

**GEOLOGIC SECTION OF THE UPDIP COASTAL PLAIN
FROM CENTRAL GEORGIA TO WESTERN SOUTH CAROLINA**

By

**David C. Prowell, Raymond A. Christopher, Lucy E. Edwards,
Laurel M. Bybell, and Harold E. Gill**

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INTRODUCTION

Stratigraphic investigations of the Atlantic and Gulf Coastal Plains of the southeastern United States have shown that the two regions contain distinctly different Cretaceous and Tertiary sedimentary rock sequences. These two regions merge in Georgia where the Southwest Georgia Embayment, representing the eastern end of the Gulf Coast strata, meets the Southeast Georgia Embayment, representing the southern end of the Atlantic Coast strata. The correlation of strata between these two regions has been the subject of longstanding controversy among Coastal Plain stratigraphers, paleontologists, and hydrologists. New drill-hole data and stratigraphic interpretations presented in this report provide additional lines of correlation between the Atlantic and Gulf sections.

As a part of a hydrologic study in central and eastern Georgia during 1981-84, the U.S. Geological Survey, in cooperation with the Georgia Geologic Survey, drilled four, discontinuously cored, hydrologic test wells in the updip Coastal Plain along a line approximating the strike of the Fall Line (index map). Other partly cored wells had been drilled previously in easternmost Georgia and adjacent South Carolina during geologic investigations for the siting of nuclear facilities in the area (Marine and Siple, 1974; Bechtel Corporation, 1982). Data from three separate wells (Arrowhead 1, Wrightsville 1, and Midville SEX-TW-2) and from two clusters of wells (Laurens 1, 2, and 3; SRP-P5R and Vogtle VSC-2) were used to construct a detailed geologic section from central Georgia to western South Carolina. In the cluster wells the best samples were used to describe the lithologic characteristics of the geologic units in the area. Laurens 1, 2, and 3 are adjacent wells at the same locality; and well VSC-2 is approximately 1 mi southeast of well SRP-P5R. Information concerning the location and depths of these wells is shown in table 1.

Descriptions of the rock units shown on the geologic section are given in this pamphlet. Geophysical logs are included on the geologic section because of their usefulness in defining unit contacts in the intervals of no core recovery. Analyses of pollen, dinoflagellates, and calcareous nannofossils in selected samples were made to determine the age of rock units and to provide evidence of paleoenvironmental

conditions. The drill hole at the west end of the section line (Arrowhead 1) contains strata correlative with the Gulf Coastal Plain formations in the Southwest Georgia Embayment, whereas the drill-hole locality at the east end (wells SRP-P5R and VSC-2) contains lithologies characteristic of the Atlantic Coastal Plain sequence.

The geologic units shown on the section are labeled only with symbols to avoid possible confusion between Gulf and Atlantic formation nomenclature and the stratigraphic implications connected with existing formation names. Formations of equivalent age are given at the end of each unit description and in the correlation chart (table 2). Diagnostic fossils are listed individually and their age significance is commonly given in terms of biologic zonation. For additional information concerning the ranges of dinoflagellates, refer to the articles by Drugg and Stover (1975) and Edwards (1980). A definition of the Paleogene calcareous nannoplankton (NP) zones can be found in Martini (1971), and a description of Cretaceous pollen zonations is included in Christopher (1978), Christopher (1982), Sohl and Christopher (1983), and Wolfe (1976).

Key aspects of the geologic section are: (1) the total absence of any pre-Santonian Cretaceous strata (for example, the Tuscaloosa Formation), (2) the gradual thinning and ultimate omission of some Cretaceous units from west to east, (3) a general transition in Cretaceous strata from marine deposits in the west to terrestrial deposits farther east, (4) the thinning of Tertiary strata from the center of the geologic section to the east and west, and (5) the low radioactivity levels (note gamma logs) of Eocene and younger strata. The low radioactivity of these strata when compared to the older Tertiary and Cretaceous strata implies a major change in provenance following the Paleocene Epoch. The gamma log signature represents a useful tool for defining the Paleocene/Eocene boundary in the study area.

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DESCRIPTION OF GEOLOGIC UNITS

Unit M₁

This unit is composed of fine to coarse, poorly sorted sand in a heavily stained clay matrix. The sand is predominantly subangular quartz containing minor amounts of dark heavy minerals and mica. The clay matrix ranges from off-white to yellow-orange to red; this variegated color is probably caused by subaerial weathering and oxidation at the present land surface. A layer of grit and fine gravel marks the basal contact, but gravel layers within the unit are rare. No traces of calcium carbonate, silicification, or megafossils were recognized in any of the samples.

No biostratigraphic data were obtained from unit M₁, but its position above units E₈ and O₁ suggests that it is post-Eocene and probably post-Oligocene in age. Accordingly, we have assigned a Miocene age to this unit. Although stratigraphic correlation of unit M₁ with other geologic units is tenuous, unit M₁ is most likely an updip lithofacies of the Hawthorn Formation of eastern Georgia and western South Carolina (table 2).

Unit O₁

This unit is composed of clay and fine to medium, well-sorted sand containing thin chert lenses and nodules. The sand is largely subangular to subrounded quartz, but also contains mica and fine dark heavy minerals. The base of the unit consists of thinly interbedded sand and clay, whereas the upper part of the unit is massive to poorly bedded and contains red staining suggestive of subaerial weathering. Some sand layers have a brown to orange clay matrix. Some chert fragments contain megafossil impressions, which suggests that the chert layers may be silicified limestone beds.

No diagnostic fossils have been recovered from unit O₁. Its position atop beds of latest Eocene age (unit E₈) suggests that it is probably Oligocene, but it may be younger. The well-sorted sand, the thinly bedded clay and sand at the base, and the fossiliferous chert layers suggest that O₁ strata were deposited in a shallow, nearshore marine environment.

