hole (GGS–3794, TR92–6, Burke 12) was drilled by the Georgia Geologic Survey (GGS) in 1993 in northeastern Burke County, 21 mi south of Augusta just above the flood plain of the Savannah River at lat 33°10'42" N., long 81°47'10" W. Surface elevation is 240 ft above sea level. The hole was cored to a depth of 1,010.5 ft and bottomed in gneissic basement rock.
- The Millers Pond test hole (GGS–3758, Burke 2) was drilled by the GGS in 1991 in northern Burke County, about 2 mi west of the Savannah River, 16 mi south of Augusta at lat 33°13'48" N., long 81°52'44" W. Surface elevation is 245 ft above sea level. The hole was cored to a depth of 859 ft and bottomed in gneissic basement rock. A nearby hole, Millers Pond test well 1, was logged for geophysical properties.
- The McBean test hole (GGS–3757, Burke 5) was drilled by the GGS in 1991 in northern Burke County on the north shoulder of Collins Road 1.1 mi east of the intersection of Georgia Route 56 and Collins Road at lat 33°13'38" N., long 81°55'50" W. Surface elevation is 297 ft above sea level. The hole was cored to a depth of 327 ft and bottomed in the Upper Cretaceous Steel Creek Formation.

STRATIGRAPHIC FRAMEWORK

The stratigraphic framework of the coastal plain section in Screven and Burke Counties is discussed in detail by Falls and Prowell (this volume, chap. A). From oldest to youngest, the lithostratigraphic units that are considered are the Cretaceous Cape Fear Formation, Middendorf Formation, Black Creek Group, and Steel Creek Formation and the Tertiary Ellenton Formation, Snapp Formation, Fourmile Branch Formation, Congaree Formation, Warley Hill Formation, Santee Limestone, and Barnwell unit. In the Middendorf Formation and Black Creek Group, informal subunits can be recognized lithostratigraphically in some cores. We have used Falls and Prowell's lithostratigraphic framework as a starting point to discuss the biostratigraphy and paleoecology.

Figure 2 shows some of the terminology that has been used for lithostratigraphic units in the Atlantic and Gulf of Mexico Coastal Plains and their chronostratigraphic correlations. In the Upper Cretaceous, we use the European stage boundaries summarized by Burnett and others (1992) and Gradstein and others (1995). The Campanian-Maastrichtian boundary position these authors use is stratigraphically higher (younger) than some previous interpretations of this boundary.

Important biostratigraphic and paleoecologic information from the three primary cores (Millhaven, Girard, and Millers Pond) is given in graphic form in figures 3, 4, 5, 6, 7, and 8.

BIOSTRATIGRAPHY AND PALEOECOLOGY

CAPE FEAR FORMATION

The Cape Fear Formation consists of gravels, sands, silts, and clays that typically are arranged in fining-upward sequences. It was sampled only in the Millers Pond core. Four clay layers were sampled, and two of these samples yielded palynomorphs. The pollen present in the lower sample (847–852 ft) represents undifferentiated pollen Zone V

(Frederiksen and others, this volume, chap. C) of late Coniacian and Santonian age. The upper sample (827–832 ft) represents the combined *Complexiopollis exigua-Santalacites minor* and *Pseudoplicapollis longiannulata-Plicapollis incisa* Zones but most likely belongs to the *Complexiopollis exigua-Santalacites minor* Zone (= Subzone V-A) of Christopher (1977, 1979, 1982a,b) of Coniacian age (Sohl and Owens, 1991). The absence of marine palynomorphs (dinoflagellates, acritarchs) and microforaminiferal linings suggests a nonmarine environment of deposition.

MIDDENDORF FORMATION

The Middendorf Formation consists predominantly of moderately to poorly sorted, unlithified sand. It is subdivided into two subunits that each consist of a basal lag deposit, sand, and interbedded and interlaminated clay and sand (Falls and Prowell, this volume, chap. A). Palynomorphs from the Middendorf Formation were studied from the Millhaven, Girard, and Millers Pond cores (Frederiksen and others, this volume, chap. C). In the Millhaven core (1,212 ft, subunit 2), pollen taxa represent undifferentiated Zone V, which is of late Coniacian and Santonian age. Each of two samples from the Girard core (1,138–1,139 ft, subunit 1, and 1,012.0–1,012.3 ft, subunit 2) contains a seemingly heterogeneous set of pollen taxa whose known occurrences are Coniacian to Santonian, Campanian, and Maastrichtian. The pollen flora of the Girard sample from subunit 2 suggests a latest Santonian(?) or earliest Campanian age.

The available data do not provide an unequivocal age for the Middendorf Formation. Two different ages may be present, one representing undifferentiated pollen Zone V and one slightly younger (perhaps correlative with the Shepherd Grove Formation in South Carolina).

Rare dinocysts in the Middendorf Formation from the Millhaven core (1,212 ft, subunit 2) suggest a marginal marine or very nearshore marine environment. The two samples from the Girard core and the sample from the Millers Pond core lack marine palynomorphs.

BLACK CREEK GROUP

The Black Creek Group consists of sands and clays. Although it is not differentiated into component formations in this study, Falls and Prowell (this volume, chap. A) recognize three distinct subunits in the two most downdip (basinward) cores. These subunits are recognized on the basis of lag deposits and possible unconformities, but they cannot be related directly to named formations of the Black Creek Group that are recognized in South Carolina (Gohn, 1992). The Black Creek Group was studied for palynomorphs in the Millhaven, Girard, Thompson Oak, and Millers Pond cores. The calcareous part of subunit 2 of the Black Creek Group in the Millhaven core was studied for calcareous nannofossils and ostracodes.

Subunit 1 of the Black Creek Group is probably mid-Campanian, pollen Zone CA-4 (Wolfe, 1976), in the Millhaven core (one sample, at 1,124.3–1,124.7 ft). Subunit 1 was not examined for pollen in the other cores (Frederiksen and others, this volume, chap. C).

The calcareous part of subunit 2 of the Black Creek in the Millhaven core (1,077–968 ft) is dated by calcareous nannofossils as late Campanian, calcareous nannofossil Zone CC 22, based on the co-occurrence of *Quadrum trifidum* (Stradner) Prins & Perch-Nielsen and *Reinhardtites anthophorus* (Deflandre) Perch-Nielsen (Bukry, this volume, chap. D). The total range of the ostracode *Haplocytheridea sarectaensis* Brown is limited to the upper part of Zone CC 22 in the Millhaven core and in South Carolina sections. Its highest occurrence can be used as a regional marker that approximates the Campanian-Maastrichtian boundary (Gohn, this volume, chap. E).

A distinctive dinoflagellate assemblage containing *Palaeohystrichophora infusorioides* Deflandre, *Xenascus ceratioides* (Deflandre) Lentin & Williams, *Cordosphaeridium fibrospinosum* Davey & Williams, and *Andalusiella spicata* (May) Lentin & Williams is found in and slightly above subunit 2 in the Millhaven core (1,029.5–913.8 ft). This dinoflagellate assemblage is used to assign a late Campanian age to correlative sections containing this assemblage in the Girard (867.7–738.6 ft) and Thompson Oak (505 ft) cores (Frederiksen and others, this volume, chap. C).

Subunit 3 of the Black Creek Group in the Millhaven core (one sample, at 849.3–849.6 ft) is dated as late Campanian by dinocysts based on the presence of *Palaeohystrichophora infusorioides* Deflandre (Frederiksen and others, this volume, chap. C).

