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Abstract

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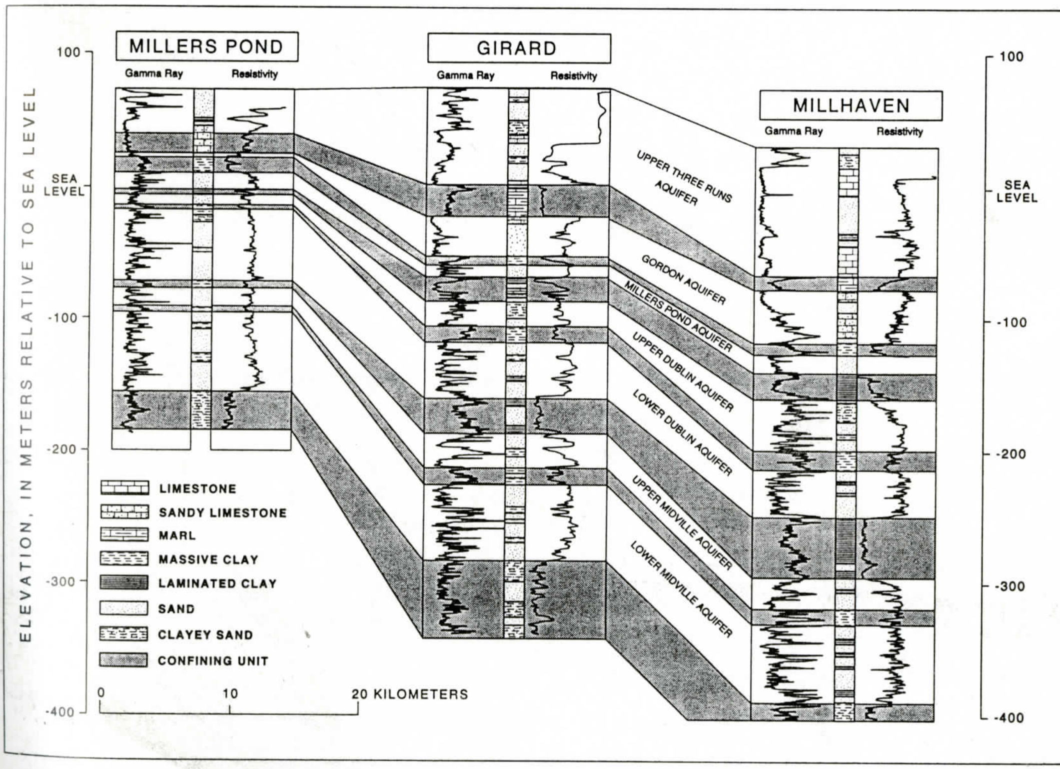

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PHYSICAL STRATIGRAPHY AND HYDROSTRATIGRAPHY OF UPPER CRETACEOUS AND PALEOCENE SEDIMENTS, BURKE AND SCREVEN COUNTIES, GEORGIA

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ABSTRACT

Six geologic units are recognized in the Cretaceous and the Paleocene sediments of eastern Burke and Screven Counties in Georgia on the basis of lithologic, geophysical, and paleontologic data collected from three continuously cored testholes in Georgia and one testhole in South Carolina. The six geologic units are separated by regional unconformities and are designated from oldest to youngest as the Cape Fear Formation, the Middendorf Formation, the Black Creek Group (undivided), and the Steel Creek Formation in the Upper Cretaceous section, and the Ellenton and the Snapp Formations in the Paleocene section.

The geologic units provide a spatial and temporal framework for the identification and correlation of a basal confining unit beneath the Midville aquifer system and five aquifers and five confining units in the Dublin and the Midville aquifer systems. The Dublin aquifer system is divided hydrostratigraphically into the Millers Pond, the upper Dublin, and the lower Dublin aquifers. The Midville aquifer system is divided hydrostratigraphically into the upper and the lower Midville aquifers. The fine-grained sediments of the Millers Pond, the lower Dublin, and the lower Midville confining units are nonmarine deposits and are present in the upper part of the Snapp Formation, the Black Creek Group (undivided), and the Middendorf Formation, respectively. Hydrologic data for specific sets of monitoring wells at the Savannah River Site in South Carolina and the Millers Pond site in Georgia confirm that these three units are leaky confining units and locally impede vertical ground-water flow between adjacent aquifers. The fine-grained sediments of the upper Dublin and the upper Midville confining units are marine-deltaic deposits of the Ellenton Formation and the Black Creek Group (undivided), respectively. Hydrologic data confirm that the upper Dublin confining unit regionally impedes vertical ground-water flow on both sides of the Savannah River. The upper Midville confining unit impedes vertical ground-water flow in the middle and downdip parts of the study area and is a leaky confining unit in the updip part of the study area. Recog-

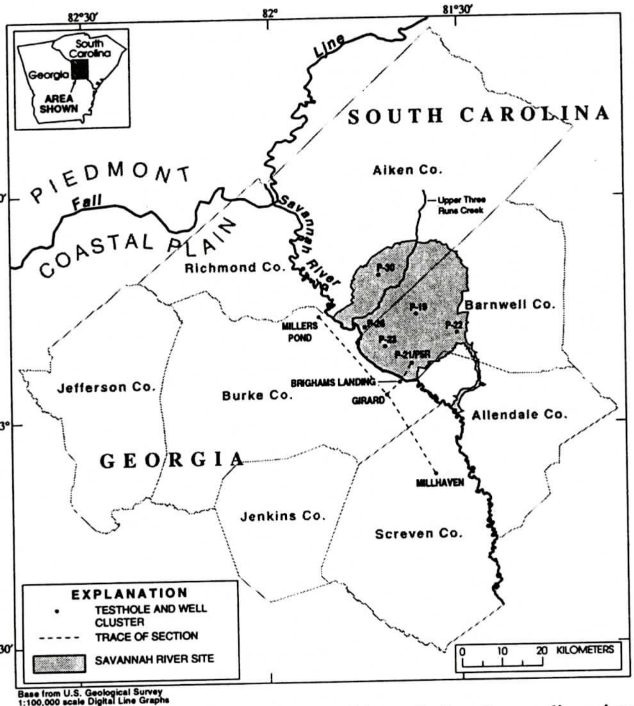

Figure 1. Location of study area and location of stratigraphic testholes along a dip-oriented section from Millers Pond to Millhaven in Georgia, and a strike-oriented section from Girard in Georgia to P-21/P5R in South Carolina.

nition of the upper Dublin confining unit as a regional confining unit between the Millers Pond and the upper Dublin aquifers also confirms that the Millers Pond aquifer is a separate hydrologic unit from the rest of the Dublin aquifer system. This multi-aquifer framework increases the vertical hydrostratigraphic resolution of hydraulic properties and gradients in the Dublin and Midville aquifer systems for the investigation of ground-water flow beneath the Savannah River in the vicinity of the U.S. Department of Energy Savannah River Site.

INTRODUCTION

The U.S. Geological Survey (USGS), in cooperation with the U.S. Department of Energy (USDOE) and the Georgia Department of Natural Resources (GDNR), began an investigation in 1991 of ground-water flow in the central Savannah River area of Georgia and South Carolina. The objectives of the study are to characterize and model ground-water flow on both sides of the Savannah River in the vicinity of the USDOE Savannah River Site (SRS) and to determine the potential for ground water to flow from one state to the other beneath the river valley, herein termed trans-river flow.

The study area for the trans-river flow investigation consists of five counties in Georgia and three counties in South Carolina and is entirely in the Coastal Plain physiographic province of the southeastern United States (fig. 1). The study area includes the SRS, a 780-square-kilometer facility on the South Carolina side of the Savannah River where nuclear materials are processed and stored. Ground water is known to be contaminated in the water table and shallow confined aquifers beneath parts of the SRS (Westinghouse Savannah River Company, 1995). The Savannah River forms the state-line boundary between South Carolina and Georgia.

Potentiometric maps for previous hydrologic studies in the vicinity of the SRS (Bechtel, 1982, Brooks and others, 1985; Clarke and oth-

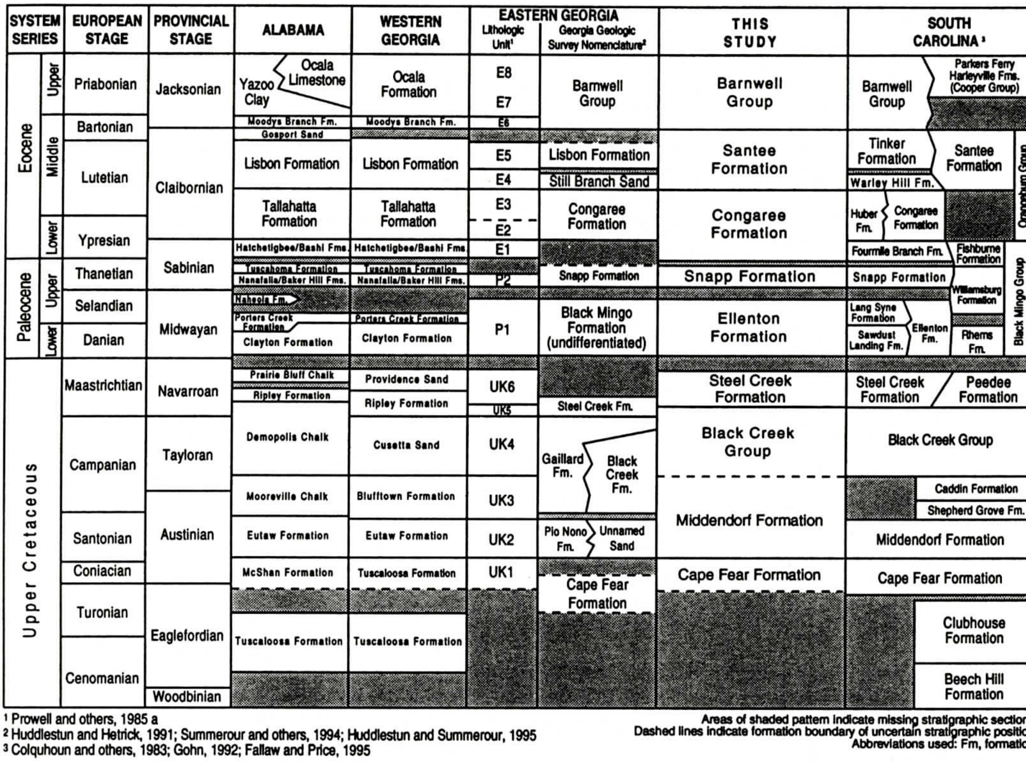

Figure 2. Generalized comparison of Cretaceous and Tertiary geologic units in the Coastal Plain physiographic province of the southeastern United States (Modified from Clarke and others, 1994).

ers, 1985; Logan and Euler, 1989; Bledsoe and others, 1990; Faye and Mayer, 1990) suggest that the direction of ground-water flow in the deep confined aquifers beneath the SRS is roughly perpendicular to the axis of the Savannah River and towards the SRS border along the Savannah River. The potentiometric maps also suggest that incision of the Savannah River alluvial valley into the Coastal Plain sediments creates a regional drain for ground-water discharge from the Coastal Plain aquifers to the modern river valley. Geologic and hydrologic data for the deeper confined aquifers beneath the Savannah River were sparse in previous investigations and leave questions about the direction of ground-water flow in the immediate vicinity of the Savannah River.

Given the uncertainties about the direction of ground-water flow at the SRS border along the Savannah River and the presence of contaminated ground water on the SRS, the trans-river flow investigation is specifically concerned with the SRS border along the Savannah River as a potential area for the trans-river flow of ground-water from the SRS to Georgia. Determining the potential for trans-river flow requires a hydrostratigraphic framework that is capable of representing the spatial distribution of hydraulic properties and hydraulic gradients in multiple aquifers beneath the study area, particularly in areas with a large vertical flow component like the area beneath the Savannah River near the SRS.

The initial phase of the study included the collection of additional subsurface data on the Georgia side of the Savannah River near the SRS. Continuously cored testholes, located in Georgia along a line parallel to the Savannah River valley, provide information about the physical stratigraphy and hydrostratigraphy in Burke and Screven Counties, Georgia (fig. 1). As a result, four Cretaceous geologic units and

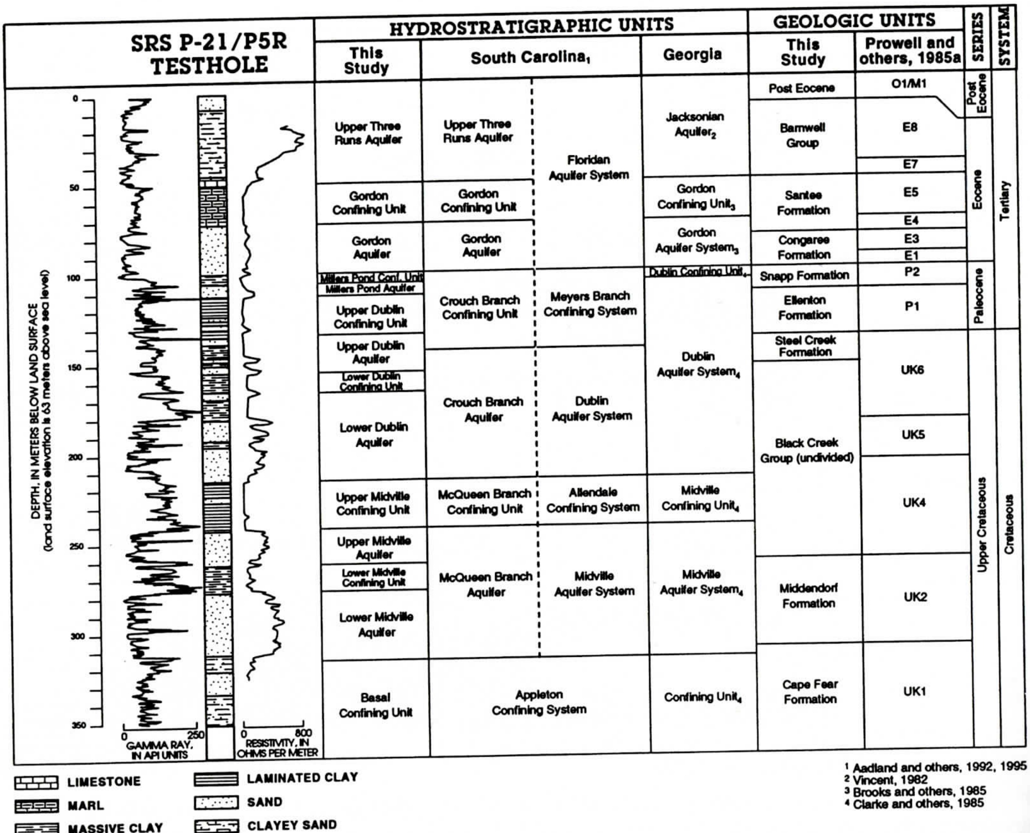

Figure 3. Comparison of hydrostratigraphic units and names applied to the P-21/P5R testhole on the U.S. Department of Energy Savannah River Site, South Carolina.

five Tertiary geologic units can be identified (fig. 2), which can be differentiated into seven aquifers and seven confining units (fig. 3).

The Savannah River alluvial valley is fully or partially incised into the two uppermost aquifers (Upper Three Runs and Gordon) along the SRS border with the Savannah River (fig. 3). The sediments of the Dublin and Midville aquifer systems are not in direct physical contact with the Savannah River alluvium in the subsurface at the SRS Savannah River border. The presence of at least one confining unit in each aquifer system and the depth of these sediments below the base of the Savannah River alluvium increases the possibility that ground water could avoid capture by the river and could flow beneath the SRS Savannah River border into Georgia in the Dublin and the Midville aquifer systems.

The sediments of the Dublin and the Midville aquifer systems (Clarke and others, 1985) are divided in this study into five aquifers and five confining units. Correlation of the aquifers and confining units is constrained by the geologic correlation of Upper Cretaceous and Paleocene strata. The internal division of these aquifer systems into aquifers and confining units provides the trans-river flow investigation with a greater hydrostratigraphic resolution, as compared to other published frameworks. Descriptions of the physical stratigraphy of the Upper Cretaceous and the Paleocene sediments and the hydrostratigraphic units of the Dublin and the Midville aquifer systems of east-central Georgia are the primary focus of this paper. Hydrologic data from specific monitoring-well sites on the SRS in South Carolina are used to evaluate the five confining units in the Dublin and the Midville aquifer systems.

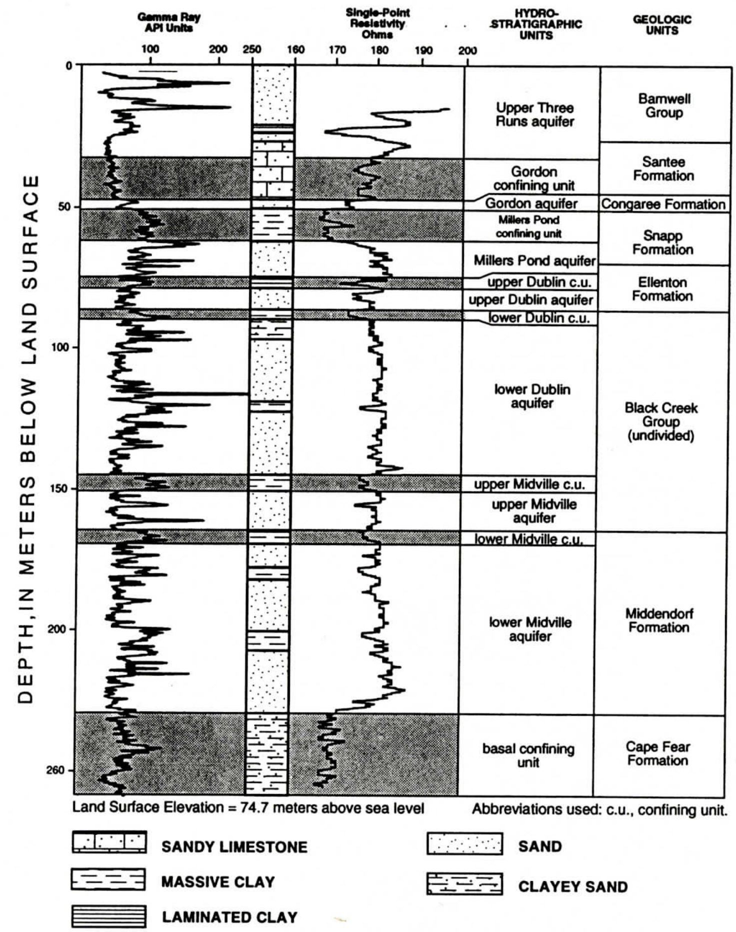

Figure 4. Geology and hydrostratigraphy of the Millers Pond site.