The probable biostratigraphic equivalent of unit O₁ in South Carolina (table 2) is the upper part of the Cooper Formation (Hazel and others, 1977). In eastern Georgia and adjacent South Carolina, the biostratigraphic and lithologic equivalent of unit O₁ could be the Tobacco Road Sand Member of the Barnwell Formation. Although the Tobacco Road Sand Member is considered late Eocene (Jacksonian) by Huddlestone and Hetrick (1979), Nystrom and Willoughby (1982) and Prowell and O'Connor (1978) present evidence that it could be Oligocene.

Unit E₈

This unit is divided into two subunits, E_{8a} and E_{8b}, to include a lithofacies recognized only in the Midville test well. Biostratigraphic evidence presented below suggests that these subunits are age-equivalent lithofacies; therefore, they are classified under the same unit heading.

Subunit E_{8a} is a fine to medium clayey sand

containing thin beds of impure limestone, thin clay layers, and beds of well-rounded gravel. The sand is largely well-sorted, subangular to subrounded quartz, but small amounts of mica, fine dark heavy minerals, and white kaolin fragments also are present. The clayey matrix, largely kaolinite with some illite/smectite, is typically buff, orange, or red. Some sand layers have a weak calcareous cement, but these are generally in the lower part of the subunit. The base of subunit E_{8a} in eastern Georgia and South Carolina is marked by very coarse grit and fine gravel, whereas west of the Midville test well the base contains thin fossiliferous limestone beds.

In the Midville test well, a thick sequence of green-to-gray marl (subunit E_{8b}) occupies the same stratigraphic position as subunit E_{8a} in the other wells. The cuttings obtained from the marl suggest that it is a fairly uniform mixture of fine sand, clay, and calcium carbonate containing minor amounts of glauconite and fine dark heavy minerals. The geophysical logs for the Midville test well suggest that the marl is massive to uniformly bedded and that it contains some phosphate layers near the top. Some shell fragments were observed in the cuttings, but the bulk percentage of shell material in the subunit is unknown.

Microfossils collected from the carbonate layers in subunit E_{8a} and from the marl at the top of subunit E_{8b} are largely dinoflagellates and calcareous nannofossils. Preservation is only fair, and many taxa are represented by only a few specimens per sample. Pollen is never more than a minor constituent. The identified calcareous nannofossils include *Isthmolithus recurvus* Deflandre, *Discoaster barbadiensis* Tan Sin Hok, and *Cyclococcolithus reticulatus* Gartner & Smith, which indicate a late Eocene (Jacksonian) age (Zones NP 19/20). Diagnostic dinoflagellates found in unit E₈ include *Adnatosphaeridium* sp., *Areosphaeridium dictyostilum* (Menéndez) Sarjeant, *Batiacasphaera compta* Drugg, *Deflandrea* cf. *D. heterophlycta* Deflandre & Cookson, *Homotryblium floripes* (Deflandre & Cookson) Stover, *Kisselovia coleothrypta* (Williams & Downie) Lentini & Williams, *Membranophoridium aspinatum* Gerlach, *Pentadinium laticinctum* Gerlach, *Samlandia chlamydochora* Eisenack, and *Spiniferites* spp. In addition, a single specimen of *Cordosphaeridium funiculatum* Morgenroth was found at Midville (100-110 ft), and *Distatodinium virgatum* Stover and *Phthanoperidinium comatum* (Morgenroth) Eisenack & Kjellström were found at Wrightsville (191 ft). The well-sorted sand and associated rounded gravels, the limestone beds, and the abundant microfossils suggest that subunit E_{8a} was deposited in a nearshore marine environment, probably as part of a shallow shelf-barrier complex. The massive nature of subunit E_{8b} suggests that it accumulated in deeper water, perhaps in a more open-shelf environment.

The biostratigraphic equivalent of unit E₈ in western Georgia and eastern Alabama is the Ocala Limestone, whereas in western Alabama it is the Yazoo Clay (table 2). In central and eastern Georgia, the biostratigraphic and lithostratigraphic equivalents of subunit E_{8a} are the Irwinton Sand Member and the Tobacco Road Sand Member(?) of the Barnwell Formation (Huddlestone and Hetrick, 1979). The equivalent of subunit E_{8b} is the lower part of the Cooper Formation of western South Carolina (Gohn and others, 1977).

Unit E₇

Unit E₇ is a dark-gray to green carbonaceous clay to marl containing beds of silt, fine sand, and limestone. Glauconite, phosphate, mica, and fine dark heavy minerals are secondary components. Silica-cemented nodules are locally present in unit E₇ but they are of uncertain origin. The lower part of the unit is generally massive, whereas the upper part is well bedded and typically thinly laminated. Cores from this unit have a hackly fracture that is commonly characteristic of a high montmorillonite content. Macrofossiliferous limestone beds occur throughout the sequence and the matrix contains abundant microfossils.

Samples from unit E₇ contain a variety of microfossils. Diagnostic calcareous nannofossils include *Isthmolithus recurvus* Deflandre, *Cyclococcolithus reticulatus* Gartner & Smith, *Discoaster barbadiensis* Tan Sin Hok, and *Discoaster saipanensis* Bramlette & Riedel, which are indicative of a late Eocene (Jacksonian) age (Zone NP 19/20). Characteristic dinoflagellates from this unit are *Batiacasphaera baculata* Drugg, *Batiacasphaera compacta* Drugg, *Cordosphaeridium funiculatum* Morgenroth, *Kisselovia coleothrypta* (Williams & Downie) Lentin & Williams, *Milliodinium* sp., *Palaeocystodinium golzowense* Alberti, *Pentadinium laticinctum* Gerlach, *Rhombodinium draco* Gocht, and *Samlandia chlamydothora* Eisenack. In addition, *Membranophoridium aspinatum* Gerlach was found in the Arrowhead well at a depth of 102 ft. Preservation is fair and diversity is low, but these species indicate a late Eocene to early Oligocene age. The abundance of marine microfossils in this unit, the beds of limestone, and the thinly laminated clay to marl suggest that this unit was deposited in a marine shallow-shelf environment.