In the Millers Pond core, the Black Creek Group is not differentiated into subunits. One sample from 578 ft contains pollen indicating a possible latest Santonian or earliest Campanian age, or some poorly defined younger age. A second sample from 517 ft contains pollen indicating an apparent mid-Campanian age.

In the Millhaven and Girard cores, subunit 1 of the Black Creek Group yielded only nonmarine palynomorphs, whereas subunits 2 and 3 yielded both marine and nonmarine palynomorphs. In the Millhaven core, part of subunit 2 contains marine calcareous nannofossils and inner-neritic ostracode assemblages. The two samples studied from the Thompson Oak core were not assigned to a subunit but contain marine palynomorphs. In the Millers Pond core, only nonmarine palynomorphs were recovered in the Black Creek Group (Frederiksen and others, this volume, chap. C).

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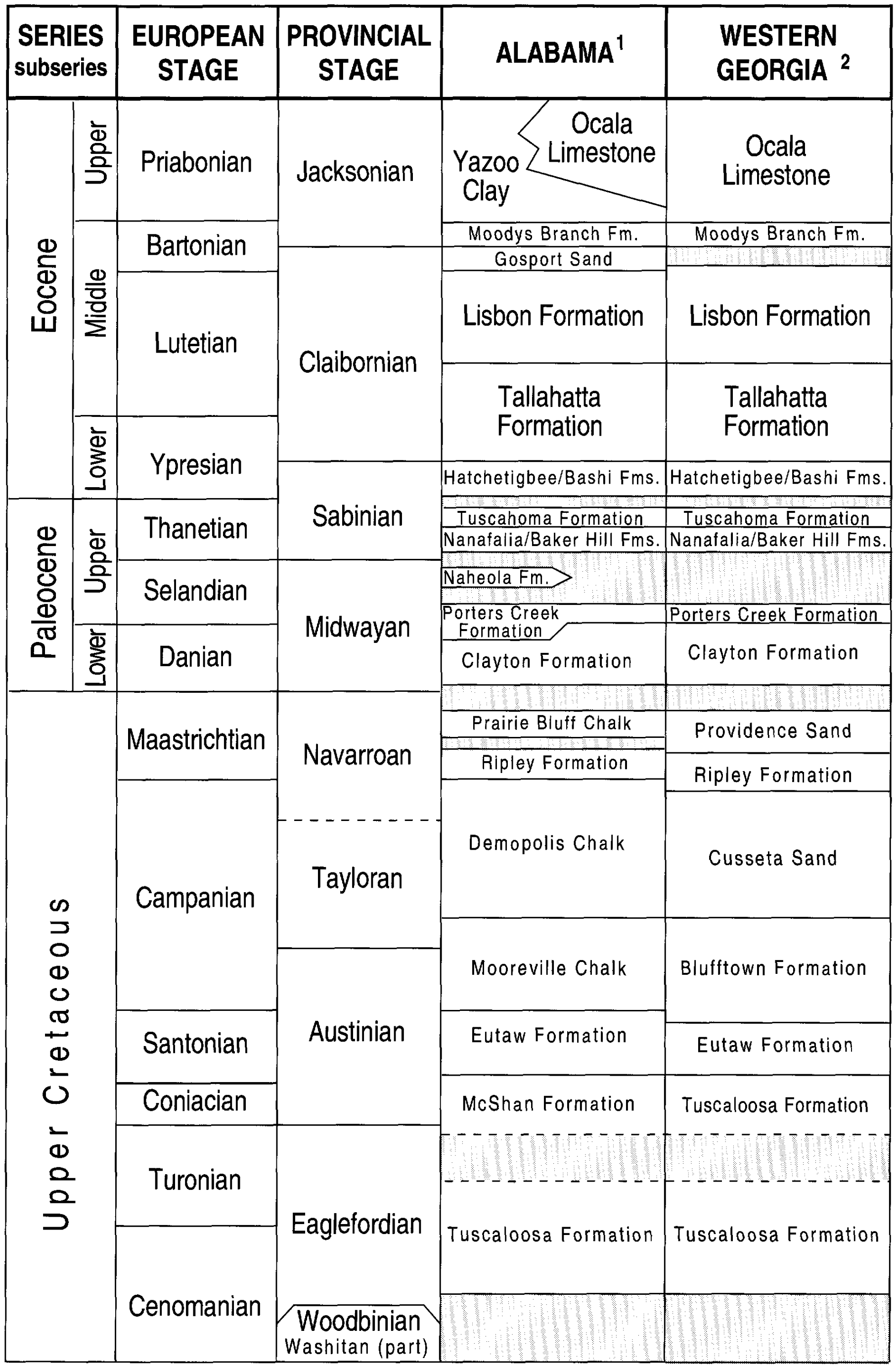
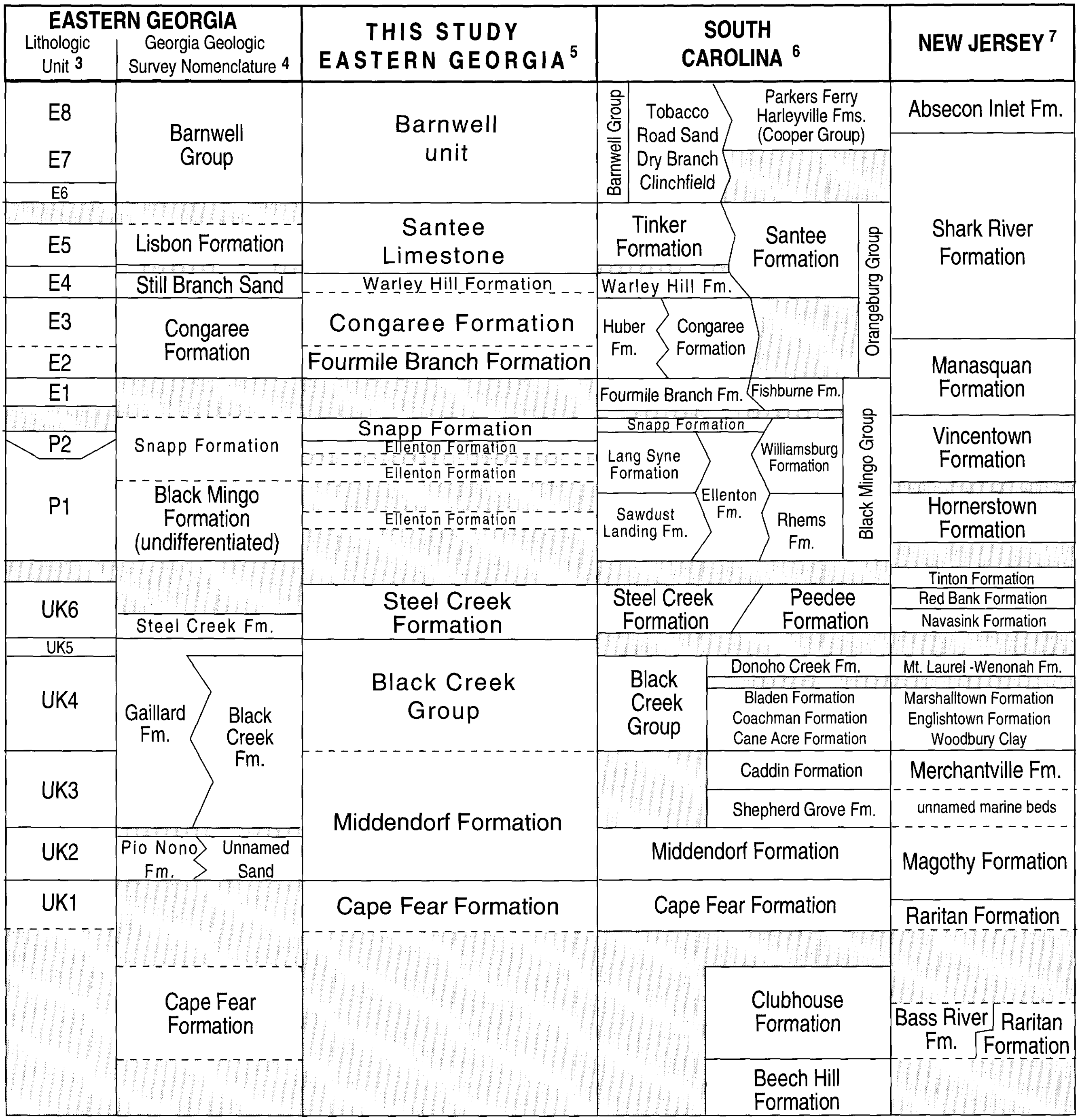