Study Area

The study area for this investigation is in and immediately adjacent to the Savannah River valley in Burke and Screven Counties in Georgia and the SRS in Aiken and Barnwell County in South Carolina (fig. 1). Poorly consolidated Cretaceous and Tertiary strata in the study area form a southeastward-thickening wedge of fluvial-deltaic and marine deposits (Prowell and others, 1985a; Colquhoun and others, 1983, Huddlestun and Hetrick, 1991, Fallaw and Price, 1995, Huddlestun and Summerour, 1995) underlain by Paleozoic crystalline rocks (Wait and Davis, 1986, Prowell, 1994) and Triassic-Jurassic sedimentary rocks (Marine, 1979; Wait and Davis, 1986, Snipes and others, 1993). The Coastal Plain sediments are more than 442 m (meters) thick in the Millhaven core at the downdip end of the study area (Clarke and others, 1996).

Previous Studies

Geologic investigations of Burke and Screven Counties in Georgia and adjacent counties in South Carolina have been published by Sloan (1908), Cooke and Shearer (1918), Cooke (1936, 1943), Cooke and MacNeil (1952), Huddlestun (1982, 1988), Huddlestun and Hetrick (1978, 1979, 1986, 1991), Nystrom and Willoughby (1982), Colquhoun and others (1983), Colquhoun and Steele (1985), Prowell and others (1985a), Gohn (1988), Harris and

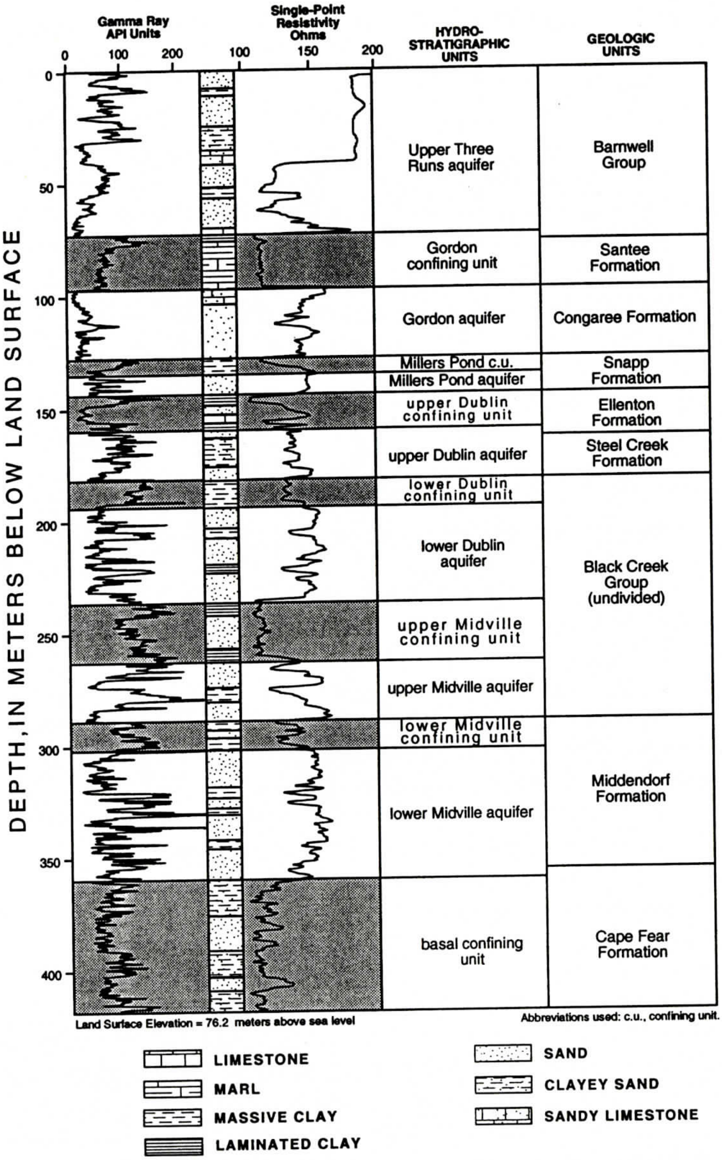

Figure 5. Geology and hydrostratigraphy of the Girard site.

Zullo (1990), Nystrom and Willoughby (1990), Fallaw and Price (1992,1995), Snipes and others (1993), and Prowell (1994). Most of the detailed geologic data in the study area are from investigations associated with the SRS, which has generated a number of engineering, hydrologic, and geologic reports, many of which have limited distribution. Site-specific reports summarizing the local geology include Christl (1964), Siple (1967), Bechtel Corporation (1972, 1973, 1982), Daniels (1974), Marine and Siple (1974), Marine (1979), Prowell and others (1985b), McClelland (1987), Dennehy and others (1989), Fallaw and others (1990a, 1990b), and Price and others (1990, 1991).

Prowell and others (1985a) correlated geologic units in the Cretaceous and Tertiary sections of the updip Coastal Plain from central Georgia to western South Carolina (fig. 2). They identified five geologic units in the Upper

Cretaceous section, two units in the Paleocene section, six units in the Eocene section, and one unit in the Oligocene section at the P-21/P5R site on the SRS (fig. 3). Their units were proposed as time-stratigraphic units and assigned an alpha-numeric designation to avoid problems with existing stratigraphic nomenclature. Subsequently, Fallaw and Price (1992, 1995) described and established a working nomenclature for the stratigraphy on the SRS. Huddlestun and Hetrick (1991) and Huddlestun and Summerour (1995) proposed a stratigraphic nomenclature for the updip part of the study area in east-central Georgia.

Hydrologic investigations in the study area and adjacent parts of South Carolina include Cahill (1982), Faye and Prowell (1982), Vincent (1982), Brooks and others (1985), Clarke and others (1985), Miller (1986), Dennehy and others (1989), Logan and Euler (1989), Bledsoe and others (1990), Faye and Mayer (1990), and Aadland and others (1992, 1995). Detailed hydrogeologic investigations of monitoring-well sites include Bledsoe (1984, 1987, 1988) and Bledsoe and others (1990) on the SRS in South Carolina; Gellici and others (1995) in South Carolina counties adjacent to the SRS; and Clarke and others (1994), Summerour and others (1994), Clarke and others (1996), Leeth and others (1996), and Kidd (1996) in Burke and Screven Counties, Georgia.

The hydrostratigraphy of the study area, as originally defined by Vincent (1982), Brooks and others (1985), and Clarke and others (1985) in east-central Georgia, and Aadland and others (1992, 1995) in South Carolina, consists of four principle aquifers/aquifer systems (fig. 3). The shallowest of the hydrostratigraphic units was designated the Upper Three Runs aquifer by Aadland and others (1992, 1995) and the Jacksonian aquifer by Vincent (1982). This unit is partially to fully incised by the Savannah River and its tributaries in the vicinity of the Savannah River border of the SRS. The Gordon aquifer system of Brooks and others (1985) beneath the SRS Savannah River border varies from unconfined at the upstream end to confined at the downstream end as a result of incision by the Savannah River alluvial valley through the sediments of the Gordon confining unit.

Clarke and others (1985) and Aadland and others (1992, 1995) described the Dublin and Midville aquifer systems as separate, confined systems in the middle and downdip parts of the study area, including the SRS Savannah River border area. Clarke and others (1985) applied the name Dublin-Midville aquifer system to the updip equivalent of the Dublin and Midville aquifer systems. Aadland and others (1992) assigned the names Crouch Branch and McQueen Branch aquifers to the updip equivalents of the Dublin and Midville aquifer systems, respectively. The change in aquifer nomenclature in updip areas corresponds to either increased leakage across confining units or the absence of a confining unit between the aquifers.

Clarke and others (1985) described a local confining unit in the Dublin aquifer system near the Savannah River which separates an upper aquifer in the Paleocene sediments from a lower aquifer in the Upper Cretaceous sediments. In South Carolina, Bledsoe and others (1990) and Aadland and others (1992, 1995) assigned the clay-dominated sediments of the Paleocene to the Crouch Branch confining unit of the Meyers Branch confining system.

METHODS

Subsurface information for the physical stratigraphy and the hydrostratigraphy in Burke and Screven Counties in Georgia was obtained from three continuously cored testholes and compared to one existing site in South Carolina (P-21/P5R) (fig. 3). Geophysical logs from a fourth testhole at Brighams Landing in the Savannah River flood plain in Burke County is used in the trans-river correlation of the Steel Creek Formation, the Ellenton Formation, and the Snapp Formation from Girard to P-21/P5R in this paper (fig. 1). The Brighams Landing testhole was not cored.

The P5R testhole was drilled in Barnwell County in 1962 as part of a study of pre-Cretaceous basement (Marine, 1979). The P-21

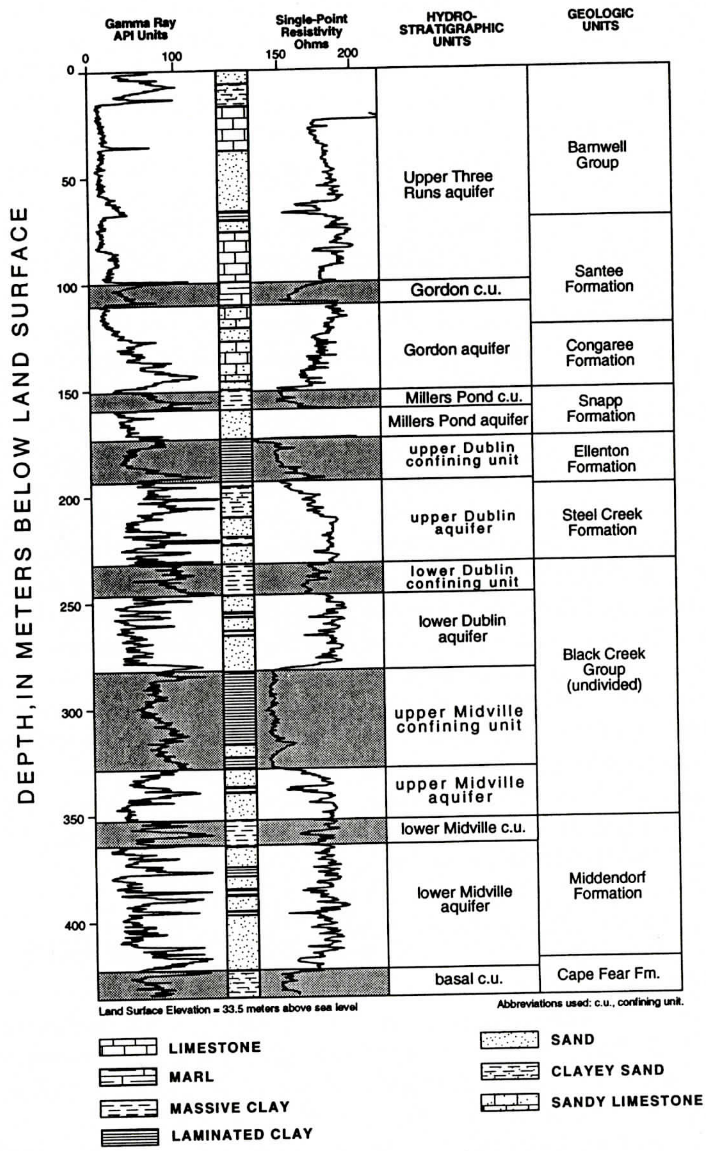

Figure 6. Geology and hydrostratigraphy of the Millhaven site.

testhole was cored adjacent to P5R in the mid-1980s as part of a baseline hydrogeologic investigation of the SRS (Bledsoe, 1987). The P-21/P5R site provides a common reference section for the comparison of the physical stratigraphy and hydrostratigraphy of this study with previous investigations.

Three of the testholes in Georgia were cored in 1991 and 1992 using a wireline-mud-rotary coring system (figs. 4, 5, and 6; Millers Pond, Girard, and Millhaven sites, respectively) and are located along a dip-oriented section in eastern Burke and Screven Counties, Georgia (fig. 7). Geophysical logging surveys for single-point and triple-point electrical resistivity, spontaneous potential, natural gamma ray, and hole diameter (caliper log) were obtained from all four Georgia testholes. Cores were examined for texture, mineralogy, sedimentary structures, diagenetic features, and recognizable

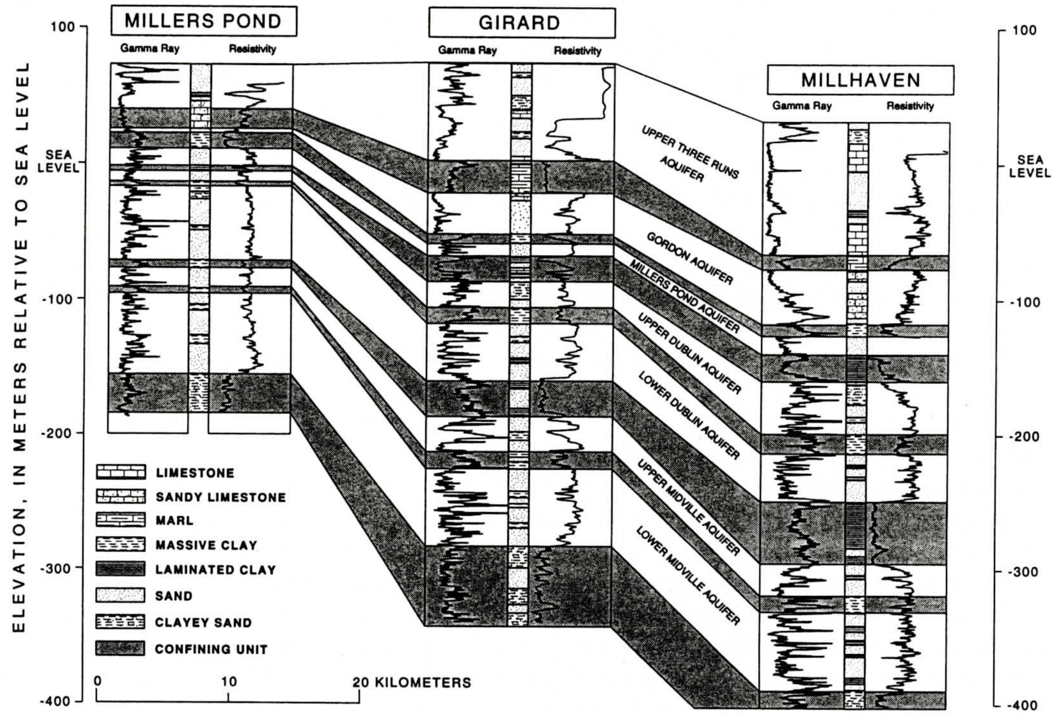

Figure 7. Dip-oriented correlation of hydrostratigraphic units from the Millers Pond testhole to the Millhaven testhole. Datum is sea level.

fossils. Selected samples were examined for dinoflagellates, pollen, foraminifera, ostracodes, and calcareous nannofossils to provide biostratigraphic control. Porosity in the aquifers was visually estimated on the basis of lithologic observations of cores (Terry and Chilingar, 1955).

Geophysical data from the testholes, and lithologic and preliminary paleontologic data from the cored sediments, were used to correlate geologic units in the Georgia testholes with the P-21/P5R site in South Carolina. The geologic units provided a spatial and temporal framework for the identification and correlation of aquifers and confining units (figs. 4, 5, and 6).

Hydrologic data from monitoring wells at Millers Pond, Girard, and Millhaven in Georgia and other monitoring-well sites on the SRS in South Carolina were used in the evaluation of hydrostratigraphic units. Monitoring wells at a specific site are closely spaced and assigned a P- well designation on the SRS as a well cluster. Each monitoring well at a cluster is screened in either a separate aquifer, part of an aquifer, or laterally transmissive part of a confining unit. The monitoring-well sites on the SRS discussed in this paper are located in areas with a strong vertical ground-water flow component. Water-level data under static and pumping conditions are used to identify vertical hydraulic gradients between aquifers in an evaluation of confining units.

Transmissivities of aquifers at the Millers Pond, the Girard, and the Millhaven sites, as reported by Snipes and others (1995), are based on time-drawdown and time-recovery aquifer tests. Their transmissivity values are divided by the saturated thickness of the aquifer, as identified in this paper, to calculate the hydraulic conductivity of the aquifers.

Vertical hydraulic conductivities of selected samples of the upper Dublin and upper Midville confining units from the Millhaven core were determined with a flexible-wall permeameter (American Society for Testing and

Materials, 1990). The vertical hydraulic conductivity was divided by the thickness of the confining unit to determine leakance of these two confining units.

PHYSICAL STRATIGRAPHY

The Upper Cretaceous and the Paleocene sections are divided in this paper into six geologic units (fig. 2). The geologic units as recognized in each of the four cored testholes are shown in figures 3, 4, 5, and 6.

The Upper Cretaceous section is divided into the Cape Fear Formation, the Middendorf Formation, the Black Creek Group (undivided), and the Steel Creek Formation (fig. 3). All four geologic units consist of siliciclastic sediments. Unit contacts, in most cases, are underlain by oxidized and iron-stained sediments and are interpreted as subaerially exposed, regional unconformities. Sediments beneath some of the unconformities are fractured or marked with root traces. The unconformities typically are overlain by lag deposits of very poorly sorted sand with granules, pebbles, and lithoclasts. All of the units are coarser-grained and more oxidized in the updip areas. This makes it more difficult to identify specific unit boundaries in the updip sediments.

The Paleocene section is divided into the Ellenton Formation and the Snapp Formation. The tops of these units are correlated as regional unconformities.

Cape Fear Formation

The Cape Fear Formation is a fine- to very coarse-grained sand with abundant granules and pebbles, and a cristobalitic clay matrix. The cristobalitic clay matrix partially lithifies the sediments in this interval and makes it lithologically distinct from the other Cretaceous units. Multiple fining-upward cycles are observed in the cores.

Most of the strata are barren of fossils. A few samples of gray and olive-gray, silty clay yield pollen. Dinoflagellates are not present in the samples from the Millers Pond core. The microflora found in the Cape Fear Formation of the Millers Pond core is similar to the microflora in unit UK1 of Prowell and others (1985a) and the Cape Fear Formation of North Carolina and South Carolina as reported by Christopher and others (1979). The microflora suggests a Coniacian to early Santonian age (Clarke and others, 1994) (fig. 2). The composition and texture of the Cape Fear sediments, as well as the microflora, are consistent with the nonmarine, upper delta-plain environment proposed by Prowell and others (1985a) and Fallaw and Price (1995).

Middendorf Formation

The Middendorf Formation is a lignitic, fine- to very coarse-grained sand with interbedded clays. This unit contains two fining-upward intervals in each of the Georgia cores. Each interval includes a basal lag and poorly sorted sand, which grades up to interbedded and interlaminated clay and sand. Mica and lignite are interlaminated with the sand and clay, particularly near the top of each interval. Clay beds at the top of each interval are generally thicker and more abundant, and have iron-oxide staining and root traces in the Millers Pond and Girard cores. Clay beds in the Millhaven core are not stained with iron oxides.