The lithologic and biostratigraphic equivalent of unit E₇ in eastern Georgia (table 2) is the Twiggs Clay Member of the Barnwell Formation (Huddleston and Hetrick, 1979). In western Georgia, the biostratigraphic equivalent is the Ocala Limestone, and in coastal South Carolina it is the lower part of the Cooper Formation (Gohn and others, 1977; Hazel and others, 1977).

Unit E₆

This unit is a well-sorted calcareous quartz sand containing beds of silty to sandy marl and layers of bivalve shells and shell fragments. The sand is fine to medium, subrounded to rounded, clear quartz enclosed in a matrix of buff to gray calcium carbonate. The base of this unit is characteristically marked by a 5-foot-thick zone of coarse calcareous sand containing numerous bivalve shells and other macrofossils. Above this basal layer, unit E₆ consists of very calcareous sand to sandy limestone and less-common sandy marl. The upper part of the unit is less calcareous fine sand with local limestone and shell layers.

Megafossils and microfossils are present throughout the entire E₆ sequence. The moderately diverse, well-preserved dinoflagellate flora includes *Adnatosphaeridium* sp., *Corrudinium incompositum* (Drugg) Stover & Evitt, *Cyclopsiella vieta* Drugg & Loeblich, *Homotryblium flortipes* (Deflandre & Cookson) Stover, *Hystriocholpoma rigaudiae*

Deflandre & Cookson, *Kisselovia coleothrypta* (Williams & Downie) Lentin & Williams, *Palaeocystodinium golzowense* Alberti, *Pentadinium laticinctum* Gerlach, *Phthanoperidinium comatum* (Morgenroth) Eisenack & Kjellström, *Samlandia chlamydothora* Eisenack, *Selenopemphix nephroides* Benedek, *Spiniferites pseudofurcatus* (Klump) Sarjeant, and *Systematophora placacantha* (Deflandre & Cookson) Davey et al. In addition, *Areosphaeridium dictyostilum* (Menéndez) Sarjeant, *Apteodinium australiense* (Deflandre & Cookson) Williams, and *Cordosphaeridium cantharellum* (Brosius) Gocht, *Corrudinium* sp., *Dapsilidinium pseudocolligerum* (Stover) Bujak et al., *Lingulodinium machaerophorum* (Deflandre & Cookson) Wall, and *Rhombodinium draco* Gocht are present in the Laurens-1 well. These species, combined with those of overlying units, suggest unit E₆ is early late Eocene (Jacksonian). Unit E₆ marks the beginning of the upper Eocene stage in this region. The abundance of megafossils and microfossils in unit E₆, and the calcium carbonate matrix and limestone beds, indicate the strata were deposited in an open-marine environment. The calcareous sand probably was deposited in a shallow-shelf environment, and the fossil bed at the base is a lag deposit from the late Eocene marine transgression.

The biostratigraphic and lithologic equivalent of unit E₆ in central and eastern Georgia (table 2) is the Clinchfield Sand Member of the Barnwell Formation (Huddleston and Hetrick, 1979). This unit also is the biostratigraphic equivalent of the Moodys Branch Formation in western Georgia (Hazel and others, 1977).

Unit E₅

This unit is a massive, fine to medium, very clayey, calcareous quartz sand containing thin beds of fossiliferous limestone and dark gray-to-green clay. The sand is typically well-sorted, subrounded, clear quartz in a calcareous clay matrix. Traces of glauconite, phosphate, and mica have been noted in some samples. Impure limestone occurs in thin beds throughout the unit, and limestone nodules are locally present in the upper part of the unit. Numerous megafossils are concentrated in layers adjacent to some of the limestone beds, and the clay matrix is very microfossiliferous.

In this unit, the floras have low diversity, preservation is only fair, and pollen is not abundant. Calcareous nannofossil samples are characterized by *Helicosphaera compacta* Bramlette & Wilcoxon, *Cyclococcolithus reticulatus* Gartner & Smith, *Pemma papillatum* Martini, *Dictyococcites bisectus* (Hay et al.) Bukry & Percival, and *Discoaster bartadiensis* Tan Sin Hok, which indicate that unit E₅ is late middle Eocene (Zone NP 16/17). Diagnostic dinoflagellates include *Pentadinium goniferum* Edwards, *Pentadinium polypodium* Edwards, *Cordosphaeridium gracile* (Eisenack) Davey & Williams, *Membranophoridium* cf. *M. aspinatum* Gerlach and *Thalassiphora pelagica* (Eisenack) Eisenack & Gocht. In addition, *Areosphaeridium dictyostilum* (Menéndez) Sarjeant and *Rhombodinium glabrum* (Cookson) Vozzhennikova are present in the Arrowhead well at 189 ft. This flora is indicative of the upper half of the middle Eocene (late Claibornian) stage in the Gulf Coastal Plain. The massive bedding in the calcareous sand, the thin limestone beds, the shell-hash zones, and the

abundance of marine microfossils suggest that the E₅ strata were deposited in an open-marine, shallow-shelf environment.

The biostratigraphic and lithostratigraphic equivalent of unit E₅ in western Georgia is the Lisbon Formation (table 2). The equivalent unit in eastern Georgia and western South Carolina is the Lisbon Formation and (or) the McBean Formation. In eastern South Carolina, the biostratigraphic equivalent is the Santee Limestone, but the two units have somewhat different lithologies.

Unit E₄

This unit is composed primarily of fine to medium, clayey to slightly calcareous sand in central Georgia, whereas it is very calcareous sand and sandy limestone in South Carolina. Accordingly unit E₄ is divided into two subunits, E_{4a} and E_{4b}, to reflect the clastic-to-carbonate change in lithofacies in eastern Georgia. The sand unit E_{4a} typically is well-sorted, clear to smoky quartz, and some grains are well polished. The majority of the sand is fine grained, but a thin layer of coarse subangular sand may be present at the basal unconformity. Mica and dark heavy minerals are abundant in some sand layers, and lignite fragments are present in the coarser intervals. Thin clay layers are prominent in the Arrowhead and Laurens-1 cores, and the clays are well-laminated to massive and commonly highly carbonaceous, with a diverse marine microflora. Cuttings from the Wrightsville and Midville wells suggest that subunit E_{4a} contains layers of fossiliferous marl and very calcareous sand, but limestone is not present.