[1]Alabama column is based on Hazel (1990), Moshkovitz and Habib (1993), and Mancini and others (1996).
[2]Western Georgia column is based on Prowell and others (1985) and Clarke and others (1994).

Figure 2. Chart showing terminology that has been used for lithostratigraphic units in the eastern United States and our interpretations of their chronostratigraphic correlations. Mesozoic series and stages are from Burnett and others (1992) and Gradstein and others (1995); the Tertiary series, subseries, and stages are from Berggren and others (1995).



[3]Lithologic unit column for eastern Georgia is based on Prowell and others (1985).

[4]Column of Georgia Geologic Survey nomenclature for eastern Georgia is based on Huddlestun and Summerour (1996).

[5]The column of names for this study of eastern Georgia shows separate entries for the Fourmile Branch Formation, the Congaree Formation, and the Warley Hill Formation. In chapter A, these three formations are combined into one unit as all three formations are not consistently present in the five cores studied.

[6]South Carolina column is based on Van Nieuwenhuise and Colquhoun (1982), Frederiksen (1991), Gohn (1992), Fallaw and Price (1995), Self-Trail and Gohn (1996), and Edwards and others (1997).

[7]New Jersey column is based on Owens and others (1970, 1988), Litwin and others (1993), Self-Trail and Bybell (1995), Kennedy and others (1995), and Browning and others (1997).

Figure 2. Continued.

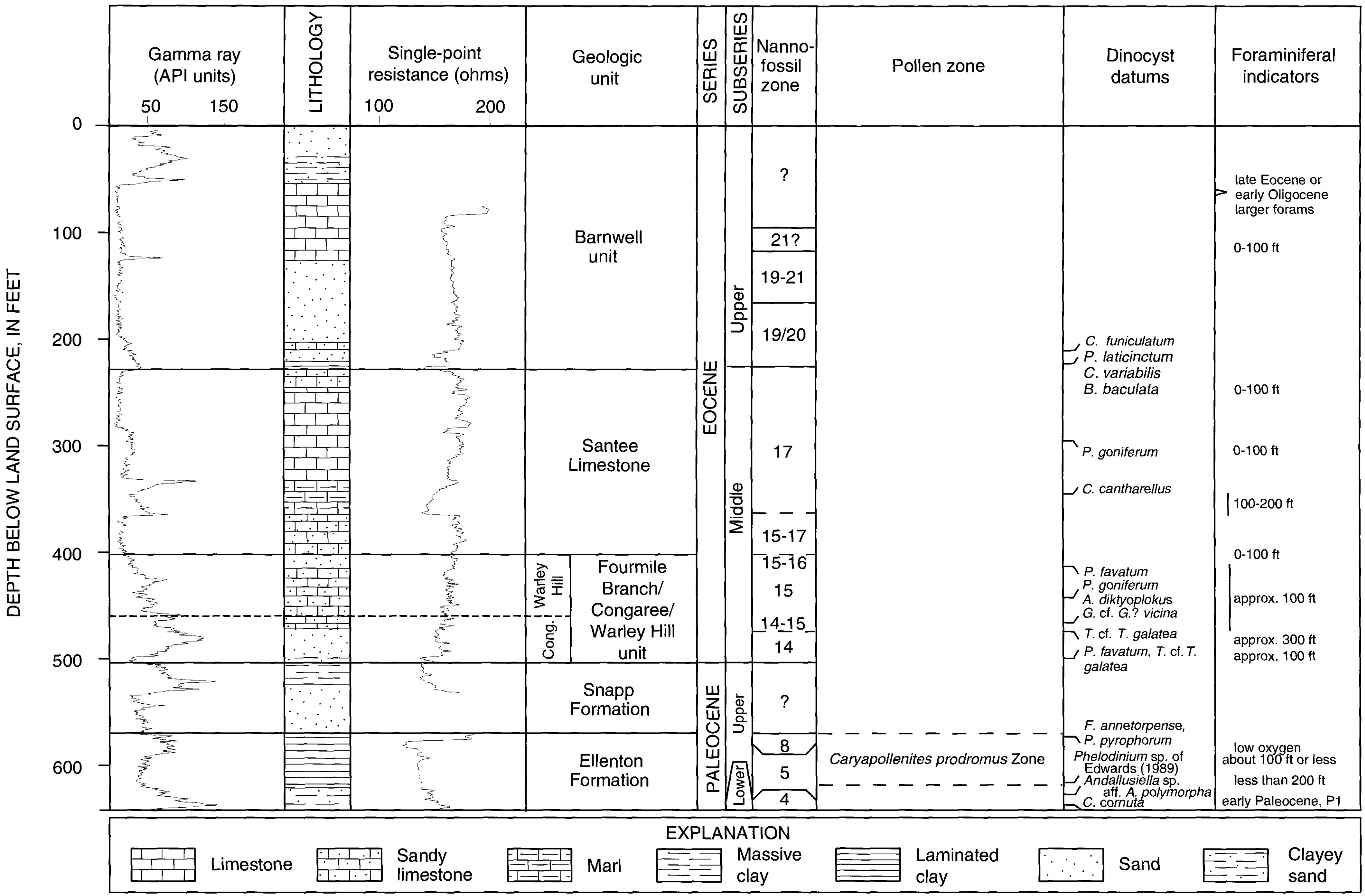


Figure 3. The stratigraphic and paleontologic summary of the Tertiary part of the Millhaven core. The lithology is from Clarke and others (1996), and the lithostratigraphy and geophysical logs are from Falls and Prowell (this volume, chap. A). Paleontologic data are from chapters F (nannofossil column), G (dinocyst column), H (pollen column), and I (foraminiferal indicators column). API, American Petroleum Institute.