The microflora in this unit predominantly consists of pollen. Dinoflagellates are not present in samples from the Millers Pond and the Girard cores and are sparse in the Millhaven core. Palynomorphs suggest a Santonian to Campanian age. The Middendorf Formation is lithologically and geophysically correlated to unit UK2 of Prowell and others (1985a), and the Middendorf Formation at the SRS (Fallaw and Price, 1995) (fig. 2). Hetrick (1992) identified this unit in the Millers Pond core as the Pio Nono Formation. Prowell and others (1985a) did not report paleontologic results for this unit at the P-21/P5R site, but interpreted the age of the interval as Santonian on the basis of lithologic and geophysical correlation to other testholes in Georgia. The absence of dinoflagellates and other marine indicators in the Millers Pond and the Girard cores suggests deposition in a nonmarine part of a delta-plain or estuarine environment, in contrast to a marginal-marine environment reported by Prowell and others (1985a) and Fallaw and Price (1995). The microflora in the Millhaven core suggest a marginal-marine environment.

Black Creek Group (Undivided)

The Black Creek Group (undivided) is noticeably finer grained than the other Cretaceous units, particularly in downdip areas, and is the only Cretaceous unit to yield an abundant marine microflora and fauna in the Georgia cores. The unit consists of four distinct lithologic intervals in the Millhaven core: a basal lignitic sand interval; a 43-m thick interval of laminated black clay; a coarsening-upward interval of fine- to very coarse-grained sand; and an interval of oxidized clay and clayey sand at the top of the unit (fig. 6). The laminated black clay in the Girard and the Millhaven cores is the only Cretaceous lithofacies in the Georgia cores with carbonate fossils and matrix. Fossils in the black clay and the interbedded sand include pelecypods, ostracodes, benthic and planktonic foraminifera, shark teeth, and spicules. The unit is sandier, more oxidized, and more poorly sorted in the Millers Pond core. The clay beds are stained with iron oxides and are thicker relative to the downdip sediments. The updip sediments generally have less than 10 percent clay matrix in the sand beds. The oxidized clay at the top of this unit is distinguished from other oxidized clay intervals by the amount of iron-oxide staining and root traces.

The microflora includes pollen in the Millers Pond core and pollen and dinoflagellates in the Girard and the Millhaven cores. Paleontologic data for the Black Creek Group (undivided) suggest a late Campanian age for the laminated black clay interval and a late Campanian to early Maastrichtian age for the upper sand unit in all three Georgia cores. These data are consistent with the lithologic and paleontologic data reported for unit UK4, unit UK5, and the lower part of unit UK6 by Prowell and others (1985a), the Black Creek Group of Fallaw and Price (1995) at the SRS, and the updip Gaillard and the downdip Black Creek Formation of Huddlestun and Hetrick (1991) (fig. 2).

Evidence of subaerial exposure and reworking consistently was recognized at the top of the Black Creek Group (undivided) in the Georgia cores and the P-21/P5R core. Pedogenic structures and iron staining at the top of the oxidized clay, and lithoclasts of the clay in the overlying lag of very poorly sorted sand and pebbles suggest an unconformable boundary between the regressive sequence of the Black Creek Group (undivided) and the overlying depositional sequence of the Steel Creek Formation at Girard, Millhaven and P-21/P5R. This contact is not the same contact that was chosen for the top of unit UK5 by Prowell and others (1985a) and the Black Creek Group by Fallaw and Price (1995) at P-21/P5R. Beneath the thick interval of oxidized clay at the top of the Black Creek Group (undivided), they recognize a sharp lithologic boundary and lag deposit as a convenient lithostratigraphic boundary. The section in the P-21/P5R core is predominantly finer-grained sand below their contact and interbedded clay and coarser-grained sand above their contact.

Kidd (1995) used a similar difference in grain size and clay content, and a sharp lithologic contact and basal lag at a depth of 121.0 m in the Millers Pond core to identify a contact between the Black Creek Group and the Steel Creek Formation. Huddlestun and Summerour (1995) also correlated the Steel Creek Formation to the updip area of Burke County and described the contact with the Black Creek sediments as either conformable or paraconformable. They acknowledged the difficulty of recognizing a specific stratigraphic contact in this part of the Upper Cretaceous section in the updip part of Burke County. We are unable mineralogically, texturally or paleontologically to recognize a specific unconformable contact in the interval between the top of the Middendorf Formation and the top of the Upper Cretaceous section in the Millers Pond core and choose to correlate this part of the Upper Cretaceous section as the Black Creek Group (undivided). The textural changes from finer- to coarser-grained sand in the Millers Pond core, as cited by Huddlestun and Summerour (1995) and Kidd (1996), are interpreted as a coarsening upward, regressive sequence of the Black Creek delta. The result is a slightly coarser-grained facies of the Black Creek Group at Miller Pond that is texturally similar to the sediments of the Steel Creek Formation.

The lower sand interval is interpreted as a transgressive near-shore deposit. The diversity and abundance of the microflora, the abundance of the marine fauna, and the presence of glauconite suggest a strong to moderate marine influence during deposition of the black clay interval in the middle and downdip parts of the study area. A decline in the abundance and diversity of dinoflagellates in the upper sand interval, and the absence of dinoflagellates near the top of the unit suggest that a nonmarine depositional environment prograded over the marine clay interval in a regressive depositional sequence. The absence of dinoflagellates in the Millers Pond core suggests that the updip sediments accumulated in a nonmarine environment. The Black Creek Group (undivided) is interpreted as representing delta-plain and distal deltaic-marine environments.

Steel Creek Formation

The Steel Creek Formation consists of unlithified, moderately to very poorly sorted clayey sand and sandy clay. In comparison with the sediments of the underlying Black Creek Group (undivided), these lithologies typically contain more intergranular clay matrix, more lignite, and more pebbles and granules of smoky quartz, and have larger grains of muscovite. The sand generally is coarser grained and is more poorly sorted. The clay beds are oxidized and contain as much as 40 percent sand by volume. Beds of coarse-grained sand grade and fine upward into clay beds, which are stained with iron oxide. Root patterns are observed in some of the clay beds near the top of this unit. Clay beds are thicker and more abundant in the core from the P-21/P5R site in comparison with the Georgia cores.

Most of the sediments are barren of fossils. Thin beds of brownish gray clay in the lower part of this unit yield Cretaceous pollen in the Georgia cores; however, the microfloras are inadequate for biostratigraphic correlation of this unit to other formally named geologic units. Stratigraphic position and lithologic characteristics are used to correlate this unit to the Steel Creek Formation of Fallaw and Price (1992, 1995) and the upper part of unit UK6 of Prowell and others (1985a). Prowell and others (1985a) identify this interval as equivalent to the Peedee Formation in South Carolina and the Providence Sand of western Georgia on the basis of paleontologic results from another core near the P-21/P5R site. The absence of dinoflagellates and other marine indicators in the microflora suggests a nonmarine environment of deposition. The coarse-grained texture, evidence of vegetated surfaces, and iron-oxide staining suggest a fluvial to upper-delta-plain environment.

The contact between the Upper Cretaceous and the Paleocene sediments is correlated as a regional unconformity in the study area. On the basis of lithologic and geophysical correlations with downdip sediments, the Steel Creek Formation is absent in the Millers Pond core.

Ellenton Formation

The Ellenton Formation in the downdip and middle parts of the study area consists of a lower interval of very glauconitic, calcareous sand and clay, a middle interval of silty clay, and an upper interval of calcareous to noncalcareous clay. The sand is fine- to coarse-grained with 10 to 30 percent clay matrix, and generally contains very fine-grained mica and lignite. The clay is laminated and varies from greenish gray to black. The lower and upper intervals include pelecypods, gastropods, carbonate nodules, and thin beds of limestone. The lower interval also contains foraminifera. Lag deposits contain shark teeth at the base of the lower interval and shark teeth with phosphate pebbles at the base

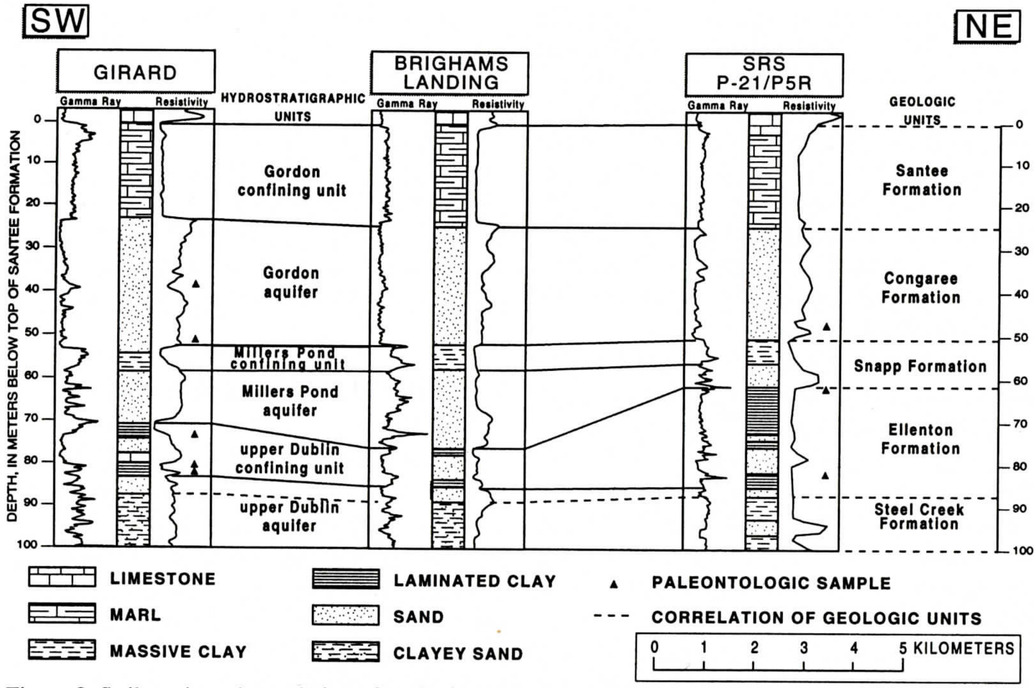

Figure 8. Strike-oriented correlation of geologic and hydrostratigraphic units from the P-21/P5R testhole in South Carolina to the Girard testhole in Georgia. Datum is top of marl in Santee Formation.

of the upper interval. The laminated black clay in the upper interval is noncalcareous in the Girard and P-21 cores. This unit in the Millers Pond core consists of a lower interval of poorly sorted sand, a middle interval of interlaminated black lignitic clay and very fine- to medium-grained sand with as much as 5 percent mica, and an upper interval of fine- to medium-grained sand.

A diverse microflora of dinoflagellates, pollen, and calcareous nannofossils as well as a faunal component of ostracodes, planktonic foraminifera, pelecypods, and gastropods are present in Millhaven and Girard cores. The black clay in the Millers Pond core contains a low-diversity microflora of dinoflagellates and pollen. The Ellenton Formation is correlative to unit P1 of Prowell and others (1985a) (fig. 2) and the Ellenton Formation of Siple (1967). Huddlestun and Summerour (1995) refer to this interval as the Black Mingo Formation in Burke County. Fallaw and Price (1995) divided the sediments of the Ellenton Formation into the lower Paleocene Sawdust Landing Formation and the upper Paleocene Lang Syne Formation. Lag deposits in the Georgia cores suggest potential unconformable surfaces in the Ellenton Formation. The biostratigraphic correlation of the Ellenton sediments in the Georgia cores to the Sawdust Landing and Lang Syne Formations at the SRS has not been determined.

The abundance and diversity of marine fossils and the abundance of glauconite and carbonate in downdip sediments indicate an open-marine, possibly distal prodelta, environment. The low diversity and abundance of dinoflagellates, and the absence of other marine indicators in updip sediments suggest a change to a more restricted marginal-marine environment.

Snapp Formation

The Snapp Formation consists of a lower interval of moderately to poorly sorted, fine- to very coarse-grained sand with granules, pebbles, a few clay clasts, and generally less than 10 percent clay matrix, and an upper interval of white to very light gray clay with as much as 30 percent sand. The lower sand interval grades into the overlying clay interval. Fining-upward cycles are common in the sand interval. Pyrite is either disseminated in the clay matrix or distributed along vertical fractures at the top of the unit in the Girard and the Millers Pond cores. The remainder of the unit is stained with iron oxide in patches and along root traces. Bedding is not easily recognized within the clay and sandy clay beds, which produced the massive appearance of this interval.

Fossils have not been identified in this interval in the Girard and the Millers Pond cores. A sparse microflora of dinoflagellates and pollen at the base of the sand interval in the Millhaven core is not age diagnostic. The Snapp Formation lithologically is equivalent to unit P2 of Prowell and others (1985a) and the Snapp Formation of Fallaw and Price (1995) (fig. 2). Huddlestun and Summerour (1995) also correlate the Snapp Formation to cored testholes in Burke County, Georgia. The stratigraphic position of this unit between the underlying Ellenton Formation and the overlying lower Eocene part of the Congaree Formation suggests that the unit is either late Paleocene or early Eocene age (Prowell and others, 1985a, 1985b; Harris and Zullo, 1990; Fallaw and others, 1990a). The alignment of Tertiary stratigraphic boundaries in the strike-oriented cross section from Girard to P-21/P5R indicates incision of the Snapp Formation into the underlying Ellenton Formation (fig. 8). Textural characteristics of the Snapp Formation and incision by this unit into the underlying Ellenton Formation suggest that the Snapp Formation may have been deposited in channel and flood-plain environments in an incised alluvial valley. The upper surface of the Snapp Formation was weathered and vegetated prior to deposition of overlying Eocene sediments, as observed in the Georgia cores. The sparse marine microflora at Millhaven suggests a marine influence on deposition in the downdip sediments.

Fallaw and Price (1995) defined the Snapp Formation and identified its updip limit beneath the SRS at roughly the position of Upper Three Runs Creek in South Carolina. The recognition of a similar lithologic unit in the three Georgia cores confirms the presence of the Snapp Formation from Millers Pond to Millhaven. If the interpretation of this unit as an alluvial-valley fill is correct, then the Snapp Formation is limited to the lateral boundaries of the paleo-valley and is of limited extent beneath the trans-river study area as compared to the more wide-spread marine and deltaic deposits of the Ellenton Formation and the four Cretaceous units.

HYDROSTRATIGRAPHY

The sediments of the Dublin and the Midville aquifer systems are divided in this paper into five aquifers and six confining units (fig. 3). The hydrostratigraphic units as recognized in each of the three cored testholes in Georgia and the one cored testhole in South Carolina are shown in figures 3, 4, 5, and 6. The Dublin aquifer system is divided into the Millers Pond, the upper Dublin, and the lower Dublin aquifers (fig. 3). The Midville aquifer system is divided into the upper and the lower Midville aquifers. The correlation of units is shown in a dip-oriented section from Millers Pond to Millhaven (fig. 7).

A confining unit in this study is defined as a mappable unit of relatively fine-grained sediment between two aquifers. True confining units are differentiated from leaky confining units on the ability of the unit to impede vertical flow between aquifers. The clay and clayey lithologies in the confining units are correlatable on geophysical logs as intervals of higher values on the natural-gamma log and lower values on the resistivity log, relative to overlying and underlying aquifers. Paleontologic results confirm the correlation of the fine-grained lithologies in the upper Dublin and the upper Midville confining units. Confining units are assigned the name of the underlying aquifer; for example, the lower Dublin confining unit overlies the lower Dublin aquifer.

An aquifer is defined as a mappable sedimentary unit of inherently high porosity and permeability. Each aquifer is correlated to a relatively coarse-grained geologic unit or coarse-grained lithofacies in a geologic unit.

Each hydrostratigraphic unit proposed in the revised hydrostratigraphy for the Dublin and Midville aquifer systems is consistently correlated across the study area on the basis of lithostratigraphic and biostratigraphic position in the sedimentary column. The units and their names are correlated regardless of the amount of leakage across confining units.

Millers Pond Confining Unit

The Millers Pond confining unit separates the finer grained sand of the Gordon aquifer from the coarser grained sand of the Millers Pond aquifer and consists of the upper interval of clay and sandy clay of the Snapp Formation. Samples from this interval were not analyzed for hydraulic conductivity. The Millers Pond confining unit is the hydrostratigraphic equivalent of the unnamed confining unit at the top of the original Dublin aquifer system of Clarke and others (1985) and the clay in the upper part of the Crouch Branch confining unit of the Meyers Branch confining system of Aadland and others (1992, 1995).

Millers Pond Aquifer

The Millers Pond aquifer consists of the sand of the Snapp Formation in the middle and downdip parts of the study area. The aquifer consists of sand of the Snapp Formation and sand in the upper part of the Ellenton Formation in the Millers Pond core. This aquifer in the three Georgia cores is almost twice as thick as it is in the P-21/P5R core.

The dominant porosity type is intergranular. The white clay matrix forms a thin coating on individual sand grains and occludes intergranular pores in a few thin beds of clayey sand. Otherwise, intergranular porosity is estimated to be 25 to 35 percent. A transmissivity of 24 m^2/d (meters squared per day), a hydraulic conductivity of 2 m/d (meters per day), and a permeability of 2 darcys was calculated from aquifer-test results at the Millers Pond site (Snipes and others, 1995, Kidd, 1996).

The Millers Pond aquifer is equivalent to the aquifer in the Paleocene sediments of the Dublin aquifer system as described by Clarke and others (1985). It is also equivalent to the sand zone in the Crouch Branch confining unit as described by Aadland and others (1992, 1995). This aquifer and its confining unit are named herein for the Millers Pond locality in Burke County, Georgia. Correlation of the Millers Pond aquifer and its overlying confining unit with the alluvial valley-fill sediments of the Snapp Formation suggests that these hydrologic units have a limited distribution beneath the trans-river study area.

Upper Dublin Confining Unit

The upper Dublin confining unit separates the coarse, porous sand of the Millers Pond aquifer from the clayey, coarse-grained sands and sandy clays of the upper Dublin aquifer. Laboratory results for the vertical hydraulic conductivity of individual samples from the Girard and the Millhaven cores range from 10^{-4} to 10^{-5} m/d (Core Laboratories, Inc., written commun., 1992). Leakance at Millhaven ranges from 10^{-6} to 10^{-7}/d.

The upper Dublin confining unit is equivalent to the clay interval in the Ellenton Formation, which is identified in Clarke and others (1985) as a confining unit within the Dublin aquifer system in eastern Georgia near the Savannah River. Aadland and others (1992, 1995) include this clay interval as part of the Crouch Branch confining unit of the Meyers Branch confining system.

Upper Dublin Aquifer

The upper Dublin aquifer consists of sand of the Ellenton Formation beneath the black laminated clay of the upper Dublin confining unit, and the sand, sandy clay, and clay of the Steel Creek Formation. The unit at the Millers Pond site is equivalent to only an interval of sand and the lag deposit in the lower part of the Ellenton Formation.