The cores from well VSC-2 and cuttings from well SRP-P5R indicate that subunit E_{4b} is largely a highly calcareous sand, grading to sandy, shelly limestone in the lower third of the section, with a very sandy limestone at the base. The calcareous sand is mostly clear, rounded to subrounded quartz, containing minor amounts of glauconite or phosphate. The carbonate cement typically is light gray and fine grained. The sandy limestone typically is very porous, is light-gray, and contains various quantities of megafossils or fossil molds and casts.

Samples taken from unit E₄ have a diverse microflora with fair preservation. Dinoflagellates from the lower part of the unit include a new species of *Eocladopyxis*, *Muratodinium fimbriatum* (Cookson & Eisenack) Drugg, *Pentadinium favatum* Edwards, *Pentadinium goniferum* Edwards, and *Polysphaeridium zoharyi* (Rossignol) Bujak et al. Samples from the upper part of the unit contain *Kisselovia coleothrypta* (Williams & Downie) Lentini & Williams, *Muratodinium fimbriatum* (Cookson & Eisenack) Drugg, *Pentadinium goniferum* Edwards, "*Rhombodinium draco*" of Drugg and Stover (1975), *Samlandia reticulifera* Cookson & Eisenack, and *Thalassiphora pelagica* (Eisenack) Eisenack & Gocht. In addition, *Lentinia* spp., *Spiniferites* spp., and *Wetzeliella* spp. are present in many samples. These species establish the age of unit E₄ as lower-middle to middle-middle Eocene (middle Claibornian). The abundance of marine microfossils, layers containing megafossils, calcareous beds, and well-sorted-sand beds suggest that subunit E_{4b} was deposited in a nearshore, sediment-starved, marine environment. The less-calcareous nature of subunit E_{4a} to the west suggests that it may be part of a barrier-dominated coastline, perhaps under deltaic

influence as implied by the carbonaceous debris and massive clay deposits.

The biostratigraphic equivalent of unit E₄ in western Georgia and Alabama is the lower half of the Lisbon Formation (table 2). The calcareous strata (E_{4b}) in the VSC-2 well may be correlative with parts of the Warley Hill Marl and (or) Congaree Formation of South Carolina (Pooser, 1965), the Moultrie Member of the Santee Limestone (Ward and others, 1979), and possibly the upper part of the Huber Formation (Buie, 1978) of eastern Georgia. The noncalcareous parts of unit E₄ are lithologically similar to strata of the Huber Formation, whereas the calcareous parts resemble the lithofacies in the Lisbon Formation.

Unit E₃

This unit is composed of fine to coarse, moderately sorted, slightly clayey sand containing a few thin beds of clay or silty clay. The sand is mostly clear or smoky quartz and is generally subrounded. Well-rounded quartz gravel locally is present in thin beds near the base of the unit. The unit also contains a moderate amount of fine to coarse muscovite, a variety of dark heavy minerals, lignite, and traces of glauconite. The matrix clays tend to be olive-green to gray, depending on the concentration of disseminated carbon, and the color of the sand ranges from white to gray to light olive, depending on the clay matrix. Clay-lined burrows are present in the sandier beds, and inclined bedding in the cored intervals suggests the presence of cross bedding. Discrete clay layers are uncommon, and those present are only a few feet thick and generally highly carbonaceous. No calcium carbonate or megafossils have been recognized anywhere in the unit. In the Arrowhead well, the top of unit E₃ is cemented and is stained bright red. This would suggest the possibility of subaerial weathering prior to the deposition of unit E₄.

The few carbonaceous clay layers in unit E₃ are characterized by a microflora of low diversity. Preservation is only fair, but some diagnostic dinoflagellates have been identified. The important species are *Achilleodinium biformoides* (Eisenack) Eaton, "*Lanternosphaeridium lanosum*" of Drugg and Stover (1975), *Pentadinium favatum* Edwards, and *Wetzeliella/Gochtodinium*. These species are indicative of an early middle Eocene (early Claibornian) age. The presence of a marine microflora, the clay-lined burrows, and predominance of sand in the unit suggests that deposition was in a very nearshore, marine environment. The presence of lignite and carbonaceous debris throughout the unit suggests that unit E₃ may have been part of a deltaic complex.

The biostratigraphic equivalent of unit E₃ in Alabama is the upper part of the Tallahatta Formation (table 2). In eastern Georgia, the biostratigraphic equivalent is the upper part of the Huber Formation. Unit E₃ is lithologically similar to the updip part of the Tallahatta Formation of western Georgia and eastern Alabama and to the sandy phases of the upper half of the Huber Formation of central and eastern Georgia.

Unit E₂

This unit is composed of fine to very coarse, subrounded to subangular, moderately sorted sand

containing a minor amount of white clay matrix. The sand is mostly clear to smoky quartz and includes some muscovite and sparse dark heavy minerals. Large lignite fragments are common in the coarser intervals, and one very thin carbonaceous clay layer is present at the base of the sequence. Unit E₂ is present only in the Arrowhead well, and core recovery in this interval was poor. Unit E₂ is very similar to unit E₃, but a red to orange staining at the top of E₂, and the distinct microflora of the carbonaceous clay layer, imply that it is a separate stratigraphic unit of limited extent.