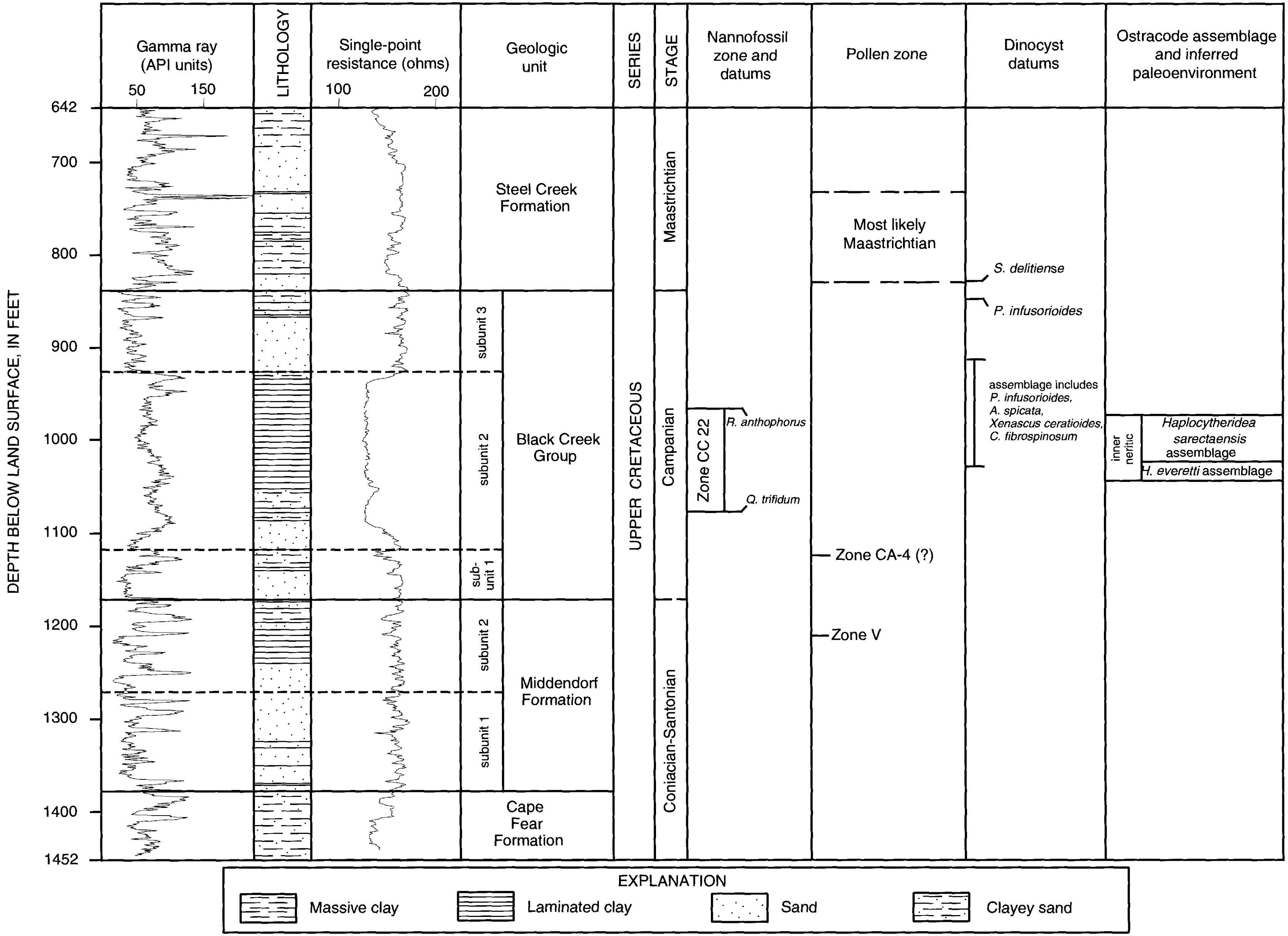


Figure 4. The stratigraphic and paleontologic summary of the Cretaceous part of the Millhaven core. The lithology is from Clarke and others (1996), and the lithostratigraphy and geophysical logs are from Falls and Prowell (this volume, chap. A). Paleontologic data are from chapters C (pollen and dinocyst columns), D (nannofossil column), and E (ostracode column). API, American Petroleum Institute.

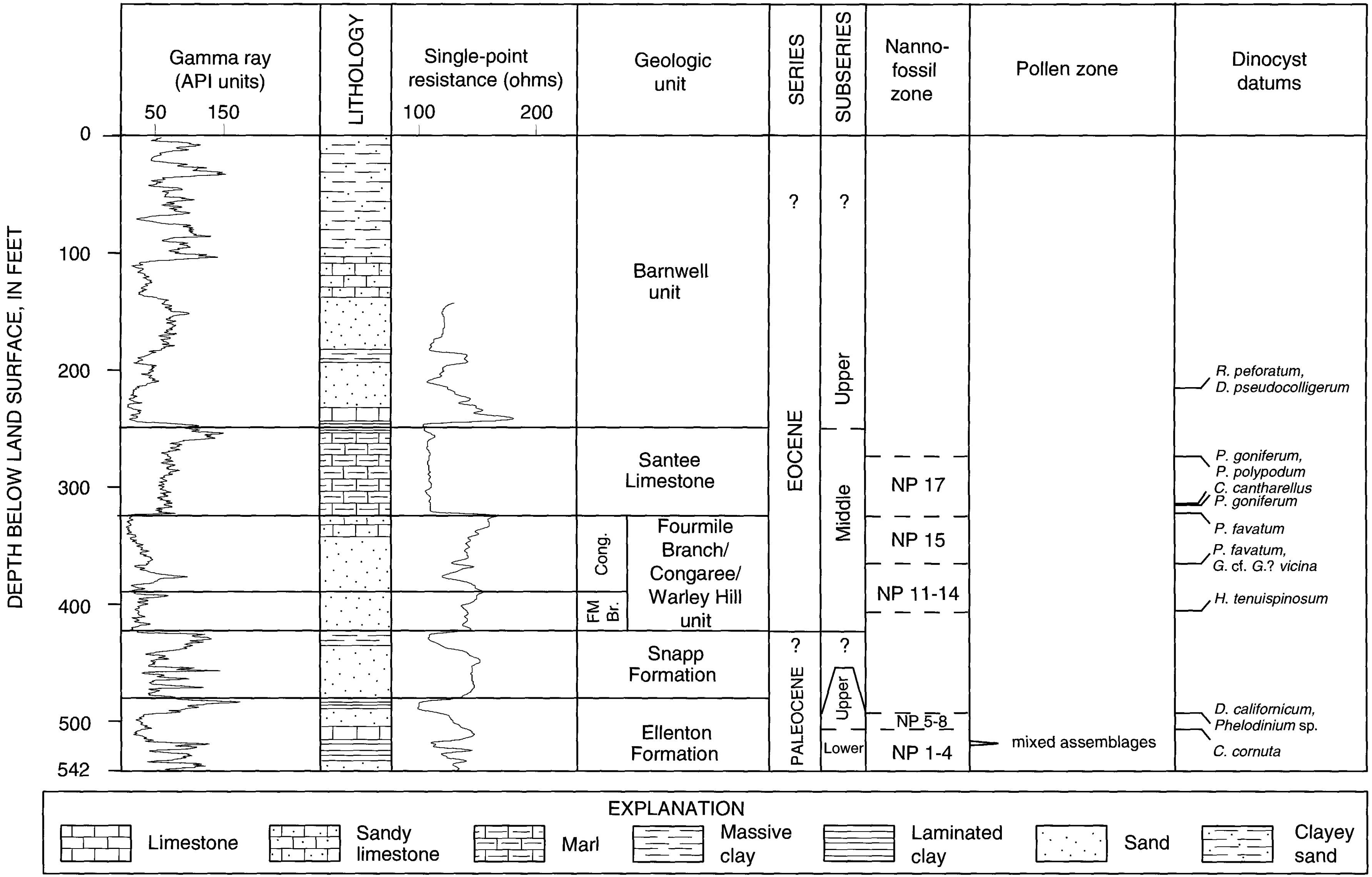


Figure 5. The stratigraphic and paleontologic summary of the Tertiary part of the Girard core. The lithology is from Leeth and others (1996), and the lithostratigraphy and geophysical logs are from Falls and Prowell (this volume, chap. A). Nannofossil zones are inferred from palynological evidence. Other paleontologic data are from chapters G (dinocyst column) and H (pollen column). API, American Petroleum Institute.