Clay matrix occludes much of the intergranular pores. Intergranular porosity of 10 to 20 percent is observed in discrete sand beds, particularly near the base of the unit. Wells are not available for aquifer tests of this unit at the Georgia testhole sites. The unit has more clay matrix than the Millers Pond and the lower Dublin aquifers, and generally has poorer sorting of the sand relative to the lower Dublin aquifer. The abundance of clay matrix and the sorting of the sand in this unit suggest a lower permeability relative to adjacent aquifers.

The upper Dublin aquifer is hydrostratigraphically equivalent to the upper part of what Clarke and others (1985) identified as the Cretaceous aquifer of the Dublin aquifer system. The clay- dominated part of the upper Dublin aquifer at the P-21/P5R site is equivalent to the lower part of the Crouch Branch confining unit of Aadland and others (1992, 1995). The thick beds of kaolin observed in the upper Dublin aquifer in the P-21/P5R core appear to be discontinuous and interbedded with sand along strike (fig. 8) and, therefore, were included as part of the upper Dublin aquifer.

Lower Dublin Confining Unit

The lower Dublin confining unit separates the sand of the upper Dublin aquifer and the sand of the lower Dublin aquifer. The unit consists of a white clay and sandy clay at the top of the Black Creek Group. Samples from this interval were not analyzed for hydraulic conductivity.

The lithologic and geophysical characteristics of the lower Dublin confining unit and its stratigraphic position between mappable lithofacies of the Black Creek Group (undivided) and the Steel Creek Formation form the basis for splitting the Cretaceous part of the Dublin aquifer system into an upper aquifer of more poorly sorted, coarser grained, clayey sand and a lower aquifer of better sorted, finer grained sand.

Lower Dublin Aquifer

The lower Dublin aquifer consists of the sand in the upper part of the Black Creek Group (undivided). This unit in the middle and downdip parts of the study area is moderately to well-sorted, and contain very minor amounts of clay matrix. The updip sediments are coarser and comprise poorly sorted, fine- to very coarse-grained sand and clay beds.

Intergranular porosity is estimated at 20 to 35 percent in the middle and downdip parts of the study area. Clay matrix in the updip sediments varies from 5 to 20 percent by volume and occludes intergranular pores in a few discrete beds. Transmissivity is 4 and 5 m^2/d for two wells at Millers Pond, 490 m^2/d at Girard, and 100 m^2/d at Millhaven. Hydraulic conductivity is 0.07 and 0.09 m/d for the two wells at Millers Pond, 12 m/d at Girard, and 3 m/d at Millhaven. Permeability is 0.14 and 0.25 darcys at Millers Pond and 64 darcys at Girard (Snipes, and others, 1995, Kidd, 1996).

The lower Dublin aquifer is hydrostratigraphically equivalent to the lower part of the Cretaceous aquifer of the Dublin aquifer system (Clarke and others, 1985), and most of the Crouch Branch aquifer (Aadland and others, 1992, 1995).

Upper Midville Confining Unit

The upper Midville confining unit separates the lower Dublin and the upper Midville aquifers. Laboratory analysis of individual samples for vertical hydraulic conductivity range from 10^{-4} to 10^{-5} m/d (Core Laboratories, Inc., written commun., 1992). Leakance at Millhaven ranges from 10^{-6} to 10^{-7}/d.

The unit consists of a 43-m thick interval of laminated black clay of the Black Creek Group (undivided), and a correlative interval of interbedded clay and sand in the other cores. The confining unit is correlated to an interval of thickly bedded, oxidized clay and fine- to medium-grained sand in the Millers Pond core on the basis of late Campanian pollen and the fine-grained texture of sands in this interval relative to the overlying and underlying sand. The upper Midville confining unit is hydrostratigraphically equivalent to the confining unit between the original Dublin and Midville aquifer systems of Clarke and others (1985) and is equivalent to the McQueen Branch confining unit of the Allendale confining system of Aadland and others (1992, 1995).

Upper Midville Aquifer

This unit consists of the lower sand interval of the Black Creek Group of Prowell and others (1985a). The sand is fine- to coarse-grained and very fine- to fine-grained and contains 5 to 10 percent clay matrix.

Intergranular porosity is estimated at 20 to 35 percent. Wells are not available for aquifer tests at the Girard and the Millhaven testhole sites. A transmissivity of 138 m^2/d, a hydraulic conductivity of 13 m/d and a permeability of 16 darcys are reported for this interval at the Millers Pond site (Snipes and others, 1995, Kidd, 1996). The upper Midville aquifer is hydrostratigraphically equivalent to the upper part of the Midville aquifer of Clarke and others (1985) and the McQueens Branch aquifer of Aadland and others (1992, 1995).

Lower Midville Confining Unit

The lower Midville confining unit separates the upper and lower aquifers in the Midville aquifer system and consists of the 3- to 12-m-thick interval of interbedded clay and sand at the top of the Middendorf Formation. Samples from this interval were not analyzed for hydraulic conductivity.

The lithologic and geophysical characteristics of the lower Midville confining unit and its stratigraphic position between mappable lithofacies of the Middendorf Formation and Black Creek Group (undivided) form the basis for splitting the Midville aquifer system into upper and lower aquifer units.The aquifers above and below the confining unit are texturally and mineralogically similar.

Lower Midville Aquifer

The lower Midville aquifer consists of the sand in the Middendorf Formation in all four cores and includes a porous, permeable sand interval in the upper 3 to 6 m of the Cape Fear Formation in the P-21/P5R and Girard cores. This unit is predominantly fine- to very coarse-grained and fine- to medium-grained sand. The sand includes generally less than 5 percent clay matrix and is moderately to poorly sorted.

Intergranular porosity is estimated at 30 to 35 percent. Transmissivities of 140 and 150 m^2/d, hydraulic conductivities of 13 and 17 m/d, and a permeability of 15 and 20 darcys are reported for two wells in this interval at the Millers Pond site (Snipes and others, 1995, Kidd, 1996). A transmissivity of 105 m^2/d, a hydraulic conductivity of 3 m/d, and a permeability of 3 darcys are reported for a well in this unit at the Girard site (Dr. D.S. Snipes, Clemson University, written commun., May 1995).

The lower Midville aquifer is hydrostratigraphically equivalent to the lower part of the Midville aquifer of Clarke and others (1985) and the lower part of the McQueens Branch aquifer of Aadland and others (1992, 1995). The lower Midville aquifer is roughly twice as thick as the upper Midville aquifer in the Georgia cores.

Basal Confining Unit

The basal confining unit separates the lower Midville aquifer from crystalline and sedimentary bedrock, and consists of the low-porosity, low-permeability sediments that characterize most of the Cape Fear Formation. Sediments in this unit are partially lithified with a cristobalitic clay matrix. The geophysical logs display low resistivity in the sands as well as the clays in most of this unit. The upper contact for the basal confining unit is recognized on geophysical logs as a sharp change from the low resistivity of the basal confining unit to the high resistivity of the lower Midville aquifer.

The cristobalitic clay matrix occludes most of the intergranular porosity in the sand beds and results in hard, dense beds of clay and sand. Intergranular porosity of generally less than 10 percent is observed on only a few sand beds.

Table 1. Water-level elevations in meters above sea level for selected well clusters in Georgia and South Carolina.

		U.S. Geological Survey Clusters			Savannah River Site Clusters					
		Millers Pond	Girard	Millhaven	P-19	P-21	P-22	P-23	P-26	P-30
	Date Water Level Measured	7/92	9/94	9/94	7/92	7/92	7/92	7/92	7/92	7/92
Aquifers	Gordon	B	B	B	80.12	40.61	46.74	43.26	36.25	64.18
	Millers Pond	41.98	B	B	A	40.98	46.95	46.04	A	A
	Upper Dublin	B	B	B	54.85	50.98	53.84	51.65	45.73	B
	Lower Dublin	48.59	48.17	45.73	54.82	51.16	53.81	51.83	47.56	62.96
	Upper Midville	48.61	B	B	55.09	55.58	57.93	53.08	59.91	60.98
	Lower Midville	48.54	53.05	57.62	55.01	55.52	58.08	53.32	52.84	58.05

A indicates unit is absent at cluster site. B indicates that a well is not screened in the unit at the cluster site.

There are no monitoring wells in this unit at the Georgia sites and, consequently, hydraulic properties are not documented in this unit.

The basal confining unit is equivalent to the Appleton confining system of Aadland and others (1992, 1995) and the unnamed confining unit beneath the Midville aquifer system of Clarke and others (1985). This interval is used as a confining unit between the lower Midville aquifer and fractured-bedrock aquifer in this and previous hydrostratigraphic studies in east-central Georgia and South Carolina (Clarke and others, 1985; Faye and Mayer, 1990; Aadland and others, 1992, 1995) because of the small amounts of intergranular porosity and permeability, and the partial lithification of most of the Cape Fear sediments by cristobalitic clay matrix. However, extension of basement faults into the Coastal Plain sediments is documented in the study area (Prowell and O'Connor, 1978, Faye and Prowell, 1982, Snipes and others, 1993, Stieve and Stephenson, 1995). Faulting would induce fracturing of the partially lithified sediments in the basal confining unit and could create a hydraulic connection between the overlying lower Midville aquifer and the underlying fractured-bedrock aquifer.

CONFINEMENT

Monitoring wells were installed at each testhole in Georgia; however, none of the Georgia sites has enough wells to adequately test all of the hydrostratigraphic units described in this paper (table 1). Therefore, the hydrostratigraphic units were correlated to monitoring-well clusters on the SRS that have at least one well screened in each aquifer of the Dublin and the Midville aquifer systems (fig. 1). Static water-level data at six South Carolina cluster sites (Bledsoe, 1987, 1988) and drawdown response during a series of aquifer tests at the Miller Pond site in Georgia (Clarke and others, 1994, Snipes and others, 1995) were used to qualitatively evaluate leakage across the five confining units in the Dublin and the Midville aquifer systems and to relate the leakage to the geologic history of the sediments of each confining unit.

Static Water-Level Data

The six South Carolina sites are located in close proximity to areas of local (e.g. P-19) and regional (e.g. P-30) ground-water recharge, and ground-water discharge (e.g. P-21, P-22, P-23, and P-26). Recharge and discharge in the vicinity of these sites create a vertical flow component in the ground-water-flow system. A large difference in static water-level elevations, defined as greater than 1 m in this paper, between adjacent aquifers (table 1) indicates that the vertical flow component is significantly impeded by the intervening confining unit. The differ-

Table 2. Vertical hydraulic gradients for confining units at selected well clusters on the Savannah River Site.

		Savannah River Site Clusters Vertical Hydraulic Gradients (meters/meters)					
		P-19	P-21	P-22	P-23	P-26	P-30
Confining Units	Millers Pond	A	0.09	0.02	0.40	A	A
	Upper Dublin	1.22	0.41	0.28	0.27	1.24	B
	Lower Dublin	<0.01	0.03	<0.01	0.02	0.16	B
	Upper Midville	0.01	0.16	0.16	0.05	0.51	0.14
	Lower Midville	<0.01	<0.01	<0.01	0.02	5.80	0.44

A indicates unit is absent at cluster site. B indicates inadequate data to assign a hydraulic gradient to confining unit.

ence in static water-level elevations between adjacent aquifers is divided by the intervening confining unit's thickness to calculate a vertical hydraulic gradient (table 2).

Static water-level data suggest that strong vertical hydraulic gradients are associated with the upper Dublin and the upper Midville confining units at most of the specified South Carolina sites. The upper Dublin confining unit separates the Millers Pond and the upper Dublin aquifers at P- 21, P-22, and P-23 on the SRS. Static water-level elevations for the Millers Pond aquifer are noticeably lower at P-21, P-22, and P-23 relative to static water-level elevations for the underlying upper Dublin aquifer. At P-19 and P-26, where the upper Dublin confining unit separates the Gordon and the upper Dublin aquifers, the static water-level elevations are 25.27-m higher and 9.48-m lower in the Gordon aquifer relative to the static water-level elevations for the upper Dublin aquifer. The upper Midville confining unit separates the lower Dublin and the upper Midville aquifers. Static water-level elevations in the lower Dublin aquifer are noticeably lower at P-21, P-22, P-23, and P-26, and higher at P-30, relative to static water-level elevations for the upper Midville aquifer. These two confining units impede the vertical flow at most of the South Carolina sites. Vertical hydraulic gradients are greater than or equal to 0.10 m/m for the upper Dublin and the upper Midville confining units at all of the P-well sites with the exception of the upper Midville confining unit at P-23 (table 2).

In contrast, static water-level elevations suggest that strong vertical hydraulic gradients usually are not associated with the Millers Pond, the lower Dublin and the upper Dublin confining units at the six South Carolina sites. The Gordon and the Millers Pond aquifers are separated by the Millers Pond confining unit and have noticeably different static water-level elevations at only P- 23 on the SRS. The upper Dublin and the lower Dublin aquifers are separated by the lower Dublin confining unit and have noticeably different static water levels at only P-26. The upper Midville and the lower Midville aquifers are separated by the lower Midville confining unit and have noticeably different static water levels at P-26 and P-30. These three confining units generally appear to be leaky at most of the P-well sites and only locally impede the vertical flow component. Vertical hydraulic gradients are less than 0.10 m/m for the Millers Pond, the lower Dublin and the lower Midville confining unit at all of the P-well sites with the exception of the Millers Pond confining unit at P-23, the lower Dublin confining unit at P-26, and the lower Midville confining at P-26 and P-30 (table 2).

Drawdown Response

Seven 72-hour aquifer tests at the Millers Pond monitoring-well cluster in Georgia were used to induce large head differences between adjacent aquifers. Drawdown during each test was monitored in the pumping well and in observation wells screened in adjacent aquifers. The drawdown response in the observation wells was used to qualitatively interpret the potential for interaquifer leakage across the upper Dublin, the lower Dublin, the upper Midville, and the lower Midville confining units (Clarke and others, 1994, Snipes and others, 1995, Kidd, 1996).

Pumping wells in five of the seven 72-hour aquifer tests were screened in the Cretaceous sediments of the lower Dublin, the upper Midville, and the lower Midville aquifers. In one of these tests, a well screened near the bottom of the lower Dublin aquifer was pumped to produce 42.00 m of drawdown and resulted in measurable drawdowns of 0.02 to 0.27 m in the observation wells screened in the lower Dublin aquifer, the upper Midville aquifer, and the lower Midville aquifer. The screens of the observation wells in this test were 36.57-m higher and as much as 70.10-m lower in the hydrostratigraphic section, relative to the screen in the pumping well. The drawdown responses in the observation wells suggest that interaquifer leakage was induced across the upper Midville and the lower Midville confining units at the Millers Pond site. The upper Midville and the lower Midville confining units at the Millers Pond site are 6.10- and 2.44-m thick, respectively.

A 72-hour aquifer test of a well screened near the top of the lower Dublin aquifer at the Millers Pond site resulted in 58.00 m of drawdown in the pumping well and no detectable drawdown (less than 0.00009 m) in the overlying Millers Pond aquifer. The well screen in the Millers Pond aquifer is 14.93 m above the screen of the pumping well. These two screened intervals are separated by the upper Dublin and the lower Dublin confining unit. Each of these confining units is 3.05-m thick. A well was not installed in the upper Dublin aquifer, so it is not possible to directly determine which of the confining units is restricting interaquifer leakage; however, the evaluation of static water levels in South Carolina would suggest that the upper Dublin confining unit has the greater potential to restrict interaquifer leakage.

Geologic Controls

The fine-grained sediments of the Millers Pond, the lower Dublin, and the lower Midville confining units accumulated in nonmarine environments and are directly overlain by regional unconformities at the top of the Snapp Formation, the Black Creek Group (undivided), and the Middendorf Formation. These fine-grained lithofacies were subaerially exposed subsequent to being buried beneath overlying sediments and were deposited in alluvial and fluvial-delta-plain environments. Deposition and reworking of the sediments in a fluvially dominated environment typically result in lenticular deposits of fine- and coarse-grained sediments. Erosion of the sediments during subaerial exposure and before the deposition of the next geologic unit also contributes to the lack of lateral continuity of the fine-grained sediments in these environments. Each of these fine-grained lithofacies can be correlated across most of the study area on the basis of stratigraphic position; however, the lack of lateral continuity results in a leaky confining unit that is only capable of locally impeding interaquifer leakage.

The fine-grained sediments of the upper Dublin confining unit were deposited in the marine- influenced part of the Ellenton delta. Incision by the overlying alluvial valley during deposition of the Snapp Formation reduces the thickness of Ellenton clay (fig. 8) and could locally reduce the effectiveness of this interval as a confining unit. In contrast to the three nonmarine lithofacies, this fine-grained lithofacies is assumed to be a more laterally continuous unit across the study area and is regionally capable of impeding interaquifer leakage.

The fine-grained sediments of the upper

Midville confining unit were deposited in the marine-influenced part of the Black Creek delta in the intermediate and downdip sections, and were deposited in a fluvially dominated, nonmarine part of the delta in the updip section at Millers Pond. The sediments of the updip section were deposited in an environment similar to that of the three nonmarine units and are correlated as a leaky confining unit. The deposition of the intermediate and downdip sections is similar to that of the Ellenton Formation and resulted in a laterally continuous confining unit that is capable of impeding interaquifer leakage.

SUMMARY AND CONCLUSIONS

Six geologic units are defined in the Cretaceous and the Paleocene sections of east-central Georgia and are designated the Cape Fear Formation, the Middendorf Formation, the Black Creek Group (undivided), and the Steel Creek Formation in the Upper Cretaceous section, and the Ellenton and the Snapp Formations in the Paleocene section. The geologic units provide a spatial and temporal framework for the identification and correlation of five aquifers and six confining units in the Dublin and the Midville aquifer systems.

The hydrostratigraphy of east-central Georgia is revised to include the Millers Pond, the upper Dublin, and the lower Dublin aquifers and confining units in the sediments of the original Dublin aquifer system, and the upper and the lower Midville aquifers and confining units in the original Midville aquifer system. The aquifers and confining units provides a greater hydrostratigraphic resolution for these aquifer systems in the vicinity of the SRS Savannah River border for the investigation of trans-river flow. Each of the aquifers in the Dublin aquifer system can be differentiated from adjacent aquifers on the basis of grain size, sorting, the amount and distribution of clay matrix, and the amount of porosity. The sediments of the two aquifers in the Midville aquifer system are texturally similar and are correlated on the basis of stratigraphic position relative to adjacent confining units.