Preservation of microflora in unit E₂ is very poor, and many specimens are fragmented. Characteristic dinoflagellates that have been identified are *Cordosphaeridium gracile* (Eisenack) Davey & Williams, *Kisselovia coleothrypta* (Williams & Downie) Lentin & Williams, and *Wetzeliella varielongituda* Williams & Downie. The presence of *K. coleothrypta* and the microflora assemblage of overlying unit E₃ suggests that the E₂ strata were deposited in the early Eocene, but E₂ clearly is not the oldest lower Eocene unit in the stratigraphic section. The relatively well-sorted quartz sand, lignite fragments, carbonaceous clay, and marine microflora suggest that unit E₂ probably is a proximal marine deposit associated with deltaic deposition.

This unit probably is the biostratigraphic equivalent of the middle lower Eocene "Tallahatta" Formation of Hazel and others (1984) and the lower Eocene part of the Tallahatta Formation as defined by Bybell and Gibson (1985) in Alabama, which is lithologically continuous with the middle Eocene Tallahatta Formation (table 2). The lithologic similarity of unit E₂ to unit E₃ in the Arrowhead test well supports the observation of Hazel and others (1984) and Bybell and Gibson (1985) regarding redefinition of the Tallahatta strata.

Unit E₁

This unit is composed of thick sequences of well-laminated to massive clay containing thinner beds of moderately to well-sorted quartz sand. The clay layers in this unit are largely silty to sandy kaolin and contain various amounts of carbonaceous material. The clay beds with no carbonaceous material appear massive and are generally off-white to buff. The presence of carbonaceous material gives the clay beds a well-laminated appearance, highlighting subtle textural differences. The amount of carbonaceous material in unit E₁ is greatest in the Arrowhead well and diminishes to the east. Cores from well VSC-2 contain only minor amounts of finely disseminated carbon, giving the clays a pale-gray color. The sand beds in unit E₁ are generally fine to medium grained, although layers of coarse sand and gravel may be present. The sand is largely subangular quartz containing large amounts of muscovite and minor dark heavy minerals. Large lignite fragments are common, and inclined layers suggest the presence of crossbedding.

The diversity of microflora in unit E₁ is low, but preservation is fair. Diagnostic dinoflagellates include "*Eocladopyxis peniculata*" of Williams and Brideaux (1975), *Hafniasphaera goodmanii* Edwards, *Wetzeliella* sp., *Wilsonidium tabulatum* (Wilson) Lentin & Williams, and *Wetzeliella* cf. *W. hampdenensis* Wilson. These species suggest that unit E₁ is of early Eocene age and slightly older than unit E₂. The

massive clays, the abundance of carbonaceous material, and a marine microflora suggest that unit E₁ was deposited in a proximal marine environment, probably as part of a large delta complex.

Unit E₁ is the biostratigraphic equivalent of the Bashi Formation (formerly Bashi Member of the Hatchetigbee Formation of Alabama) and possibly of the Fishburne Formation of eastern South Carolina (table 2). The clayey parts of the unit are lithologically similar to the clayey parts of the Bashi Formation except that the Bashi tend to be calcareous, whereas E₁ strata are not.

Unit P₂

This unit is composed of fairly dense, silty to sandy kaolin containing some mica, fine dark heavy minerals, and minor amounts of carbonaceous material. The kaolin is largely off-white to buff, with pale red and orange streaks in most of the unit. Coarse sand in a clay matrix may be present at the base of P₂, but the unit is otherwise largely clay in western areas and becomes much siltier to the east. The sand in the section is fine to coarse and largely angular. Finely disseminated carbon is present in many areas, as evidenced by the pale gray color in some intervals. Only in the Arrowhead well is there a concentration of carbonaceous material suitable for paleontological analysis. The upper surface of unit P₂ locally shows signs of desiccation and neomineralization in the form of pyrite-filled cracks localized in the upper foot of the kaolin.

Unit P₂ is barely fossiliferous and preservation of microflora is poor. The sample from the Arrowhead well contains the dinoflagellates *Eocladopyxis peniculata* Morgenroth and *Lentinia* sp. The former species ranges in age from late Paleocene to Eocene, but the position of unit P₂ relative to unit E₁ and the lithologic similarity of P₂ with known Paleocene formations strongly suggest that its age is late Paleocene. The presence of marine microfossils indicates that unit P₂ was deposited in or near a marine environment, but the uniformity and post-deposition alteration of the unit makes it difficult to establish the depositional environment. This unit could have been laid down in a large delta complex during late Paleocene time, or it could be an open-marine shelf deposit with post-depositional processes removing the characteristic marine constituents.

The biostratigraphic equivalents of unit P₂ in western Georgia are the Nanafalia Formation and the Baker Hill Formation of Gibson (1982). In western South Carolina, the biostratigraphic equivalent of unit P₂ is probably the upper Paleocene Black Mingo Formation, whereas in eastern South Carolina it is the upper part of the Black Mingo Group of Van Nieuwenhuise and Colquhoun (1982).

Unit P₁

This unit is a poorly consolidated clayey sand grading vertically to a laminated silty clay. The basal contact is marked by a coarse, angular quartz sand containing a small percentage of kaolin matrix. The sediment overlying this basal sand is generally fine to medium, poorly sorted, angular quartz sand and silt. Matrix kaolin reaches a maximum of 30 percent of the bulk sample. The sand is typically smoky quartz, which combines with the off-white to pale-gray clay to

give unit P₁ a characteristic light-gray appearance. Mica, dark heavy minerals, clay clasts, and lignite fragments are also common in the sandier parts of this unit. The upper half of unit P₁ is characteristically very clayey and very carbonaceous as compared to the lower half of the unit. The upper clayey sequence is composed of thinly laminated silty clay and very micaceous clay. Medium- to dark-gray layers of thinly bedded, highly carbonaceous clay are indicative of the upper part of unit P₁. In eastern Georgia and South Carolina, the upper part of P₁ contains beds of sandy clay, which contain significant amounts of cristobalite. The cristobalite, in conjunction with the kaolin matrix, causes the beds to be moderately indurated and colors them pale green. The tops of clay-rich beds may show red staining, probably from the oxidation of iron-bearing heavy minerals during a hiatus in deposition.