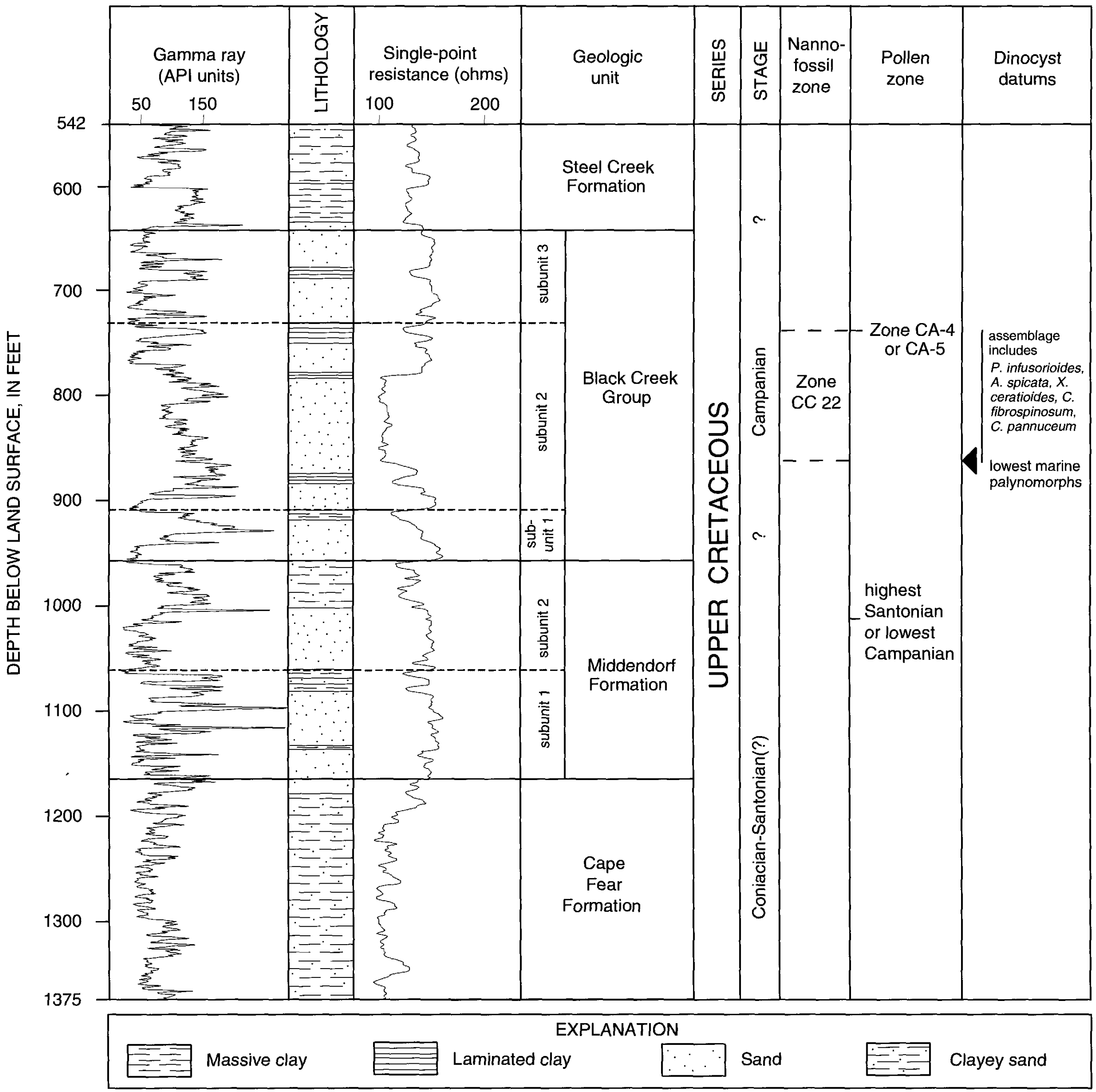


Figure 6. The stratigraphic and paleontologic summary of the Cretaceous part of the Girard core. The lithology is from Leeth and others (1996), and the lithostratigraphy and geophysical logs are from Falls and Prowell (this volume, chap. A). Nannofossil Zone CC 22 is inferred from palynological evidence. Other paleontologic data are from chapter C. API, American Petroleum Institute.

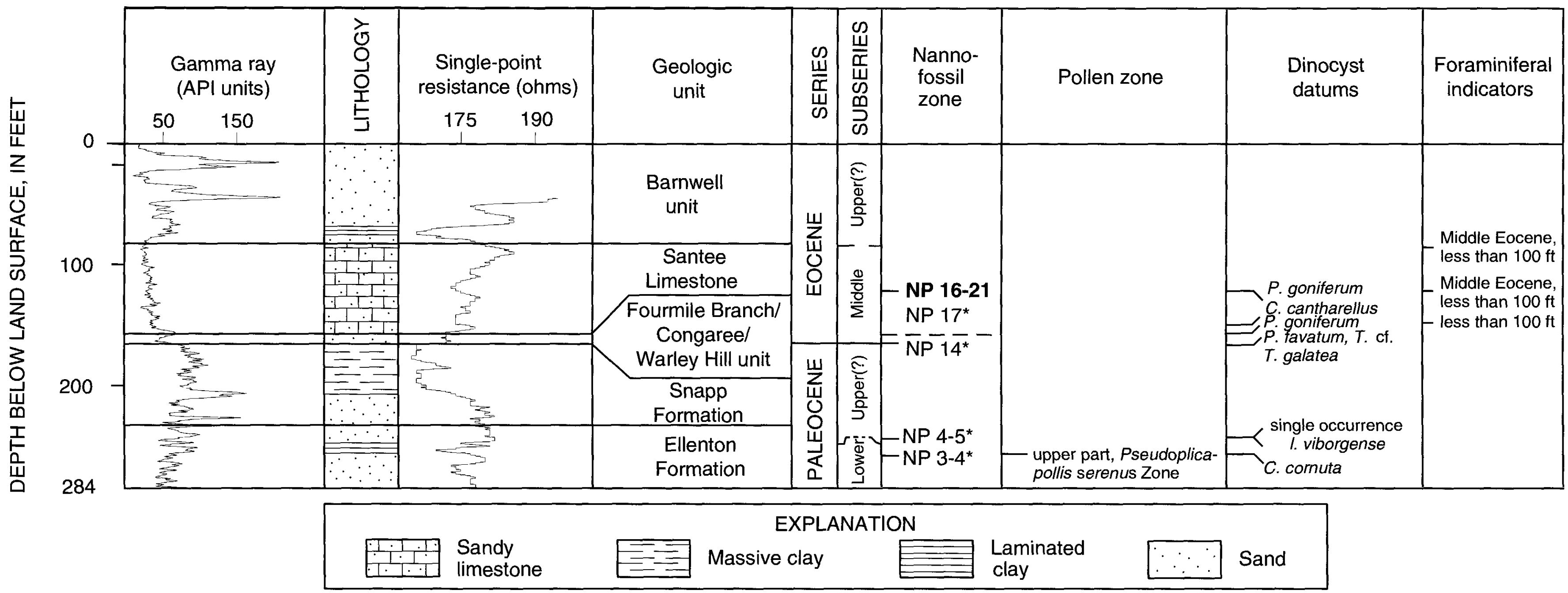


Figure 7. The stratigraphic and paleontologic summary of the Tertiary part of the Millers Pond core. The lithology is from Clarke and others (1994), and the lithostratigraphy and geophysical logs are from Falls and Prowell (this volume, chap. A). Nannofossil zone in bold is based on observed calcareous nannofossils (chapter F); nannofossils zones with an asterisk are inferred from palynological evidence (chapters G and H). Other paleontologic data are from chapters G (dinocyst column), H (pollen column), and I (foraminiferal indicators column). API, American Petroleum Institute.