The fine-grained sediments of the Millers Pond, the lower Dublin, and the lower Midville confining units were deposited in nonmarine environments, and are directly overlain by regional unconformities at the top of the Snapp Formation, the Black Creek Group, and the Middendorf Formation, respectively. These three units are interpreted as leaky confining units between regionally mappable aquifers and locally impede vertical flow between adjacent aquifers. The fine-grained sediments of the upper Dublin and the upper Midville confining units were deposited in marine-influenced parts of deltaic environments. The upper Dublin confining unit is interpreted as a regional confining unit across the study area. The upper Midville confining unit is interpreted as a confining unit in middle and downdip sections, and as a leaky confining unit in the updip section at Millers Pond.

The recognition of the upper Dublin confining unit as a regional confining unit between the Millers Pond and upper Dublin aquifers suggests that the Millers Pond aquifer is a separate hydrologic unit from the rest of the Dublin aquifer system. Additional long-term aquifer tests are needed to evaluate interaquifer leakage between the Millers Pond aquifer and the overlying Gordon aquifer, and to test the true regional hydrologic significance of the Millers Pond, the lower Dublin, and the lower Midville confining units.

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SOUTHEASTERN GEOLOGY
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STRATIGRAPHY, DEPOSITIONAL ENVIRONMENTS AND SEQUENCE STRATIGRAPHY OF THE UPPER CRETACEOUS IN THE HILTON HEAD ISLAND TEST WELL # 1, BEAUFORT COUNTY, SOUTH CAROLINA

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ABSTRACT

The Hilton Head Island Test Well #1 was drilled to a depth of 3833 ft. in July of 1992, penetrating 2003 ft. of Upper Cretaceous sediments before bottoming in a rhyolite. The biostratigraphy, lithostratigraphy, depositional environments and sequence stratigraphy, delineated by using geophysical logs, sidewall cores and cuttings, were used to identify seven Upper Cretaceous depositional systems. Three supercycle boundaries and their corresponding third order sequences were also identified within these systems. These depositional systems can be divided into three general types; transgressive (systems 1, 3, 5, and 6), regressive (systems 2,4) and transitional or fluctuating (system 7).

Microfossils (foraminifera, nannoplankton, pollen and spores) date the oldest Cretaceous fossils as middle Cenomanian in age. Identification of all the Upper Cretaceous stages was achieved. Separation of the Santonian and Conacian into distinct stages was accomplished though the use of sequence stratigraphy and paleontology.

A new formation, the Folly Field Formation was identified. It is Cenomanian in age and represents the 2.3 third order cycle of the global sea-level curve. The formation is a medium grained, moderately sorted, rounded litharenite deposited in an open marine environment.

Upper Cretaceous units lie unconformably on Paleozoic Suwannee Terrain volcanics. These lithostratigraphic units form oldest to youngest are: Folly Field Formation, Beech Hill Formation, Clubhouse Formation, Cape Fear Formation, Middendorf Formation, lower Black Creek Group, Upper Black Creek Group, and Peedee Formations.

INTRODUCTION AND METHODS

Most previous work in Beaufort County, South Carolina has dealt almost exclusively with the Tertiary section. A Tertiary limestone (Floridan) aquifer is the primary drinking water supply in the county. Investigation of the Cretaceous has been driven by increased pressure being placed on the Floridan aquifer resources due to the rapid growth in the Beaufort area.

In July 1992, the town of Hilton Head on Hilton Head Island, in cooperation with the Public Utility districts on the island, drilled the Hilton Head Island Test Well #1(BFT-2055) to test the feasibility of using a Cretaceous aquifer as a potential water supply. The well located at lat 32°11'29.42" N., long 80°42'14.06" W (Figure 1), off Singleton Beach Road just southwest of Folly Field, was drilled to a total depth of 3833 feet.

A total of 2003 feet of Cretaceous was penetrated before the well bottomed in what appears to be an altered rhyolite (Snipes and others, 1995). Upon completion of drilling, ten geophysical logs were run by Atlas Wireline (Temples and Waddell, 1996) and 239 sidewall cores were taken.

This study examines the lithostratigraphy, sequence stratigraphy and environments of deposition of the Upper Cretaceous sediments pen-

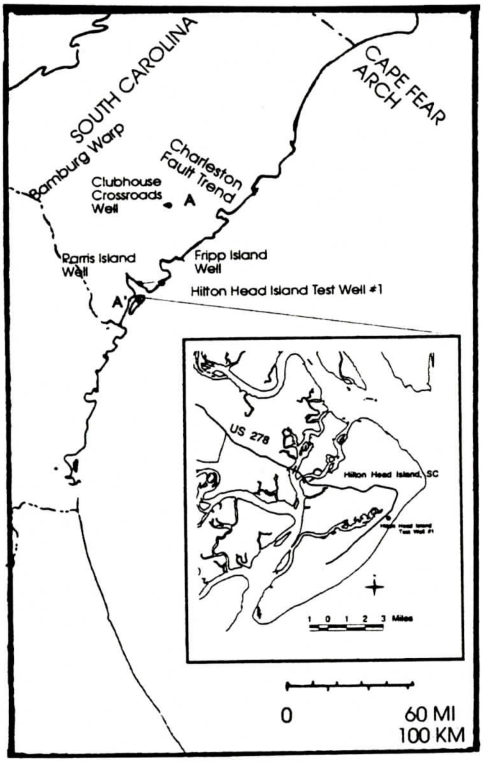

Figure 1. Location of Hilton Head Island test Well #1, Hilton Head Island, Beaufort County, South Carolina.

etrated in the well. The stratigraphy was determined using standard log correlation techniques with nearby wells in conjunction with sequence stratigraphy. The sequence stratigraphy established in the well was tied to the published Cretaceous sequences of Haq and others (1988) (Figure 2).

Sediments penetrated in the Hilton Head Island Test Well #1 were examined through drill cuttings, sidewall cores and geophysical logs. The gamma ray, spontaneous potential, resistivity and conductivity curves were used for correlation to Fripp Island, Parris Island and Clubhouse Crossroads wells (Figure 3). Curve shapes were matched and compared to interval thickness and overall patterns exhibited by the logs.

Paleontologic analyses were made on the drill cuttings and sidewall cores for foraminifera, pollen, spores and dinoflagellates. Where an age discrepancy was found between the sidewall core data and the cuttings, the data from the sidewall cores were used. These data were compared with published data (Hazel and others, 1977; McLean, 1960; Valentine, 1982, 1984) in nearby wells.

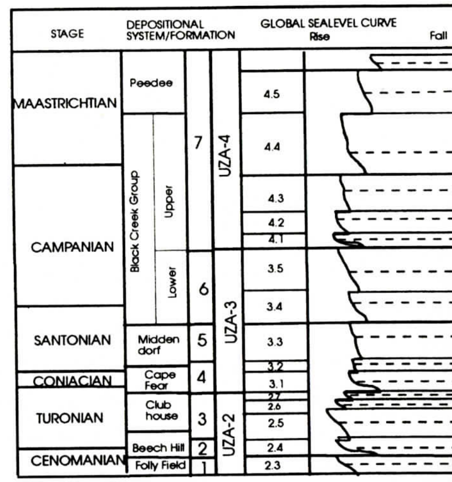

Figure 2. Stratigraphic Column used in this study showing the relationship of stages, sequences, and formations

The sequence stratigraphy was determined from the geophysical logs using the techniques outlined by Vail and Wornardt (1993). Using the paleontological data, systems were assigned to the commonly used international stages (Figure 3). Interpretations of the environments of deposition of each unit were made by the types of fossils present in association with the lithologies.

The sequences present (Figure 2) were compared to the global sequence stratigraphy for the Cretaceous (Haq and others, 1988). Depositional sequences were combined to form depositional systems. In some instances, the systems are comprised of only one sequence. Formational boundaries were picked based on the correlation with nearby wells (Table 1).

Attempts were made to carry formation names where applicable, into the Hilton Head Well. In instances where a facies relationship could be established then these units were correlated and called equivalent. Correlations in

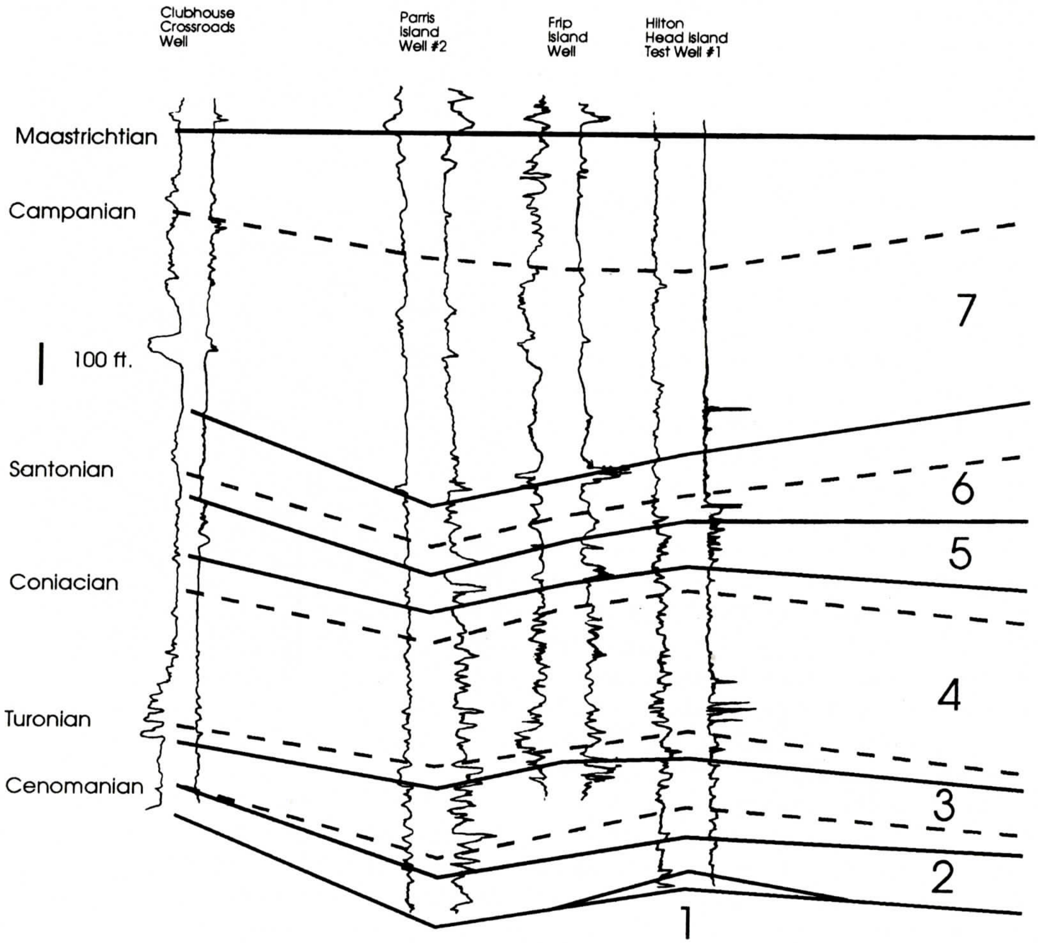

Figure 3. Stratigraphic cross-section showing the Upper Cretaceous units from Dorchester to Beaufort Counties, South Carolina. Datum is top of the Cretaceous

Table 1. Well number, name, location, total depth, and approximate elevation of wells used in this study.

Well #	Well Name	Location	Total Depth	Elevation (approx.)
1	USGS Clubhouse Crossroads	Dorchester County, SC	2530 ft	18 ft
2	Lane Atlantic Parris Island	Beaufort County, SC	3454 ft	15 ft
3	Fripp Island Well	Beaufort County, SC	3454 ft	5 ft
4	Hilton Head Island Test Well #1	Beaufort County, SC	3833 ft	10 ft

the Cenomanian were based on the Clubhouse Crossroads Well. The remainder of the Upper Cretaceous section was defined using the closer Fripp Island well.

PREVIOUS WORKS

The initial work in the Atlantic Coastal Plain of South Carolina by Sloan (1908) was followed by Stephenson (1923), Cooke (1936), and Heron (1956) who established a lithostratigraphic framework based on macrofossils. In the 1960's, an attempt was made (Brett and Wheeler, 1961 and Swift and Heron, 1969) to better define the Cretaceous units through stricter use of the stratigraphic code and reduced reliance on biostratigraphy.

Prior to 1990, Swift and Heron's (1969) four formations oldest to youngest: Cape Fear, Middendorf, Black Creek and Peedee Formations were used for the Upper Cretaceous. Sohl and Owens (1991) compiled a chart demonstrating the range of ages for these formations proposed by various authors and refined the nomenclature. The conflicting ages of these formations are due in general to the lack of distinctive age restrictive fauna and rapid lithofaces changes, both vertically and laterally.

The best studied well in the Coastal Plain of South Carolina, the Clubhouse Crossroads Well was drilled by the USGS in Dorchester County. Hazel and others (1977) assigned biostratigraphic ages to the lithostratigraphy described in the well by Gohn and others (1977). Gohn (1992) later revised the stratigraphy of the well utilizing Caster's (1934) concept of magnafacies and parvasequences.

The stratigraphy and biostratigraphy in the Parris Island well were described by McLean (1960) and subsequently revised by Gohn and others (1978) along with the Fripp Island well. Valentine (1982, 1984) refined the Cretaceous biostratigraphy of both the Fripp Island well and the Parris Island well.

Figure 5. 100X plane light photomicrograph of the Folly Field Formation, a coarse grained, poorly sorted litharenitic sandstone. 1"=0.25mm

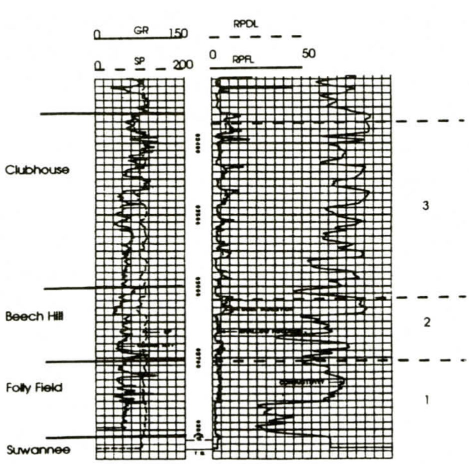

Figure 4. Gamma, Spontaneous potential, and resistivity logs for Depositional System 1,2 and 3. Formation contacts for the Folly Field, Beech Hill, and Clubhouse are indicated.

STRATIGRAPHY OF THE HILTON HEAD WELL

Depositional System 1 (3833-3708)

The lower part of System 1 (Figure 4), from 3833-3767 ft. consists of a medium grained, moderately to poorly sorted, rounded to subrounded clayey litharenite. Detrital minerals include monocrystalline and polycrystalline quartz, metamorphic rock fragments (schist, gneiss, metaquartzite, and slate), chert, feldspar, volcanic rock fragments, limestone and sedimentary rock fragments. Authigenic minerals include smectite, calcite, authigenic quartz overgrowths, siderite, pyrite, and iron oxide cements. Lesser amounts of siderite and chlorite are also present (Figure 5). The gamma ray signature of this unit indicates a fining upward cycle and is characterized by low resistivity. The upper interval from 3767-3708 ft. has blocky gamma ray signature with a slightly higher resistivity and contains a dense clay interbedded with a fine grained sand. The lower contact at 3833 ft. has a poorly sorted litharenite unconformably overlying an altered rhyolite (Snipes and others 1995) of the North Florida Volcanic Series (Suwannee terrane) described by Chowns and Williams (1983).

The Folly Field Formation is newly defined herein as the section from 3695-3833 ft. (Figs. 3 and 4) in the Hilton Head Island Test Well #1. The formation name is taken from the nearby Folly Field on Hilton Head Island. The upper contact with the overlying Beech Hill Formation is picked at 3695 ft. on the geophysical logs and represents a sharp change from the dominantly brown and yellow sands and clays of the Folly Field formation to the red and brown sands and clays of the Beech Hill Formation. The dipmeter and CBIL log indicate the possibility of a fault striking N5°E with a dip of 50° as the upper contact.

Diagnostic Cenomanian dinoflagellates such as *Paleoperidinum cretaceum*, *Trithyrodinium suspectum*, and *Paleohystrichophora infusoides* are present in a sample at 3810 ft. in the well. *Paleohystrichophora infusoides* ranges from 72-95 Ma (Williams and others, 1993). *Trithyrodinium suspectum* (Williams and others, 1993) has a first appearance in the middle Cenomanian and disappears in the upper Cenomanian. These microfossils are also indicative of open marine conditions.

Correlations with the Clubhouse Crossroads well indicate that the Folly Field Formation is stratigraphically lower than the Beech Hill Formation. This along with the presence of *T. suspectum* at 3810 ft. establishes an age of the unit that can be no older than the latest highstand of third order cycle 2.3. The log character and fossil content indicate a marine origin consistent with highstand deposits deposited during a transgression near the end of the cycle.

Depositional System 2 (3708-3620)

Sediments from 3695-3600 ft. consist of interbedded sand and clay, yellow, red, brown and purple in color. The gamma ray pattern is similar in nature to the underlying zone, a pattern of gradual shift to the right (more radioactive) indicating fining upward capped by a blocky pattern with the cycle repeating (Figure 4).

Comparative lithologies and log characteristics of the zone from 3620-3708 ft. (Fig 3 and 4) correlate with the Beech Hill Formation in the Clubhouse Crossroads well (Gohn, 1992). The lack of marine fauna indicates that this unit is most likely fluvial in origin. The basal zone at 3680 ft. contains red clay balls indicative of proximity to an unconformity. This unconformity zone marks the boundary at 3695 ft. between the marine sediments below and fluvial deposits above. The Beech Hill Formation represents the third order cycle 2.4.

Depositional System 3 (3620-3375)

Sediments from 3620-3520 ft. consist of interbedded coarse to medium sands, red, green and brown in color, fining upward. The top of the interval is capped by a greenish sandy clay from 3520-3540 ft (Fig 4). The interval from 3520-3485 ft. is a reddish, fine to coarse, quartz sand with a blocky gamma ray pattern. Locally, white limestone stringers are present between 3502-3485 ft. The reddish sand grades upward into an interbedded greenish sand and clay containing mica, glauconite and carbonaceous material with a calcite cement from 3485 ft. to the top of the sequence at 3375 ft. Limestone is present from 3430-3422 ft. The Clubhouse Formation ranges from 3600-3360 ft. in the well.

At Hilton Head, this interval is marginal marine, similar to the updip sediments. This unit represents an environment which contains a series of transgressive marginal marine wedges capped by small unconformities representing cycles 2.5, 2.6, and 2.7 on the global chart. The unconformity at 3375 ft. separates the marginal marine sediments of System 3 from the deltaic sediments of the overlying System 4.