Samples of the gray clays from cores in unit P₁ contain diagnostic assemblages of pollen, dinoflagellates, and calcareous nannofossils. Calcareous nannofossils from the middle of unit P₁ include *Chiasmolithus consuetus* (Bramlette & Sullivan) Hay *et al.*, *Cruciplacolithus tenuis* (Stradner) Hay & Mohler, and *Neochiastozygus concinnus* (Martini) Perch-Nelson, which are characteristic of Zone NP 3. Dinoflagellates from this unit are poorly preserved but include *Cordosphaeridium fibrospinosum* Davey & Williams, *Deflandrea* sp. cf. *D. diebelii* of Drugg (1967), Peridiniacean cyst sp. B of Edwards (1980), *Senegalinium obscurum* (Drugg) Stover & Evitt, *Palaeoperidinium pyrophorum* (Ehrenberg) Sarjeant, and *Spinidinium densispinatum* Stanley. In addition, samples from the base of unit P₁ in the western wells contain *Danea californica* (Drugg) Stover & Evitt, and samples from the top of P₁ contain *Andalusiella* sp. aff. *A. polymorpha* of Edwards (1980), *Fibradinium annetorpense* Morgenroth, *Fibrocysta bipolaris* (Cookson & Eisenack) Stover & Evitt, *Hafniasphaera septata* (Cookson & Eisenack) Hansen, and Peridiniacean cyst sp. C of Edwards (1980). All of these microflora are indicative of a Paleocene (Midwayan) age. The well-developed marine flora in unit P₁ and the high percentage of organic debris suggest that the unit was deposited in a restricted to open-marine environment, perhaps along the margin of a large delta. The sand at the base of the unit may represent the delta-front deposits, whereas the clays in the top of the unit may be bay and channel fills or back-barrier lagoon deposits.

In some wells (for example, the Arrowhead well), unit P₁ can be easily subdivided into a sand unit and an overlying clay unit; however, they are considered together in this report because this separation is not always possible (for example, Laurens 1). Biostratigraphically, the sand in the lower part of P₁ in the Arrowhead well is equivalent to the Clayton Formation of western Georgia, and the clay in the upper part of P₁ is equivalent to the Porters Creek Formation (table 2). The lower part of P₁ contains a considerable amount of sand, as does the updip Clayton Formation (Reinhardt and Gibson, 1980), but open-marine indicators such as glauconite and megafossils, which characterize the Clayton, are not present in P₁. Similarly, only the black, finely laminated clays in the upper part of P₁ resemble the Porters Creek lithology of western Georgia. The white kaolinic clays in the upper part of P₁ resemble the lower part of the Huber Formation of Buie (1978). However,

sediments of the Ellenton Formation of Siple (1967) more closely match the lithology of unit P₁ and also are biostratigraphically equivalent (Faye and Prowell, 1982).

Unit UK₆

This unit is a silty clay to very clayey sand containing thin beds of clayey coarse sand and gravel. The sand is predominantly fine to medium, subangular, clear or smoky quartz, which is moderately sorted. Mica, minor feldspar, garnet, and other dark heavy minerals are present as accessory minerals. This sand characterizes the basal part of unit UK₆ and is also interbedded with the clays in the upper part of the unit. In the upper part, white to buff kaolin constitutes as much as 40 percent of the sandier beds and as much as 80 percent of the silty clay beds. Very clayey beds are typically micaceous, and some contain thin, medium- to dark-gray carbonaceous intervals. Carbonaceous debris also is present in the sandier beds but generally in the form of lignitic fragments. The top of unit UK₆ characteristically contains an orange-red oxidized zone 20 to 40 ft thick. This zone probably reflects post-UK₆ and pre-Paleocene weathering of the top of the Cretaceous strata.

Samples of pollen from the carbonaceous clay layers in this unit contain a variety of palynomorphs including *Rugbivesiculites* sp., *Pseudatlantopollis* cf. *P. simulatus*, and *Momipites* sp. (NK 3) that are representative of Upper Cretaceous (middle Maestrichtian) strata elsewhere (Christopher, 1973; Sohl and Christopher, 1983). This age designation makes unit UK₆ the youngest Cretaceous unit in the updip Coastal Plain of central Georgia. Dinoflagellates and acritarchs are present in most of the UK₆ pollen samples, but they are plentiful only in the lower parts of the unit (sandy phase). The sorting of the sand and the abundant marine microflora suggest the lower sandy beds formed in an open-marine environment. The scarcity of marine indicators and the very clayey, carbonaceous, well-sorted nature of the clayey upper part of this unit suggest that it probably is part of a restricted-marine delta plain.

The Providence Sand of western Georgia and parts of the Peedee Formation of South and North Carolina are the biostratigraphic equivalents of unit UK₆. None of these units are lithostratigraphic equivalents, but it is likely that the clayey silt and sand of UK₆ represent the more continental facies of the Providence Sand.

Unit UK₅

This unit is predominantly a well-sorted, fine to medium, subrounded quartz sand and silt containing minor amounts of fine mica, feldspar, and dark heavy minerals. Off-white to buff kaolin forms a matrix for the sand east of the Laurens-1 well, whereas the clay in the Laurens and Pulaski wells is medium to dark green and probably montmorillonitic. Samples from these wells also contain shell fragments in small quantities. The sand at the base of the unit typically contains more clay in the matrix, whereas the top of the unit is generally finer and may or may not contain clay. Thin beds of micaceous, highly carbonaceous clay are present throughout the unit, and lignitized wood is present in many samples of this clay.