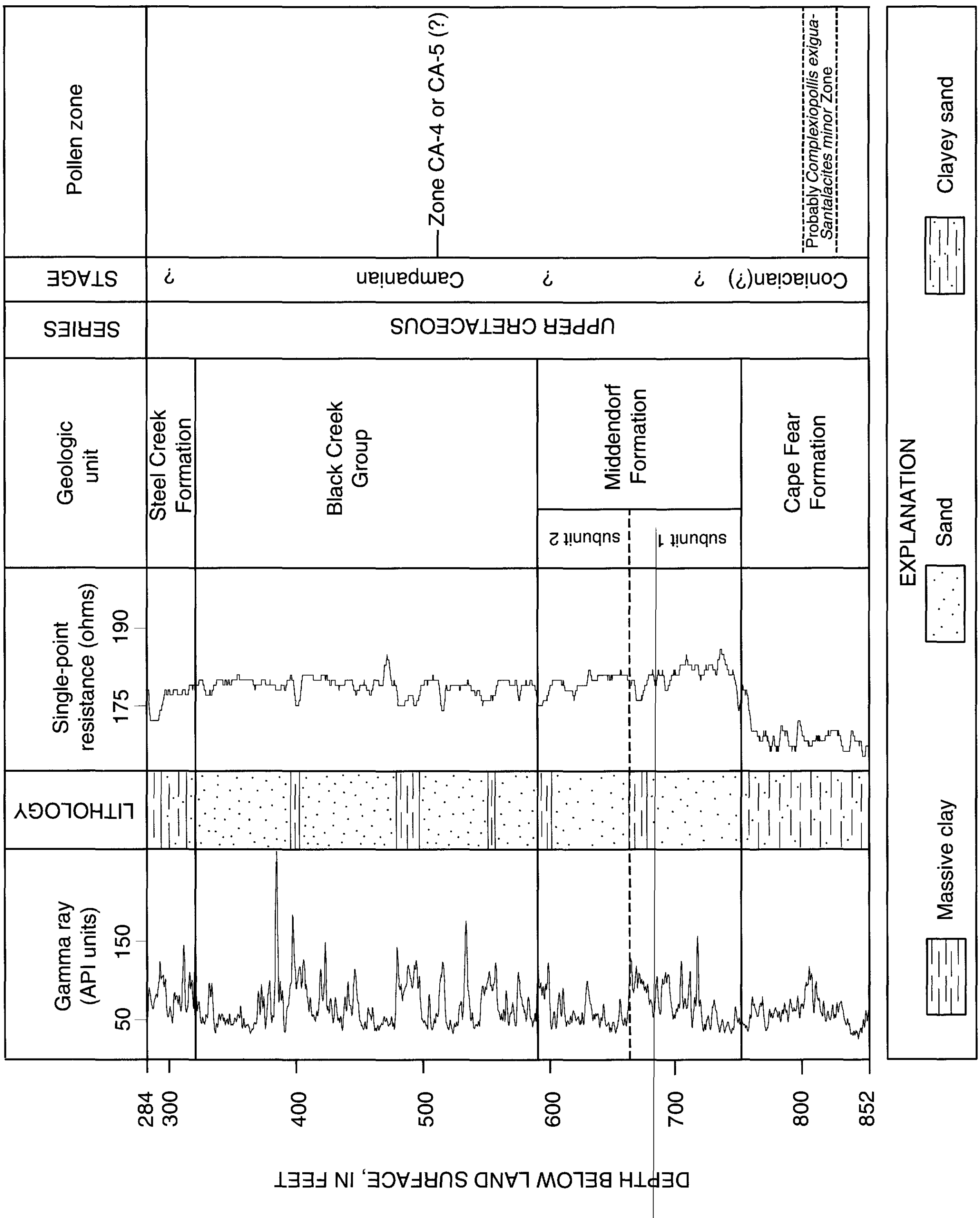


Figure 8. The stratigraphic and paleontologic summary of the Cretaceous part of the Millers Pond core. The lithology is from Clarke and others (1994), and the lithostratigraphy and geophysical logs are from Falls and Prowell (this volume, chap. A). The pollen data are from chapter C. API, American Petroleum Institute.

STEEL CREEK FORMATION

The Steel Creek Formation consists of multiple fining-upward sequences of gravel, sand, and clay, in which many of the clay beds are stained with iron oxide (Falls and Prowell, this volume, chap. A). The formation was sampled unproductively in the Millers Pond core and was not sampled in the Girard and Thompson Oak cores. Ten samples from the Millhaven core were examined for palynomorphs (Frederiksen and others, this volume, chap. C).

The lowest Steel Creek samples contain pollen taxa that were not found to range below this formation in the Millhaven core. A new species, *Momipites* n. sp. 1, is known only from the Maastrichtian. These samples are correlative with middle or late Maastrichtian units in New Jersey, or perhaps the unconformity below them. The sample at 830.3–830.5 ft contains a rather sparse dinoflagellate assemblage that includes *Spongodinium delitiense* (Ehrenberg) Deflandre (lowest occurrence is in the uppermost Campanian in New Jersey). Samples at 768.8–769.0 and 733.2–733.3 ft contain long-ranging Cretaceous forms of pollen, and a sample at 680.8–681.0 ft is barren of palynomorphs and contains only plant debris. Samples from the correlative interval (based on geophysical logs) in the C-10 core (Allendale County, S.C.) yielded nonmarine assemblages dated as Maastrichtian (Joyce Clark, 1989, written commun. to the South Carolina Water Resources Commission). Thus, a combination of pollen and dinoflagellate data suggests that the Black Creek Group-Steel Creek Formation boundary approximates the Campanian-Maastrichtian boundary in the Millhaven core.

The lowest Steel Creek sample in the Millhaven core contains a few marine dinoflagellates. No marine fossils were recovered higher in the unit.

ELLENTON FORMATION

The Ellenton Formation consists of sands and clays that are partly glauconitic and calcareous in the Millhaven core (most basinward) and lignitic in the Millers Pond core (Falls and Prowell, this volume, chap. A). This unit was studied for calcareous nannofossils, foraminifers, and marine and nonmarine palynomorphs in the Millhaven core. It was studied for palynomorphs in the Girard, Thompson Oak, and Millers Pond cores. A very thin lower Paleocene (Danian) section is present in at least three of the Georgia cores. Most of the Ellenton is early late Paleocene (Selandian). Two samples in the Millhaven core are middle late Paleocene (Thanetian).

In the Millhaven core, the Ellenton yields three distinct calcareous nannofossil zones: NP 4 (early Paleocene, 639.6–635.4 ft), NP 5 (early part of the late Paleocene, 631.3–579.2 ft), and NP 8 (middle part of the late Paleocene, 578.0–577.2 ft) (Bybell, this volume, chap. F). Although calcareous nannofossil Zone NP 4 includes both early and late Paleocene time, dinocysts and planktonic foraminifers indicate that only the early Paleocene part of the zone is present in this core. Two samples from the Girard core were examined for calcareous nannofossils; both proved barren.