A sidewall core at 3494 ft. contained only *Complexipollis sp.* indicative of the lower *Complexipollis-Atlantopollis* zone (Christopher, 1979). Christopher (1979) assigned an age of upper Cenomanian to lower Turonian to the *Complexipollis-Atlantopollis* zone. Valentine (1984) assigned an age of early Turonian to the *Complexipollis-Atlantopollis* zone along the Atlantic Margin. The top of the Cenomanian was picked at the base of the clay rich zone from 3522-3540 ft below the core at 3494 ft. that caps the fining upward cycle. This clay zone is interpreted to be the condensed section in the 2.5 cycle which contains the Turonian/Cenomanian boundary. The top of System 3 is correlative to the UZA-2 supercycle.

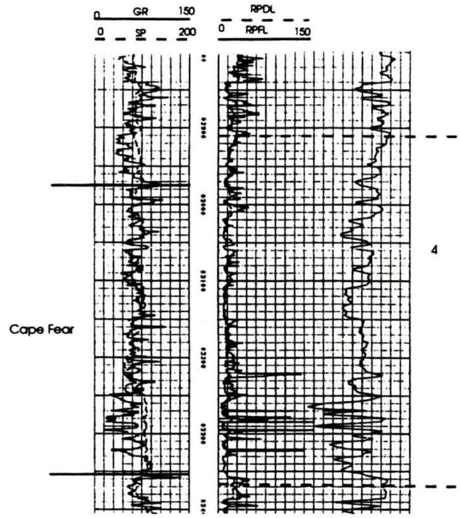

Figure 6. Gamma, Spontaneous potential, and resistivity logs for Depositional System 4. Formation contact for the Cape Fear is indicated.

Depositional System 4 (3375-2912)

The sediments from 3375-2912 ft. contain olive gray to green, fine to coarse grained micaeous sands interbedded with dark purple clays. The gamma log signature consists of a series of blocky patterns deflected to the right (clays) and left (sands) interbedded that has a rather erratic habit. Localized zones of fine grained phosphate were identified in cuttings at 2945 ft. and 2992 ft. Abundant shell fragments are present throughout the interval, but occur in thicker lenses at 3270, 3090, 3010, and 2930-2970 ft (Figure 6).

The down dip marine equivalent of the Cape Fear Formation of Gohn (1992) and Sohl and Owens (1991) in the Clubhouse Crossroads well extends lithologically from 3360 to 2975 ft. in Hilton Head. Two third-order cycles (3.1 and 3.2) are present in the Cape Fear Formation. Although the Cape Fear Formation is dominantly fluvial in origin, marine fauna are present sporadically in the samples at Clubhouse Crossroads. Gohn (1992) proposed a model of a tide dominated delta sequence for the Cape Fear Formation. The abrupt transition from fluvial to marine between the Fripp Island Well and Hilton Head well is consistent with this interpretation. The sediments present represent a shelf margin deposit in open marine conditions. The abundant shell fragments in conjunction with planktonic foraminifera and dinoflagellates support an open marine interpretation.

Cuttings from 3430-3440 ft. contain a foraminiferal assemblage characteristic of the *Globotrunca. helvetica* Zone which is middle Turonian in age. This zone correlates with the interval in the Fripp Island well designated as Pollen Zone IV (Valentine, 1982). The top of the Turonian was picked in a clay layer at 3342 ft. A sidewall core at 3290 ft. contained *Stephodinium coronatum* which does not extend beyond the Conacian. Foraminifera present between 3180-3190 ft. fall within the *Globotruncana concavata* zone (upper Conacian to lower Santonian). The top of the Conacian was picked at 2980 ft. and is interpreted to be the condensed section of the 3.2 cycle.

Depositional Sequence 5 (2912-2800)

Lithologies present in System 5 consist of interbedded gray sand, silt, and clay at the base grading to silty sand near the top. Traces of light olive gray limestone and shell fragments are present though out the interval indicating a shallow marine origin. This interval is lithologically similar to the Middendorf Formation

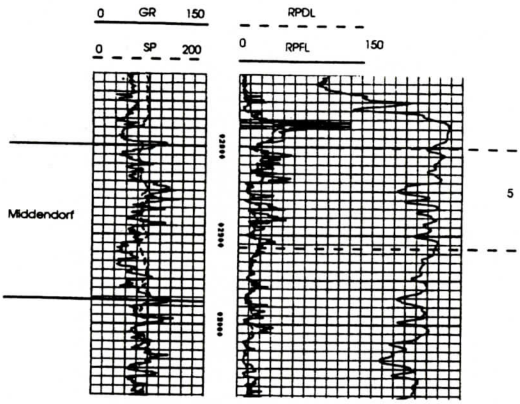

Figure 7. Gamma, Spontaneous potential, and resistivity logs for Depositional System 5. Formation contact for the Middendorf is indicated.

(Gohn, 1992; Sohl and Owens, 1991) in the Clubhouse Crossroads well and is consistent with the interval in the Fripp Island well called Middendorf Formation by Colquhoun and others (1983). The Middendorf ranges from 2975 2800 ft. (Fig 7). The presence of *Chatangiella ditissima* in a core plug at 2832 ft in the Hilton Head well is diagnostic of basal Santonian.

Depositional System 6 (2800-2582)

The lithology from 2800-2582 ft. consists of a greenish-gray glauconitic sandy silt interbedded with dark greenish gray clay and carbonate stringers. The gamma log displays a series of pyramid shaped patterns that grade into a fining upward cycle from 2600-2580 ft. (Fig 8) at the top. In general, the gamma ray log over this section is more radioactive than the interval below indicating a higher clay content. The interval from 2778-2788 ft. contains abundant plant fragments. A carbonate bed seen as a resistive zone on the logs, is present from 2778-2740 ft. (Figure 8).

System 6 contains the Shepherd Grove (3.4 cycle) and Caddin (3.5 cycle) Formations (Gohn, 1992) and the lower Tar Heel Formation of Sohl and Owens (1991) in the Clubhouse Crossroads. In the Fripp Island Well, the lower Black Creek and upper Middendorf Formations of Colquhoun and others (1983) correlates to this interval. The interval could not be subdivided on lithology and has been assigned to the Lower Black Creek Formation in the Hilton Head Well.

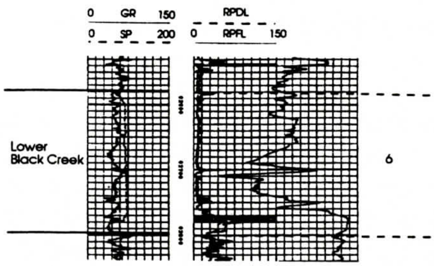

Figure 8. Gamma, Spontaneous potential, and resistivity logs for Depositional System 6. The lower Black Creek contact is indicated.

The top of Depositional System 6 is the top of the UZA-3 supercycle (Haq and others, 1988), a type 1 unconformity. Even though this is a major sequence boundary, it is not recognized as a major unconformity in this well. The upper cycle (3.5) of this unit represents the maximum incursion of the ocean onto the South Carolina coast, and sediments were deposited in the deepest water during the Upper Cretaceous. When sea level fell at the end of System 6 the shoreline still remained a significant distance from its present day position. Sediments deposited during this time remained marine at Hilton Head. The boundary is represented by a increase in sand content of the basal cycle (4.1) in the overlying Depositional System 7 at Hilton Head.

Senoniasphera protusa at 2713 ft. indicates a Santonian age. A sidewall core at 2832 ft. contains a palynomorph assemblage characteristic of the lower Santonian.

The base of the Santonian was picked to coincide with a gamma ray and resisitivity break at 2980 ft. a clay rich zone. This clay zone is interpreted to be the condensed section of the 3.2 cycle, which contains the Conacian/ Santonian boundary. Valentine (1982) placed the top of Santonian at 2427 ft. in the Fripp Island well. This correlates to 2680 ft at Hilton Head. This pick was adjusted downward to coincide with a condensed zone within the 3.4 cycle. The top of Santonian was assigned at 2705 ft. (Figure 8).

Depositional System 7 (2582-1808)

Dark greenish gray clayey silt to silty clay containing phosphate, carbonate and fossil fragments occur from 2582-2170 ft. This silt and clay zone grades upward into a dominantly greenish gray clay interbedded with silt. Trace amounts of carbonate, phosphate, calcareous mud and organic layers are present. Glauconite is moderately abundant throughout the interval. The interval from 2580-2475 ft. is characterized by a gamma shift and low in resistivity except, for a streak at 2530-40 ft. that has a high resistivity (Fig 9). The remainder of the interval displays a uniform gamma ray that is less radioactive (higher sand content) as compared to the interval below. The interval is dominated by a dark greenish-gray to greenish-black clay containing glauconite and phosphate. Calcareous clays, silts and sands containing locally abundant fossil lenses occur from 2170-1808 ft. A clay zone exists from 1888-1865 ft. signified on the gamma ray.

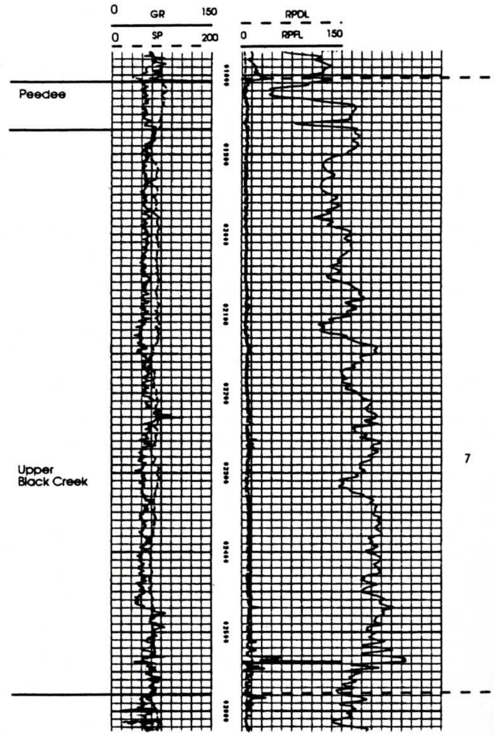

Figure 9. Gamma, Spontaneous potential, and resistivity logs for Depositional System 7. The Upper Black Creek and Peedee contacts are indicated.

Depositional System 7 contains five third order cycles and is the down dip equivalent of the Cane Acre (4.1), Coachman (4.2), Bladen (4.3), and Donoho Creek (4.4) and Peedee (4.5) Formations (Gohn, 1992) at Clubhouse Crossroads. Sohl and Owens (1991) identified the same interval at Clubhouse Crossroads as upper Tar Heel, Bladen, Donoho Creek and Peedee Formations. The top of System 7 is near the Cretaceous/Tertiary boundary.

Based on the descriptions of the formations within the Black Creek Group in Sohl and Owens (1991), the lower four cycles of System 7 (4.1, 4.2, 4.3, and 4.4) is the Upper Black Creek Group in the Hilton Head well. The break between the Upper and Lower Black Creek at 2580 ft. is based on an increase in limestone in the Upper Black Creek.

The appearance of *Gabonisporis vigourouxii, Cribroperidinium edwardsi* in side wall cores between 2356-2494 ft. indicates a Campanian age. *Globotruncana canaliculata var. ventricosa* (Campanian) was present at 2355 ft. in the Parris Island well (McLean, 1960). This zone was correlated into Hilton Head at a depth of 2495 ft. A foraminiferal assemblage of the *G. calcarata* zone is present from 2425-2436 ft. The top of Campanian was picked at the base of a clay rich zone that is interpreted to be the condensed section of the 4.4 cycle. The Campanian interval in the Hilton Head well ranges from 2230-2705 ft.

The Peedee Formation ranges from 1865-1808 ft. in the well (Fig 9). The Peedee is separated from the Upper Black Creek by a break in the gamma ray and by a prominent low resistivity spike. Lithologically the Peedee at Hilton Head contains more glauconite than the underlying Black Creek. Sediments of the Peedee Formation reflect deposition in an open shelf marine environment. These sediments are dominated by the highstand wedge of the 4.5 cycle on the global sea level curve. The presence of disseminated glauconite and phosphate is typical of sediments deposited during a highstand wedge.

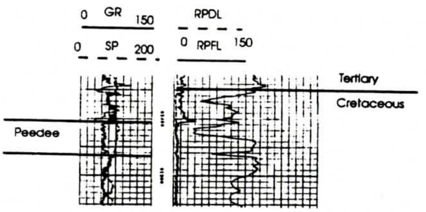

Figure 10. Gamma, Spontaneous potential, and resistivity logs for the Cretaceous/Tertiary boundary in relation to the top of the Peedee.

Sidewall cores taken at 2080 and 2170 ft. contain *Chatangiella biapertura, Cleistosphaeridium huguonotii, Cyclonephelium distinctum,* and *Isabelidinium cooksoniae.* The first appearance of these microplankton define the base Maastrichtian. Sediments of the Maastrichtian age range from 1704-2170 ft. in the well.

The top of System 7 corresponds to the top of UZA-4 supercycle. The UZA-4 boundary however is not the top of the Cretaceous in the South Carolina Coastal Plain. The sequence stratigraphy places the top of Cretaceous at 1742 ft. in the well above a transgressive deposit (Figure 10).

SUMMARY AND CONCLUSIONS

A basal unconformity separates the Upper Cretaceous from the underlying Paleozoic volcanics. The basal third order cycle is 2.2. Type 1 unconformities are present at the top of Depositional System 1, 3, 5, 6, and 7. These unconformities represent a major basinward shift in depositional environments on the shelf. Usually fluvial or marginal marine deposits prograde over marine sediments as a result of a drop in sea-level.

Type 2 unconformities are present at the top of Systems 2 and 4. Sediments deposited on these unconformities represent slight basinward shifts in depositional environments. In general, the overall pattern of deposition in the Upper Cretaceous is transgressive in nature.

Four of the Systems (1,3,5,6) can be considered transgressive in nature. The sediments within these units are marine to marginal marine in nature. They were deposited during a rise in sea level and are all capped by a type 1 unconformity.

Depositional Systems 2 and 4 were deposited during a regressive phase. These Systems contain sediments deposited during a fall in sea level. System 4 contains the large delta complex (Cape Fear) that prograded out onto the shelf during the Conacian.

Depositional system 4 is somewhat unique in its origin. The sediments in the other wells in the area are a deltaic complex deposited in a fluvial environment. However, the interval at Hilton Head is exclusively marine. The delta at this location was under the influence of tides rather than the river

By far, the thickest unit over a given time interval is the Cape Fear Formation (within System 4). This unit represents the largest influx of sediment into the area. The abrupt transition from fluvial to marine sediments between the Fripp Island Well and Hilton Head implies a tide dominated system. With the deposition of each younger system on top of the Cape Fear Formation, the shoreline retreated landward reaching its maximum during the Campanian (System 6). System 7 represents a fluctuating shoreline that gradually moved seaward in response to a gradual drop in sea level.

The upper System (7) contains alternating pulses of sand and sandy clays representing a fluctuating sea level on a small scale. These fluctuations can be tied up dip to the Cane acre, Coachman, Bladden, Donoho Creek and Peedee Formations at Clubhouse Crossroads. These formations could not be delineated with the exception of the Peedee Formation at Hilton Head due to the lack of distinctive lithologies.

Most of the formations present in the Clubhouse Crossroads well can be carried into the Hilton Head Well. The exceptions due to the lack of distinctive lithologies are the Cane Acre, Coachman, Bladen and Donoho Creek Formations. These units correlate to the upper Black Creek in Hilton Head. The lower Black Creek is equivalent to the Caddin and Shepherd Grove Formations. The Cape Fear, Clubhouse and Beech Hill Formations can be carried into the

Hilton Head Well. One new formation, the Folly Field Formation was identified.

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FACIES, STRATIGRAPHY AND PROVENANCE OF THE WARREN POINT SANDSTONE (PENNSYLVANIAN), CUMBERLAND PLATEAU, CENTRAL TENNESSEE

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ABSTRACT

The Warren Point Sandstone is a fine-grained, locally conglomeratic, quartz arenite that is disconformably bounded on its upper and lower contacts and is composed primarily of two facies: A) tabular cross-beds organized into planar-bedded cosets, and B) thin, planar-laminated beds. Channel-fills up to several meters deep and 10's of meters wide, ripple cross-laminated sandstone, and laminated shale facies are also present. These facies units can be grouped into four of Miall (1992)'s major architectural elements: 1) sandy bedforms, 2) laminated sand sheets, 3) channel-fills, and 4) overbank fines. The larger bar forms defined by third and fourth-order bounding surfaces are conspicuously absent. Paleocurrents measured on the tabular cross-beds indicate southwest transport. Throughout the Tennessee Cumberland Plateau, the Warren Point Sandstone occurs as a nearly continuous 7 to 18-meter-thick sandstone sheet. We interpret a sandy braid-plain depositional environment for the Warren Point. Sand composition data suggest a foreland uplift provenance, the southeastern Appalachian orogen. Because the southwestern transport is parallel to the orogen, the sandy braid-plain represents deposition in an axial fluvial system.

INTRODUCTION

The Warren Point Sandstone is a well-sorted, fine-grained, quartz arenite over most of the Tennessee Cumberland Plateau, however, it is medium-grained with abundant quartz pebbles at a few central and southern localities. It occurs from north-central Tennessee where it is a member of the Fentress Formation to north-central Alabama where it is tentatively correlated with the lower sandstone of the Boyles Sandstone Member of the Pottsville Formation. To the northeast, the Warren Point is now recognized as the basal sandstone of the Pennsylvanian Breathitt Group in southeastern Kentucky (Chesnut, 1992) (Figure 1). This is a reinterpretation of Englund (1964)'s Chadwell and White Rocks Members and the lower part of the Middlesboro Member of the Lee Formation.

Along the central Cumberland Plateau, the Warren Point varies in thickness between 7 and 18 meters, however, it is as much as 85 meters thick near Chattanooga, Tennessee. The Warren Point is disconformably bounded by the Mississippian Pennington Formation and the Pennsylvanian Raccoon Mountain Formation on its lower contact and by the Pennsylvanian Sewanee Conglomerate on its upper contact (Figure 2). Up to 100 meters of relief have been recognized on the Mississippian-Pennsylvanian unconformity (Bergenback and Wilson, 1961).