Pollen samples taken from the carbonaceous

clays in unit UK₅ contain a diverse assemblage. The microflora includes *Rugubivesiculites* sp., *Triatriopollenites* sp. B (NP 2), *Betulaceipollenites* sp. A (NO-3), and aff. *Plicapollis* sp. A (NN-1), which are indicative of Late Cretaceous (early Maestrichtian) age elsewhere (Christopher, 1978; Sohl and Christopher, 1983). All of the samples contain an abundance of dinoflagellates and acritarchs, suggesting an open-marine environment. The subrounded, well-sorted nature of the sand and the microfossil evidence suggest that unit UK₅ is part of a back-barrier and barrier-bar complex.

The biostratigraphic equivalents of unit UK₅ are the Ripley and upper Cusseta Formations in western Georgia (Sohl and Smith, 1980), the Black Creek Formation of South Carolina, and the lower part of the Peedee Formation in North Carolina (Christopher, 1978; Sohl and Christopher, 1983). In many ways, the sands of unit UK₅ lithologically resemble the crossbedded sand in the Ripley Formation described by Reinhardt and Gibson (1980). Similarly, unit UK₅ also resembles some lithofacies of the Black Creek Formation, but does not contain the abundant carbonaceous debris characteristic of the Black Creek.

Unit UK₄

Unit UK₄ is divided into two subunits, UK_{4a} and UK_{4b}, to describe a facies change that occurs between the Arrowhead and Laurens test wells. The upper part of UK_{4b} in the Laurens-1 and -3 wells may contain some of the UK_{4a} lithofacies, but no core was recovered from this interval.

Subunit UK_{4a} is a gray-to-green clayey silt to fine sand that is very micaceous, very carbonaceous, and locally glauconitic. The base of the subunit is marked by a slightly clayey, fine to coarse quartz sand about 25 ft thick, whereas the overlying strata are thinly laminated and some intervals are burrowed. Parts of UK_{4a} contain shells of bivalves and other microfossils, but they typically are not confined to discrete beds. The fossiliferous part of the subunit contains some thin limestone beds and calcareous cement in the clays. Dark heavy minerals are present, but they have not been identified individually.

Subunit UK_{4b} is a clayey quartz sand to silty clay containing thick carbonaceous clay beds. The sand is generally fine to medium, subangular to subrounded quartz and is typically light gray. Dark heavy minerals and minor amounts of feldspar, mica, and nodular pyrite are also present. Clay-rich layers contain minor amounts of silt and sand and are thinly laminated. Some of the laminae contain abundant mica and fine-grained heavy minerals. Beds of soft, coarsely crystalline kaolin are characteristic of the top of unit UK_{4b} and are of commercial purity in many instances.

Pollen samples collected from the carbonaceous clays in unit UK₄ contain *Rugubivesiculites* sp., *Plicapollis* sp. B (NN-1), *Holkopollenites* sp. (CP3E-1), *Casuarinidites* cf. *C. granilabratus* (NO-2), *Choanopollenites* sp. B (NA-7), and *Osculapollis aequalis* (NO-1). These fossils indicate a Late Cretaceous (late Campanian to earliest Maestrichtian(?)) age (Christopher, 1978; Sohl and Christopher, 1983). Samples from the Arrowhead and Laurens-1 and -3 test wells contain an abundance of dinoflagellates and acritarchs suggestive of an open-marine source. An open-marine environment would

similarly explain the numerous bivalve shells in the Arrowhead samples. Marine macrofossils are absent in unit UK₄ east of the Arrowhead test well, and marine microfossils are much less abundant east of the Laurens test wells. The decline in the number of marine organisms from west to east suggests that the environment of deposition becomes marginal marine to restricted marine in eastern Georgia and South Carolina. The thinly laminated sand, silt, and clay of subunit UK_{4b} and its highly carbonaceous clays most likely reflect a delta-plain environment subjected to active marine influence. The massive, glauconitic, and fossiliferous nature of subunit UK_{4a}, however, probably reflects a delta-front or prodelta environment.

Unit UK₄ is the biostratigraphic equivalent of the lower part of the Cusseta Formation of western Georgia and parts of the Black Creek Formation of South and North Carolina (table 2). Subunit UK_{4a} resembles some lithofacies of the Cusseta, but otherwise could not be lithologically equated with the formation. The black laminated parts of subunit UK_{4b}, however, are very similar to the outcropping Black Creek Formation of the Carolinas, and a lithologic correlation with that unit is reasonable.

Unit UK₃

This unit exists only in the Arrowhead and Laurens-3 test wells and consists of a basal clayey sand to silt overlain by thick alternating beds of silty clay and medium to coarse sand. The silty clays in the basal part of the unit are highly carbonaceous and contain abundant mica. In the Arrowhead test well, a section consisting of well-defined cyclic alternations of sand and clay overlies this basal section. Three complete sand-clay cycles are present in the Arrowhead well, and perhaps one is present in the top of unit UK₃ in the Laurens-3 well. The sand layer in a typical cycle generally consists of medium to coarse, moderately sorted, subangular quartz with only a minor amount of clay as a matrix. The quartz typically is clear or light gray, and accessory minerals include feldspar, mica, and dark heavy minerals. The clay layer in a typical cycle is largely clayey silt to silty clay with minor amounts of sand dispersed throughout the layer. Sandier intervals within the clay layer characteristically contain abundant mica. Some intervals within the clay layers are highly carbonaceous, but typically the tops of the clay layers are stained red by iron oxidation, possibly due to subaerial weathering.

Pollen samples collected from the carbonaceous clay layers contain a diverse suite of palynomorphs including *Rugubivesiculites* sp., *Comp'extipollis abditus* (NB-1), *Holkopollenites* sp. A (CP3D-1), *Proteacidites* sp. B (PR-1), and *Trudopollis* sp. A (NF-1), which indicate a Late Cretaceous (early to middle Campanian) age (Christopher, 1978; Sohl and Christopher, 1983). Dinoflagellates and acritarchs are present in all of the samples, but the quantity and diversity of forms is very limited. The sand-clay cycles and the marine microfossils suggest that unit UK₃ was probably part of a delta-plain or nearshore estuarine environment similar to the depositional environment of unit UK₂. Unit UK₃, however, lacks many of the high-energy characteristics typical of unit UK₂.