A distinctive early Paleocene dinocyst assemblage that includes *Carpatella cornuta* Grigorovich, *Spinidinium pulchrum* (Benson) Lentin & Williams, *Tectatodinium rugulatum* (Hansen) McMinn, and *Tenua* sp. cf *T. formosa* of Kurita and McIntyre (1995) is present in the lowest Ellenton in the Millhaven core (one sample at 639.5 ft), the Girard core (521.2–517.9 ft, questionably to 514 ft), and the Millers Pond core (one sample at 252–257 ft). In the Millhaven core, the late Paleocene dinoflagellate assemblage includes *Palaeoperidinium pyrophorum* (Ehrenberg) Sarjeant and *Fibradinium annetorpense* Morgenroth in the highest sample (571 ft).

Early Paleocene (Danian) pollen was identified in the Millers Pond core in the lowest Tertiary sample (252–257 ft). In the Girard core, the pollen assemblage in one of the Ellenton samples (521.0–521.2 ft) consists of species that normally do not occur together. Although alternative interpretations are possible, contamination from above into lower Paleocene material is most likely. In the Thompson Oak core, pollen at 302 ft depth could be either late early or early late Paleocene. Late Paleocene pollen was found in six samples in the Millhaven core (620.8–571.0 ft) and in the Thompson Oak core (281 ft). In the McBean core, the Ellenton was barren of pollen (Frederiksen, this volume, chap. H).

In the Ellenton of the Millhaven core, five intervals with differing foraminiferal assemblages are present: (1) a highly altered, low-diversity assemblage of early, but not earliest, Paleocene age, planktonic foraminiferal Zone P1 (636.8 ft); (2) an assemblage containing apparent mixing of specimens from lower Paleocene beds with early late Paleocene specimens (631.3 ft); (3) an assemblage suggesting normal productivity and oxygen levels with a probable water depth range of 100 to 200 ft (628.7 ft); (4) an assemblage suggestive of water depths of less than 100 ft but having high-productivity or low-oxygen conditions or both (621.2–599.1 ft); and (5) an assemblage suggestive of water depths of less than 100 ft with normal marine oxygen conditions (593.7–581 ft). Age-diagnostic planktonic foraminifers are present only in the lowest part of the Ellenton, but benthic species and immature planktonic species are present throughout (Gibson, this volume, chap. I).

SNAPP FORMATION

The Snapp Formation consists of a lower sand-dominated part and an upper clay-dominated part. The formation was studied for palynomorphs in the Millhaven and

McBean cores. No samples from the Snapp Formation were taken from the Millers Pond and Girard cores, and the formation is absent from the Thompson Oak core. In the McBean core, where the Snapp Formation consists only of sand with no overlying kaolin, nonmarine palynomorphs are present (Frederiksen, this volume, chap. H). The overlapping ranges of pollen taxa in the one productive sample (254 ft) indicate an age no older than earliest late Paleocene and no younger than middle late Paleocene age (Selandian or Thanetian).

A single Snapp sample in the Millhaven core (564–565 ft) yielded rare dinocyst fragments that are not age diagnostic but indicate at least marginally marine conditions (Edwards, this volume, chap. G).

FOURMILE BRANCH FORMATION

The Fourmile Branch Formation, a medium to coarse sand, was recognized only in the Girard and Thompson Oak cores (Falls and Prowell, this volume, chap. A). It was examined for palynomorphs in these cores.

A distinctive dinocyst assemblage, containing both *Hafniasphaera goodmanii* Edwards and primitive forms of *Pentadinium favatum* Edwards, was found in the Fourmile Branch Formation in the Thompson Oak core. *Homotryblium abbreviatum* Eaton is also present. These species are also found in the lower part of the Tallahatta Formation in Alabama and thus suggest correlation with lower Eocene calcareous nannofossil Zones NP 12 or NP 13. Sediments in the Fourmile Branch Formation in the Girard core contain *Dracodinium varielongitudum* (Williams & Downie) Costa & Downie and *Homotryblium tenuispinosum* Davey & Williams and are probably of early Eocene age as well (Edwards, this volume, chap. G).

Pollen from the Fourmile Branch Formation indicates an early Eocene age, or possibly early middle Eocene, in the Girard core. The dinocysts present indicate that sediments from the Fourmile Branch Formation are marine.

CONGAREE FORMATION

The Congaree Formation consists of quartz sand, marl, and limestone. Samples from the Congaree Formation were studied for calcareous nannofossils, foraminifers, and palynomorphs from the Millhaven core and for palynomorphs in the Girard, Thompson Oak, Millers Pond, and McBean cores.

In the Millhaven core, the Congaree Formation yields calcareous nannofossils that are placed in Zone NP 14 (early and middle Eocene, 497.4–473.5 ft); the uppermost sample (465.5 ft) could be either NP 14 or NP 15 (middle Eocene) (Bybell, this volume, chap. F).

Two distinctive dinocyst assemblages, both of early middle Eocene age, can be recognized in the Congaree Formation in the studied cores (Edwards, this volume, chap. G). Both assemblages contain *Pentadinium favatum* Edwards. One assemblage, which contains *Turbiosphaera* cf. *T. galatea* Eaton, is found in the lower part of the Congaree Formation in the Millhaven core (498.5–473.5 ft), the Thompson Oak core (231.5 ft), and the Millers Pond (165 ft) core. The dinocysts in this assemblage appear to be correlative with those in the upper part of the Tallahatta Formation in Alabama and unit E3 of Prowell and others (1985) in Georgia. A second assemblage, which contains *Glaphyrocysta* cf. *G.*? *vicina* (Eaton) Stover & Evitt, is found in the Millhaven core at 466 ft and also in the Girard (362.3–327.3 ft) and Thompson Oak (194–183.5 ft) cores. This assemblage is correlative with that from the lower part of the Lisbon Formation in Alabama.

Pollen studies of the Congaree yielded generally broad age possibilities: early or middle Eocene in the Millhaven core and correlative with calcareous nannofossil Zone NP 12 to early NP 16 in the Thompson Oak core (Frederiksen, this volume, chap. H).

Foraminifers from the Congaree Formation in the Millhaven core indicate a middle Eocene age and generally indicate a water depth of approximately 100 ft. A single sample at 481 ft indicates much deeper water, approximately 300 ft (Gibson, this volume, chap. I).

WARLEY HILL FORMATION

The Warley Hill Formation, a sandy limestone, was recognized only in the Millhaven core (Falls and Prowell, this volume, chap. A). It was studied for calcareous nannofossils, foraminifers, and palynomorphs.

Most samples from the Warley Hill Formation in the Millhaven core (458.1–413.0 ft) are assigned to the middle Eocene calcareous nannofossil Zone NP 15. The lowest sample (462 ft) could be either NP 14 or NP 15, and the highest sample (404 ft) could be either NP 15 or 16. Preservation in all samples is fair or poor.

The dinocyst assemblage from the Millhaven samples at 442 and 413 ft contains both *Pentadinium goniferum* Edwards and *P. favatum* Edwards. These two species are found together only in sediments from a narrow interval in the middle Eocene that is probably correlative with the middle part of the Lisbon Formation in Mississippi and with an unconformity or condensed interval within the Lisbon Formation in Alabama (Edwards, this volume, chap. G). These species were observed to overlap in part of unit E4 of Prowell and others (1985).

Foraminifers from samples at 455 and 426.5 ft in the Millhaven core were probably deposited in 100-ft water depth or slightly deeper, whereas those in samples at 413 and 404 ft in the core were probably deposited in less than 100 ft of water (Gibson, this volume, chap. I).