The earliest stratigraphic work done in this area was by Campbell (1893) who proposed and described many lower Pennsylvanian formations as well as the Mississippian Pennington Formation. Glenn (1925) studied in detail lower Pennsylvanian stratigraphy in northern Tennessee, while Nelson (1925) named the lowest Pennsylvanian sandstone body as the Warren Point Sandstone farther to the south in central Tennessee. Wanless (1946) was the first to regionally correlate lower Pennsylvanian

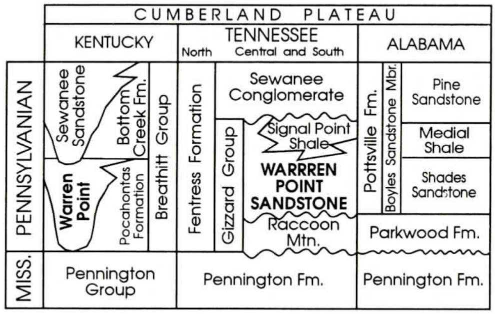

Figure 1. Stratigraphic columns showing the Warren Point Sandstone and adjacent units in central Tennessee, southeastern Kentucky, and north central Alabama. The term Fentress Formation is only used in north central Tennessee adjacent to Kentucky. The wavy lines indicate regional unconformities identified in Tennessee and the locally identified unconformity in north central Alabama, Henry and others (1985). The lithostratigraphic correlation of the Raccoon Mountain with the Parkwood is from Culbertson (1962a). The very tentative lithostratigraphic correlation of the Shades with the Warren Point and the Pine with the Sewanee is from Culbertson (1962a, 1962b). It should be emphasized that this tentative correlation is based on only 10 sections covering some 350 kilometers. The Kentucky column is from Chesnut (1992).

strata for the purpose of defining economic coal reserves. Wilson and others (1956) regionally mapped the entire Pennsylvanian section of the Cumberland Plateau and introduced an improved system of stratigraphic nomenclature (presented in Figure 1). Ferm and others (1972) and Milici (1974) interpreted the Warren Point as a barrier sandstone deposited by west and south-moving littoral currents. This depositional environment was based primarily on 1) interpreting low-angle, tabular cross-beds as low-angle, beach-face beds and 2) the near-shore marine model developed by Hobday (1969) for exposures in northeast Alabama. Warren and Bergenback (1977) interpreted the sandstone near Chattanooga as part of a tidal delta with components of tidal flats and tidal channel deposits. Churnet and Bergenback (1984) first recognized its fluvial characteristics based on sedimentary structures; shortly after, Churnet and others (1986) interpreted a braided fluvial origin for the Warren Point Sandstone based on sedimentary structures associated with braided systems, unimodal paleocurrent directions, and a complete absence of marine fossils.

The lower Pennsylvanian sheet-like sandstones in southeastern Kentucky and southwest-

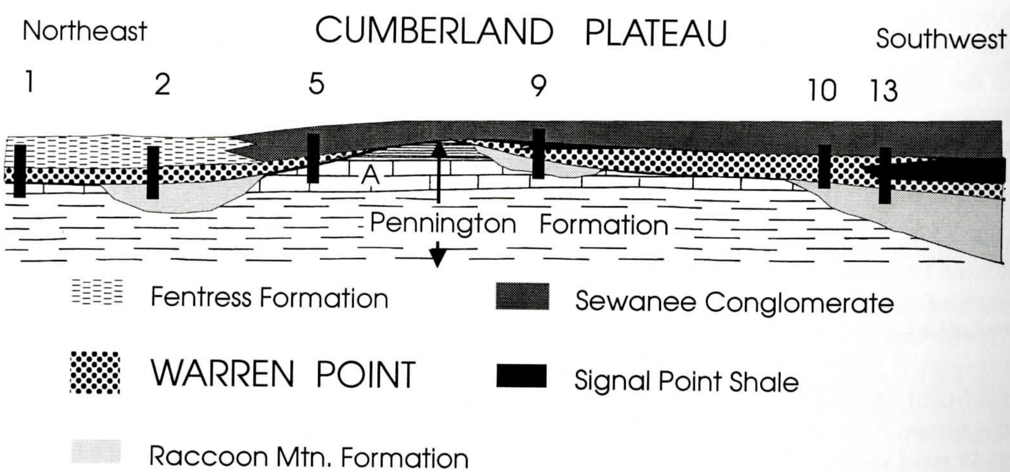

Figure 2. Diagram illustrating the stratigraphic relationships among the Pennington Formation, Raccoon Mountain Formation, Warren Point Sandstone, Signal Point Shale, Fentress Formation, and Sewanee Conglomerate along the Cumberland Plateau in central Tennessee. The numbers refer to measured sections in Figures 3 and 4. The letter 'A' denotes a limestone that comprises the youngest Pennington member throughout most of the Cumberland Plateau. The Warren Point is missing and the Sewanee Conglomerate overlies even younger shales of the Pennington Formation near Monterey and Sparta, TN, between sections 5 and 9. The surfaces that bound these stratigraphic units are interpreted to be disconformities.

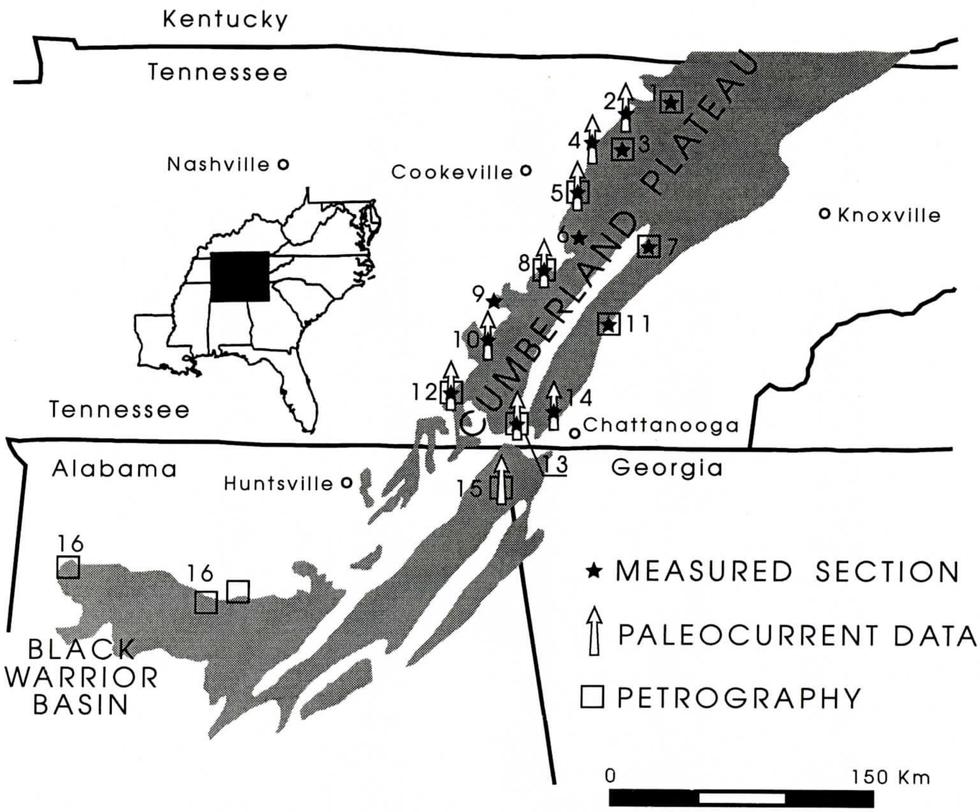

Figure 3. Location map of sections used in this study. Locality 15 is the Lookout Mountain study area of Chen and Goodell (1964); localities 16 identify the sections of Pfleeger (1981).

ern Virginia, the oldest of which is now called the Warren Point (Chesnut, 1992), were interpreted by Englund (1974) and Miller (1974) to be nearshore marine deposits that resulted from northwestward progradation from a low-rank metamorphic source. BeMent (1976) concluded that these sandstones were braided stream deposits based on their erosional basal contacts, fining-upward grain sizes, unimodal cross-bedding (SW-directed), and their upward gradation into siltstones that contain discontinuous coal and underclay beds. Rice (1984, 1985) affirmed the braided stream interpretation.

The correlative Boyles Sandstone Member of the Pottsville Formation in north central Alabama as been interpreted to be a nearshore marine deposit by Hobday (1969, 1974) based primarily on sedimentary structures, especially low-angle, planar cross-bedding that he considered to be beach face bedding. In addition, Hobday considered the sharp basal contact with the underlying marine Pennington units to be a facies contact and not a disconformity. Pfleeger (1981) also concluded that the Boyles was a nearshore marine deposit.

There are two goals in this study: 1) to develop a facies model and interpret the depositional environment of the Warren Point Sandstone to help resolve marine versus non marine origin, and 2) to discern the nature of the sediment source as either a stable continental block or a recycled orogen.

METHODS

Fourteen localities of the Warren Point Sandstone were examined in this study (Figs. 3 and 4). Sections were chosen based on exposure of the formation with emphasis being placed on

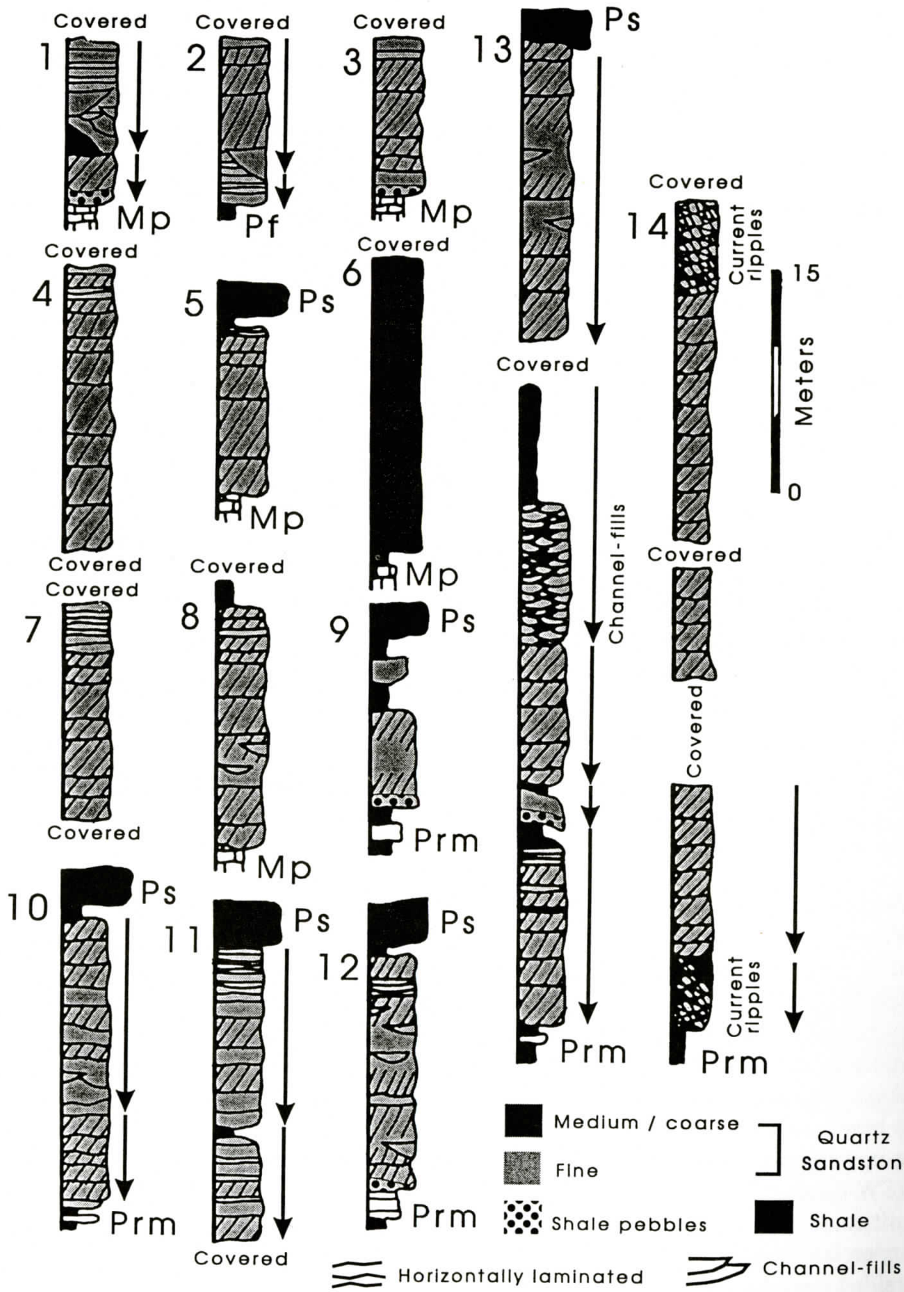

Figure 4. Detailed measured sections of the Warren Point Sandstone used in this study. The numbers match the localities shown in Figure 3; the Pennington Formation is indicated by Mp, the Raccoon Mountain by Prm, the Fentress by Pf, and the Sewanee Conglomerate by Ps. The arrows indicate individual channel-belt deposits in a multistory sandstone. Section 6 is one of only two Warren Point exposures of conglomeratic, medium/coarse-grained quartz sandstone identified in this study (the other is shown in Figure 5). Stratigraphic position, especially the presence of the overlying Sewanee Conglomerate, and geographically adjacent, laterally equivalent, fine-grained sandstone supports a Warren Point identification (Wilson and others, 1956) rather than a Sewanee (Nelson, 1925).

visible upper and basal contacts, completeness of exposure, location, and accessibility. Each section was measured and described using a hand level and tape measure. Where possible, cross-bed dip directions were measured to determine paleotransport direction. Of the fourteen localities, only eight had sufficient numbers of well-exposed cross-beds to record paleocurrent directions. Eight localities were also selected for petrographic information. Thin sections were stained to highlight K-feldspar (sodium cobaltinitrite) and plagioclase (barium chloride plus rhodizonate); a 500-grain, point-count analysis for QFL percentages was performed on each sample. Results were then plotted on QFL and QmFLt diagrams (Dickinson and others, 1983) to evaluate sediment provenance.

STRATIGRAPHY

Lithostratigraphic Correlation

Throughout the Cumberland Plateau in Tennessee and the adjacent parts of Kentucky and Alabama, this formation is a fine-grained, quartz sandstone, locally conglomeratic, with an overall sheet-like geometry. Its thickness in the central Cumberland Plateau area ranges from 7 to about 18 meters.

The Warren Point in north-central Tennessee is thin (sites 1 and 2, Figure 4) and has been considered to be a unit that is only locally recognizable within the Fentress Formation (Wilson and others, 1956). The Warren Point has also been included with the Breathitt Group of eastern Kentucky and western Virginia and is thought to interfinger with the Bottom Creek formation in its southeastern extent in southeastern Kentucky and northern Tennessee (Chesnut, 1992). In this study, the unit is consistently recognized north of the Cookeville, Tennessee, region within the southern portions of the Fentress Formation. The present writers did not lithostratigraphically correlate the Warren Point Sandstone into Kentucky. Distinguishing characteristics include the formation's tabular cross-bedding, its thinning and fining upward nature, and its relative position in relation to adjacent distinctive units in the Fentress Formation. The Warren Point thickens dramatically (sites 13 and 14, Figure 4) in the Chattanooga area (south-central Tennessee, northeast Alabama, and northwest Georgia) and has quartz-pebble conglomerates near its base. The Warren Point is probably equivalent to at least the lower part of the Boyles Sandstone Member of the Pottsville Formation (Figure 1), which has many of the same composition, texture, and bedding characteristics (Hobday, 1974). Farther to the south near Birmingham, Alabama, Culbertson (1962a) divided the Boyles Sandstone Member into two separate members, the Shades Sandstone that sits atop the Parkwood Formation (equivalent to the Raccoon Mountain Formation in Tennessee, Figure 1) and the Pine Sandstone separated from the underlying Shades by an unnamed shale member. It is tempting to use stratigraphic position and lithologic similarity to correlate the Warren Point with the Shades and possibly the Sewanee with the Pine (Culbertson, 1962a and 1962b), however, a lithostratigraphic correlation by means of closely spaced sections has not been done.

Basal Contact

The basal contact of the Warren Point is a sharp, scour surface cutting primarily the unnamed upper limestone member of the Mississippian Pennington Formation and locally the shales and silty sandstones of the Pennsylvanian Raccoon Mountain Formation. Throughout much of the northern and central Tennessee Cumberland Plateau the Raccoon Mountain Formation is either missing (Figure 5) or only several meters thick. The locally preserved remnants are tens of meters thick and occur where the unnamed marine limestone (up to ten meters thick) at the top of the Pennington is absent (Figure 2). In the Chattanooga region (site 13, Figure 2), the Warren Point disconformably overlies the shales and silty sandstones of the Raccoon Mountain Formation.

In many exposures of the basal surface, the Warren Point contains an extensive lag con-

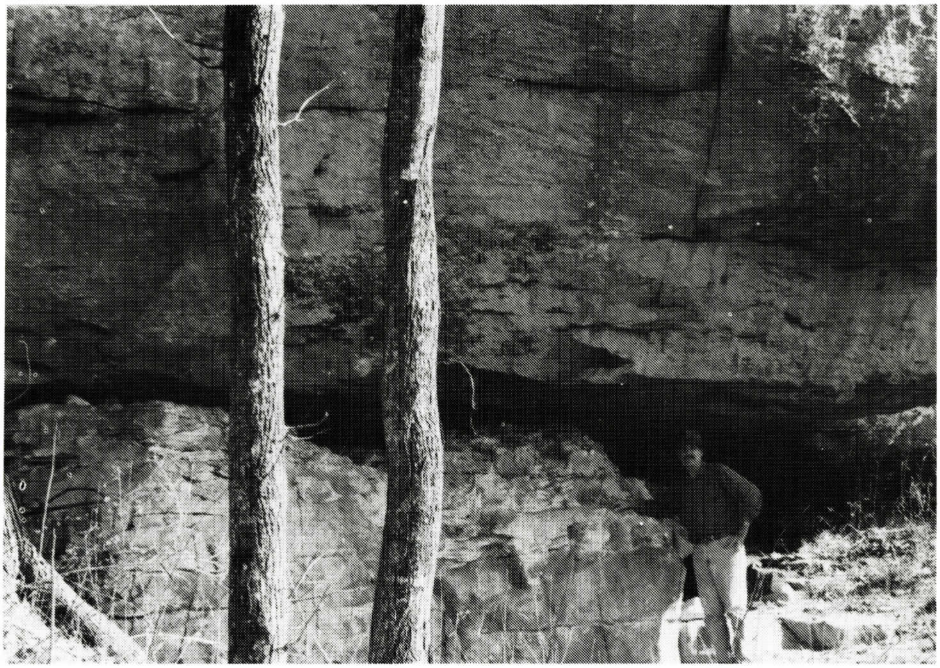

Figure 5. Conglomeratic Warren Point Sandstone resting directly on the upper marine limestone member of the Pennington Formation, TN Highway 30, 1 km west of Spencer, TN. (locality 8, Figure 3). The hat is at the disconformity; note the decimeter-scale tabular cross-beds.

glomerate consisting of pebble-size, rounded, elongate, claystone clasts in a sandstone matrix that decreases upward in grain-size from medium to fine. Replaced wood logs (up to 1-meter in length and 0.5- meter in width) and thin, wavy, discontinuous coal spur rip-ups are also present. Relief on the disconformity at the base of the Warren Point is no more than a decimeter over distances of meters to tens of meters.