The Blufftown Formation of western Georgia is

the biostratigraphic equivalent of unit UK₃, but it is not the lithostratigraphic equivalent. The Blufftown, according to Reinhardt and Gibson (1980), contains a significant amount of glauconite, calcareous clay, and other open-marine indicators. Strata of similar age have not been reported from the outcropping Cretaceous in South Carolina, but Christopher (1978) identified a similar microflora in the Clubhouse Crossroads corehole near Charleston, S.C., and along the Cape Fear River in North Carolina (Sohl and Christopher, 1983). Gohn and others (1977) described the South Carolina sediments as gray to grayish-green, calcareous, fossiliferous silty clay and muddy sand, and placed them in the lower part of the Black Creek Formation. Hence, it appears that unit UK₃ is confined to the subsurface of central and eastern Georgia.

Unit UK₂

This unit is a poorly consolidated clayey sand composed of fine to very coarse, angular to subangular quartz sand, silt, and some smoky-quartz gravel in a matrix of soft, white to buff kaolin. The quartz sand is generally clear to white, or, less commonly, gray to light red, whereas the quartz gravel is predominantly light to dark gray. Minor amounts of feldspar, sparse to abundant mica, staurolite, garnet, pyrite, monazite, and unidentified heavy minerals are also present. Kaolin balls and lignite fragments are present in the sandier beds. Bed thickness and grain size are highly variable, and inclined bedding suggests the presence of crossbedding. Fining-upward cycles consisting of coarse sands that grade upward into clay-and-silt layers are common, and a zone of iron oxidation and red staining typically exists at the top of the clay and silt beds.

Pollen samples from unit UK₂ yield moderate numbers of palynomorphs including *Rugubivesiculites* sp., *Porocolpopollenites* sp. (CP-3b), *Minorpollis* sp. B, *Complexiopollis* sp. B, and *Complexiopollis* sp. D, which characterize Pollen Zone V and indicate a Late Cretaceous (Santonian) age (Christopher, 1982). The occurrence of dinoflagellates and acritarchs in the pollen-bearing clays indicates a definite marine influence during deposition, but the relatively low percentage of marine microfossils per sample suggests that marine influence was restricted. The variability of grain size, evidence of crossbedding and fining-upward cycles, and marine microflora suggest that unit UK₂ was deposited in a lower delta plain or in a proximal marine environment.

Christopher and others (1979) report that a similar microflora exists in the Middendorf Formation of South and North Carolina and in the Eutaw Formation of western Georgia. In regard to environment of deposition and lithology, unit UK₂ closely resembles the Middendorf Formation of the Carolinas. In eastern Georgia, unit UK₂ can be distinguished from unit UK₁ by its lack of cristobalite, lack of induration, and increased amount of carbonaceous debris.

Unit UK₁

This unit is a dense clayey sand composed of poorly sorted, fine to very coarse, angular quartz sand and some smoky-quartz gravel in a matrix of buff to pale-green cristobalitic kaolin. A 1- to 2-foot-thick

bed of very coarse quartz gravel marks the basal unconformity, regardless of underlying rock type. The sand fraction in this unit is largely quartz in a variety of colors (pink-to-red, white, gray, and clear), but it also contains minor amounts of potassium feldspar, mica, and a variety of heavy minerals including garnet, staurolite, and monazite. The clay forming the matrix and individual clay beds is mostly kaolinite with minor montmorillonite. Alternating beds of different grain size are present in fining-upward cycles, suggesting considerable variation in energy of deposition. Carbonaceous clays are rare, but lignite fragments are more common. Much of the primary carbon may have been destroyed by oxidation. Pale-orange and red staining in many of the cores suggests that the strata have experienced periodic weathering and oxidation. The abundance of cristobalite in the matrix gives unit UK₁ its distinct internal cohesion, resulting in characteristically low resistivity on electric logs. The abundance of cristobalite cannot be attributed to local rock terranes and suggests the influence of distant felsic volcanic activity.

Pollen samples from thin carbonaceous clay layers yield a low diversity of palynomorphs, which include *Rugubivesiculites* sp., *Porocolpopollenites* sp. (CP-3b), *Complexiopollis* sp. B, and *Complexiopollis* sp. D (Christopher and others, 1979). These palynomorphs are indicative of Pollen Zone V of Late Cretaceous (Santonian) age. Dinoflagellates are rare in these samples, which suggests a distal marine influence. The variability in grain size, the abundance of cristobalite, and the sparse marine flora suggest that unit UK₁ was deposited in an upper-delta-plain environment.

Christopher and others (1979) report that a similar microflora exists in the Cape Fear Formation of North and South Carolina and the Eutaw Formation of western Georgia (table 2). Lithologically, however, unit UK₁ closely resembles the Cape Fear Formation.

Unit R

This unit consists of a laterally extensive group of highly oxidized red beds that are characterized by very indurated claystones, siltstones, sandstones, and fanglomerates. Lithologic descriptions from nearby petroleum test wells (for example, Dana 1; Milton and Hurst, 1965, p. 43) indicate that similar red-bed sequences are thousands of feet thick. These rocks are stratigraphically and lithologically equivalent to the Triassic and Jurassic continental red beds exposed in North Carolina, South Carolina, and Virginia, and to similar rocks in the subsurface of the Atlantic and Gulf Coastal Plains.

Unit Pz

This unit consists of saprolite or phyllite at the upper greenschist facies of regional metamorphism and is present only in the Laurens-3 test well. Most of these rocks are probably derived from volcanoclastic materials of felsic to intermediate composition. They closely resemble metavolcanic phyllites exposed in the southern Piedmont of Georgia and South Carolina, where they have been dated by megafossil evidence as early Paleozoic (probably Cambrian) (Maher and others, 1981). Similar rock types have been reported in other Coastal Plain drill holes in nearby areas by Applin (1951) and Milton and Hurst (1965).

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