SANTEE LIMESTONE

The Santee Limestone consists primarily of limestone and unlithified carbonate sediments with a few beds of calcareous sand and clay (Falls and Prowell, this volume, chap. A). Samples from the Santee were studied for calcareous nannofossils, foraminifers, and palynomorphs from the Millhaven and Millers Pond cores and for palynomorphs from the Girard, Thompson Oak, and McBean cores.

In the Millhaven core, the samples from 400.0–370.9 ft have poorly preserved calcareous nannofossil assemblages and could be in Zones NP 15, 16, or 17 (middle Eocene). Beginning at 368.0 ft and continuing to the top of the formation, calcareous nannofossils indicate late middle Eocene Zone NP 17. The Santee Limestone in the Millers Pond core contains Eocene calcareous nannofossils that are not very age diagnostic. The Santee Limestone was not studied for calcareous nannofossils in the other three cores because of the anticipated poor assemblages (Bybell, this volume, chap. F).

In the Millhaven core, dinocyst samples have poor recovery in the lower part of the Santee Limestone but have abundant and distinctive assemblages above 346 ft that are typical of the late middle Eocene, correlative with the upper part of the Lisbon Formation in Alabama and perhaps the Gosport Formation. In the Girard, Thompson Oak, Millers Pond and McBean cores, the Santee Limestone contains late middle Eocene dinocyst assemblages similar to those found in the Millhaven core (Edwards, this volume, chap. G).

Foraminifera from the Millhaven and Millers Pond cores indicate a middle Eocene age, and most samples contain the distinctive benthic species *Cibicides westi* Howe (Gibson, this volume, chap. I).

The Santee Limestone contains only poorly dated pollen (Frederiksen, this volume, chap. H).

Foraminifers indicate paleo-water depths of 100 to 200 ft in the lower part of the Santee Limestone and less than 100 ft in its upper part in the Millhaven core and water depths of less than 100 ft in the Millers Pond core (Gibson, this volume, chap. I).

BARNWELL UNIT

The Barnwell unit is a mixed lithologic sequence of sandy limestone, marl, clay, and sand. It is treated as a unit, although unconformities can be recognized within it (Falls and Prowell, this volume, chap. A). Sediments of the unit are poorly fossiliferous. The unit was sampled in the Millhaven core for calcareous nannofossils and palynomorphs and in the Girard core for palynomorphs only. Sediments of the Barnwell unit from the Thompson Oak, Millers Pond, and McBean cores either were not sampled in this study or did not contain palynomorphs.

In the Millhaven core, nannofossil samples from 225.9 to 168.5 ft are late Eocene (Zone NP 19/20). Samples from 118.0 to 95.0 ft are questionably dated as Zone NP 21 (latest Eocene or earliest Oligocene).

Dinocysts from Millhaven samples at 216.5, 210, and 205 ft are most likely of late Eocene age, and the two upper samples suggest correlation with the upper Eocene Yazoo Clay in Alabama and the Harleyville and Parkers Ferry Formations in South Carolina. Samples at 195, 118, and 105 ft were barren of dinocysts. In the Girard core, the sample at 211.1–211.3 ft contains dinocyst species that suggest a late Eocene age. The sample at 146.7 ft contains a very sparse and nondiagnostic dinocyst assemblage, and samples at 104 and 64 ft were barren of dinocysts.

Most samples from the Barnwell unit yielded marine calcareous microfossils and marine palynomorphs. The foraminiferal assemblage suggests shallow-marine environments, probably in the deeper portion of the 0- to 100-ft depth interval.

SUMMARY AND IMPLICATIONS

The Cape Fear Formation, where studied, is of probable Coniacian age and is nonmarine.

The available data do not provide an unequivocal age for the Middendorf Formation. Two different ages may be present, one representing undifferentiated pollen Zone V (late Coniacian and Santonian) and one slightly younger (latest Santonian(?) and early Campanian, perhaps correlative with the Shepherd Grove Formation in South Carolina). The possibility of similar lithofacies representing different ages should be considered and investigated further. Most of the Middendorf Formation is nonmarine. Rare dinocysts in a single sample from the Millhaven core (1,212 ft, subunit 2) suggest a marginal marine or very nearshore marine environment.

The Black Creek Group is dated as Campanian. It is nonmarine in its lower part (subunit 1). In all but the most updip core, the Black Creek Group includes marine fossils in its upper part (subunits 2 and 3). Subunit 2 contains ostracodes correlative with those in the Donoho Creek Formation, the highest formation in the Black Creek Group in central South Carolina (Gohn, 1992). Subunit 3 may represent deposition in Georgia that has no counterpart in central South Carolina.

The Steel Creek Formation is Maastrichtian in the Millhaven core. It contains a few marine dinoflagellate cysts near its base; no marine fossils were recovered higher in the unit.

The placement of the Cretaceous-Tertiary boundary in all cores is, of necessity, based on the lithostratigraphy (Falls and Prowell, this volume, chap. A). Thick undated intervals are found between the Maastrichtian of the Steel

Creek Formation or Campanian of the Black Creek Group and the Danian of the Ellenton Formation.

A very thin lower Paleocene (Danian) section is present at the base of the Ellenton Formation in at least three cores. Most of the Ellenton Formation is early late Paleocene (Selandian). Two samples in the Millhaven core are middle late Paleocene (Thanetian). The oldest Paleocene material contains a significant component of planktonic foraminifers and, thus, represents deeper water deposition than the remainder of the Ellenton Formation.

The Snapp Formation is present in varying thicknesses in four of the five cores and is dated as late Paleocene (Selandian or Thanetian). It is mostly nonmarine. A single sample from the Millhaven core yielded dinocyst fragments that indicate marginally marine conditions.

The Snapp Formation is conspicuously absent from the Thompson Oak core, and the upper kaolinitic part is not present in the McBean core. Because the Snapp Formation is present in the most updip cores, it was probably also present in the Thompson Oak area originally but subsequently removed. Faulting is well documented in South Carolina (Snipes and others, 1993), but the Thompson Oak core is located on the downthrown side of the Pen Branch fault (Huddlestun and Summerour, 1996). We suggest that erosion by a predecessor to the Savannah River should be considered and investigated further.

The Fourmile Branch Formation is early Eocene and is only found in the Thompson Oak and Girard cores. Erosion of the underlying Snapp Formation in the Thompson Oak core may have facilitated preservation of these early Eocene sediments. The presence of dinocysts indicates that sediments from the Fourmile Branch Formation are marine.

The Congaree Formation is of middle Eocene age. It contains two recognizable dinocyst assemblages that are roughly equivalent to those from the upper part of the Tallahatta Formation and from the lower part of the Lisbon Formation of the Gulf Coast. Foraminifers from the Congaree Formation in the Millhaven core generally indicate a water depth of approximately 100 ft; a single sample at 481 ft indicates much deeper water, approximately 300 ft.

The Warley Hill Formation, a marine unit of middle Eocene age, is recognized only in the Millhaven core. Foraminifers from samples at 455 and 426.5 ft in the Millhaven core were probably deposited in 100-ft water depth or slightly deeper; whereas those from higher samples were probably deposited in less than 100 ft of water.

The Santee Limestone is of late middle Eocene age. It contains calcareous fossils even in the most updip cores. Not surprisingly, the paleo-water depth increases basinward. In the Millers Pond core, inferred depths are less than 100 ft throughout the unit; in the Millhaven core, inferred depths range from 100 to 200 ft in the lower part of the formation and are less than 100 ft near the top.

Sediments of the Barnwell unit are poorly fossiliferous. Where they can be dated, they are late Eocene to questionably early Oligocene. Most samples are shallow marine.

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