Upper Contact

The Signal Point Shale locally overlies the Warren Point Sandstone (Figs. 1 and 2) in central Tennessee and throughout the Chattanooga region. The Signal Point is a mixture of fine-grained sandstone, siltstone, and shale, which contains abundant plant fossils. Locally the uppermost unit is the decimeter-thick Wilder Coal, which was economically important in the central plateau in the earlier part of the twentieth century. In the central Cumberland Plateau region, the Signal Point is up to 7 meters thick; in the Chattanooga region, the type locality, it is up to 18 meters thick. The Signal Point is disconformably overlain by the Sewanee Conglomerate.

The Warren Point's contact with the overlying Sewanee Conglomerate is predominantly observed in central and north-central Tennessee. The Sewanee is characterized as a coarse-grained, quartz arenite containing abundant quartz pebbles, that has a disconformity with the Warren Point with as much as 15-meters of relief over several kilometers distance (site 10, Figure 2). The grain size discrepancy between the Warren Point and the Sewanee proves to be the primary characteristic in distinguishing between the two sand bodies when they are juxtaposed. The Warren Point's overall blanket geometry contains widely scattered "thins" and possible "holes" produced by pre-Sewanee scouring and by topographic "highs" of the Pennington Formation (Figure 2, between sites 5 and 9).

FACIES

The Warren Point Sandstone of the central Cumberland Plateau is a quartz arenite that consists of two major facies: 1) tabular cross-bedded sandstone, primarily fine-grained except in sections where quartz pebbles are locally present and then it coarsens to medium; and 2) fine-grained, planar-laminated, thin-bedded sandstone. Four minor facies are also present: 3) channel-fill sandstone; 4) fine-grained, cross-laminated sandstone; 5) shale; and 6) coarse-grained, gravel lag.

Tabular Cross-bedded Sandstone

Tabular cross-bedded sandstone is the dominant facies of the Warren Point in abundance. It comprises 63 percent of the measured stratigraphic sections (Figure 4). Tabular cross-beds are bounded by flat, horizontal bedding planes ranging from 0.2 to 1.5 meters in thickness and are generally greater than 10's of meters wide, the typical outcrop width (Figure 6a). This facies was used for the paleocurrent measurements. Lenticular scours occur and locally truncate this facies. This facies is fine-grained, however, the grain size coarsens to medium sand in those few sections characterized by abundant quartz pebbles (locality 6, Figs. 4 and 6b).

Fine-grained, Planar-laminated, Thin-bedded Sandstone

Approximately 14 percent of the Warren Point measured sections is composed of fine-grained, planar-laminated, thin-bedded sandstone (Figure 4). Stratification ranges from approximately 1 to 20 centimeters thick with a lateral extent equal to that of the exposure, meters to several tens of meters. This facies has sharp contacts with adjacent facies units, which typically is the tabular cross-bedded sandstone (below) and the channel-fill sandstone (above).

Channel-fill Sandstone

The third most common facies found in the Warren Point is the scoured, channel-fill sandstone making up 9 percent of the measured sections (Figure 4). The scours are typically 1 to 8 meters wide and less than 1.5 meters thick. Two types of channel-fills are commonly observed: those occurring within the main sandstone body and those occurring in the lag deposit at the basal contact. Medium- to fine-grain sandstone organized into low-angle, planar cross-beds characterizes channel-fills within the main sandstone body. The basal portions of channel-fills within the mid-sandstone unit in the Chattanooga area have rounded quartz pebbles in coarse-grained sandstone that grade upward into the fine-grain sandstone that is more characteristic of the Warren Point in central Tennessee. Channel-fills occurring in the basal lag of the Warren Point generally have less internal structures and a much more poorly sorted grain/clast assemblage. Large claystone clasts (10's of millimeters) and replaced wood logs (10's of centimeters) are common in the basal scours. Wood fragments and logs are also found in the scours in the main sandstone body. In many central and northern localities, the channel-fill facies is entirely absent from the Warren Point sections. The channel-fill facies increases in abundance, scour-size, and grain-size south toward the Chattanooga area.

Fine-grained, Cross-laminated Sandstone

Although the fine-grained, cross-laminated sandstone facies makes up approximately 8 percent of the total measured Warren Point sections, it is restricted to only one measured section in the Chattanooga area (locality 14, Figs. 3 and 4). The cross-laminations define both form-concordant and form-discordant current ripples and are organized into thin (5 to 15 centimeters-thick), wavy, irregular, discontinuous cosets.

A

B

Figure 6. Tabular cross-bedded facies of the Warren Point Sandstone. Note the planar coset boundaries. A) fine-grained sandstone (locality 4, Figure 3), note prominent soft-sediment deformation features in basal bed; B) conglomeratic, fine to medium-grained sandstone (Spencer, TN, region about 5 km northwest of locality 8 in Figure 3).

Shale

The shale facies is characterized by interbedded, laminated silt and clay with rare coal interbeds and makes up about 5 percent of the measured sections. Shale deposits range in thickness from a few centimeters to 9 meters and are laterally cut out by fine-grained, channel-fill sandstone. The coal beds can reach thicknesses of 45 centimeters but most are less

Table 1. Analysis of Warren Point paleocurrent measurements. Localities are shown in Figs. 3 and 7. All R-magnitude values are sufficient to reject the hypothesis of a random distribution at the 0.05 significance level.

Locality	Measurements	Mean (degrees)	95% Confidence Interval (degrees)	R - magnitude
2	25	271	16	0.77
4	25	205	14	0.81
5	42	242	7	0.91
8	65	262	10	0.76
10	32	247	13	0.80
12	42	253	22	0.51
13	33 (C, upper)	180	18	0.66
13	15 (B, middle)	30	26	0.68
13	17 (A, lower)	218	14	0.88
14	32	283	12	0.82
Composite	314	246	7	0.60

than 3 centimeters thick. This facies contains abundant plant fossils, preserved of both carbonized films and sand-filled casts. Where this facies occurs directly beneath the Sewanee Conglomerate, it is called the Signal Point Shale, however, where it occurs between two fine-grained sandstones characteristic of the Warren Point, it is unnamed. Because this shale facies is identical in both occurrences, the present writers consider the Signal Point to be a geographically restricted facies of the Warren Point and not a separate unit that originally blanketed much of the Cumberland Plateau region.

Coarse-grained Gravel Lag

This facies makes up about 1 percent of the measured Warren Point sections and typically occurs immediately above the basal contact (Figure 4). The gravel lag is composed of rounded, elliptical claystone rip-up clasts 2-6 centimeters long, siderite nodules up to 1 centimeter in diameter, pebble-size coal clasts, and centimeter-thick, sinuous, discontinuous coal stringers, as well as replaced wood logs and imprints. Poorly defined, discontinuous, wavy bedding characterizes this facies. This gravel lag is also found at the base of some channel-fills overlying the shale facies.

PALEOCURRENT ANALYSIS

Nine localities were chosen for a paleocurrent analysis because of their accessibility and suitable exposure of a cross-bedded sandstone facies. Due to the almost complete absence of trough cross-bedding in the measured sections, the tabular cross-bedded facies was exclusively used for the paleocurrent analysis. Figure 7 is a regional distribution map with the paleocurrent data of each locality centered over that site's geographic location. The individual transport directions are shown with an equal-area Rose diagram (Nemec, 1988) divided into 30 degree

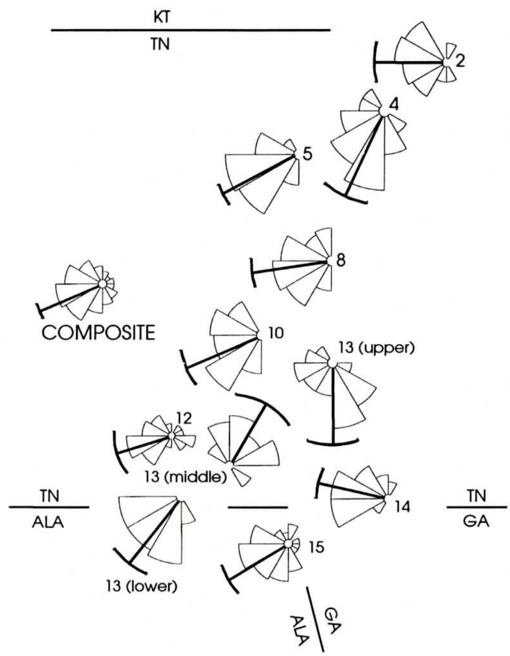

Figure 7. Paleocurrent rose diagrams for the Warren Point Sandstone based on tabular cross-bed measurements. The numbers refer to the localities in Figures 3 and 4; the detailed statistics for each rose are in Table 1. The solid black lines are the mean directions and the arcs at their ends define the 95% confidence interval. Note the overall southwest transport (composite).

intervals. Mean transport directions range from west to south (Figure 7 and Table 1). A composite of all 314 measurements yields a mean direction of 246 degrees with a R-magnitude of 0.60 (Table 1 and Figure 7). Chen and Goodell (1964) report a similar resultant for the Warren Point from the Lookout Mountain region of northwest Georgia and northeast Alabama (locality 15, Figure 7).

The average paleocurrent directions at all but one locality (13, Figure 7) have R-magnitude values sufficient to reject the hypothesis of random distribution at the 0.05 significance level (Table 1); these measurements can be considered to have come from unimodal populations. Locality 13 contains measurements collected from three superposed sand bodies (Figure 4). The paleocurrent measurements from each individual sand body yield average directions that have R-magnitude values sufficient to reject the hypothesis of random distribution at the 0.05 significance level (Table 1). The upper and lower bodies have essentially southerly transport directions, however, the middle sand body has a northeastern direction.

ENVIRONMENT OF DEPOSITION

The summarized facies column for the Warren Point Sandstone (Figure 8) emphasizes an upward decrease in bed thickness and grain size. The base of the Warren Point commonly contains a gravel lag representing a high-energy influx of quartz sand over limestone or shale. Plant remains and log imprints are commonly associated with the basal contact and the gravel lag, although they may be found anywhere within the section. Channel-fills occur both within and immediately above the gravel lag. Overlying the channel fills and sometimes directly over the gravel lag are planar-bedded cosets of tabular cross-beds that make up the bulk of the section. The cross-beds record unimodal paleotransport to the west, southwest, and south. Near the upper part of a typical Warren Point sand body, cross-bed cosets decrease in thickness to approximately 10 to 20 centimeters and are locally overlain by planar-laminated, thin-bedded sandstone. Within discontinuous shale lenses, plant imprints, sand-filled log and root casts, and thin beds and stringers of coal are quite common. Because these shale interbeds are truncated and locally removed by overlying channel-fills (locality 1, Figure 4) and gravel lags (locality 13, Figure 4) they are considered to represent the final facies unit deposited within a Warren Point depositional unit.

Thinning and fining upward are evidences of an upward decrease in energy level and, possibly, water depth. The presence of plant imprints and log casts near the basal contact, plant remains and coal beds within shale lenses, a predominant unimodal paleotransport suggested by the cross-beds, and the relative fining upward from the gravel lag at the basal contact all support a fluvial origin for the Warren Point

Sandstone. The absence of tidal bundles, mud drapes, reversing crest ripples and dunes, bioturbation, and marine fossils suggest that the Warren Point of the central Cumberland Plateau region of Tennessee does not have a near-shore marine or tidal influenced origin.

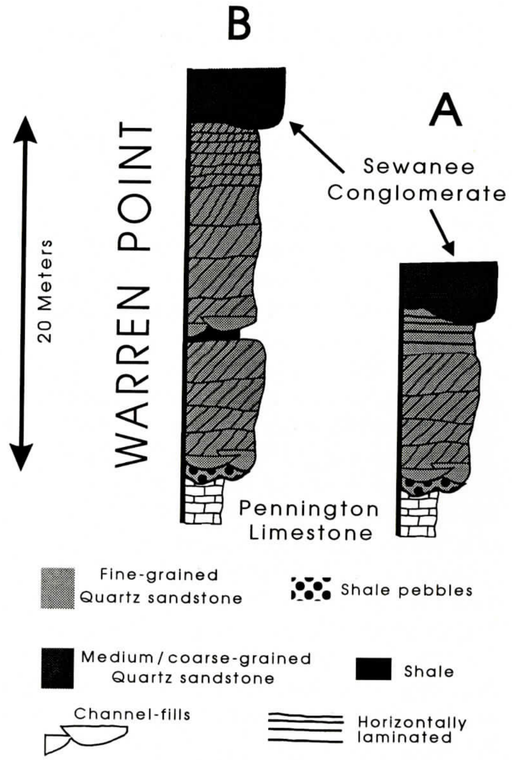

Figure 8. Generalized facies sequence and stratigraphic models for the Warren Point Sandstone along the Cumberland Plateau in central Tennessee. This facies sequence emphasizes the predominance of the tabular cross-bedded facies and the basal position of both shale-pebble conglomerate and channel-fills. The stratigraphic models illustrate the regional paucity of shale interbeds, and the scoured, disconformable contacts with the underlying Pennington Formation and the overlying Sewanee Conglomerate. Model A represents the typical situation found throughout the Cumberland Plateau in central Tennessee--a single channel-belt deposit, see sections 3, 4, 5, 6, 7, 8, 9, and 12 in Figure 4. Model B represents the multistory sandstone typical of the southern plateau near Chattanooga, sections 10, 11, 13, and 14 in Figure 4. Each channel-belt sequence is interpreted to have been deposited by a sand-rich, low sinuosity or braided, fluvial system.

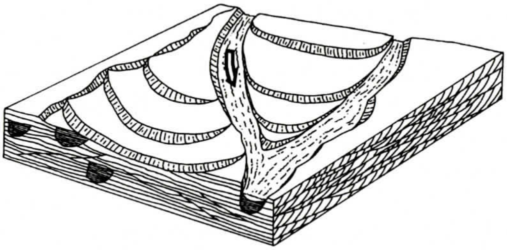

Figure 9. Block-diagram illustrating the channel-bed configuration hypothesized for the Warren Point fluvial system. Downstream migration and piggyback climbing of the straight-crested, 2-D dunes create the predominant tabular cross-bedding. The shallow and narrow channels here represent the low-flow condition; we hypothesize that they tend to concentrate toward the base of a complete channel-belt sequence.

The channel of the fluvial system that deposited the Warren Point was relatively straight, suggested by the low variability of the paleocurrent measurements. Its bed was characterized by straight-crested, 2-D dunes, indicated by the predominant tabular cross-beds. The channel-fill facies represents deposition in shallow channels that, although common at the base of a depositional unit, occur scattered throughout the cross-bedded facies as well. The discontinuous shale lenses present in the central Cumberland Plateau region represent floodplain deposits that, because of their scarcity, had a very low preservation potential. Abundant coal and preservation of rooting suggest these floodplains were well vegetated. No evidence for lateral accretion surfaces was discovered in the Warren Point. These factors suggest a low sinuosity, sand-rich fluvial system with deposition resulting primarily through the aggradation of 2-D bedforms migrating downstream in piggyback fashion (Figure 9). Local vertical accretion resulted in the deposition of horizontally laminated sand as well as sheets of current ripples. Given the Warren Point's sheet-like geometry and the scarcity of floodplain deposits, avulsion rates were probably high.

Groups of fluvial facies can be combined into architectural elements (Miall, 1992) that describe the macroforms of an ancient river system. They are used to identify major sedimentologic forms when parts of the form are removed by erosion. The Warren Point facies units can be assigned to four distinct Miall-type architectural elements: 1) sandy bedform, 2) laminated sand, 3) channel, and 4) overbank fines. The sandy bedform is the most significant architectural element present in the Warren Point and consists of the fine-grained, cross-bedded and cross-laminated facies units. The expected downstream accretion element (various bar-types) is conspicuously missing; neither third nor fourth-order bounding surfaces used to define this bar macroform were identified throughout the central Tennessee Cumberland Plateau. The overbank fines record floodplain deposition.

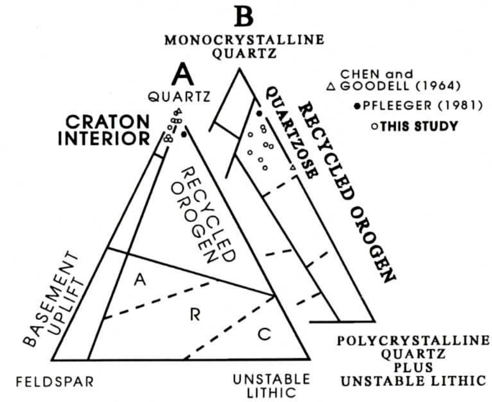

Figure 10. Warren Point Sandstone grain compositions plotted on Dickinson and others (1983) provenance diagrams. On the QFL plot (A) the data fall within the craton interior field or along its boundary with the recycled orogen; the average of Chen and Goodell (1964), 32 samples, from the Lookout Mountain region of northwest Georgia and northeast Alabama also falls within the craton interior field. On the QmFLt plot (B) in which polycrystalline quartz grains are grouped with lithic fragments, both the data from this study and the mean of Chen and Goodell (1964) fall well within the quartzose recycled orogen field. On both diagrams the mean of 36 samples from the basal Boyles Sandstone Member of the Pottsville Formation in north central Alabama (Pfleeger, 1981) falls within the quartzose recycled orogen field. This basal Boyles unit is tentatively correlated with the Warren Point (Culbertson, 1962a and 1962b).

PROVENANCE

A petrographic investigation of the Warren Point Sandstone from eight localities (Figure 3) determined the percentage composition of monocrystalline quartz, polycrystalline quartz, feldspar, and lithic fragments. The QFL diagram (Dickinson and others, 1983) (Figure 10A) shows primarily a cratonic interior source with some data points lying in the recycled orogen zone. Warren Point composition data collected from the Lookout Mountain region of northwest Georgia and northeast Alabama by Chen and Goodell (1964) also suggest a craton interior source (triangle in Figure 10A). However, composition data reported by Pfleeger (1981) from the coeval? lower Boyles Sandstone Member of the Pottsville Formation in north central Alabama indicates a recycled orogen source (solid hexagon in Figure 10A). Polycrystalline quartz is an arguable indicator of low-rank metamorphic source rocks, Basu and others (1975) and Young (1976). Because it is not separated from monocrystalline quartz in the QFL diagram, this plot may not adequately discriminate provenance for quartz-rich sandstones.

However, the QmFLt diagram (Dickinson and others, 1983) (Figure 10B) separates monocrystalline and polycrystalline quartz with the latter being included with lithic fragments. All of the Warren Point data points from central Tennessee fall well within the recycled orogen (quartzose) zone on this diagram, as well as those of Chen and Goodell (1964). Therefore, it is probable that eroding highlands along a suture zone of a collisional orogen, and/or along a thin-skinned foreland fold-thrust zone next to a collisional orogen (Dickinson and others, 1983) supplied recycled quartz grains and *not* the craton interior. The orogen would have been the Appalachian of late Mississippian/early Pennsylvanian age located southeast of the Warren Point outcrop belt. These results suggest that during the early Pennsylvanian the Appalachian orogen was in an early stage of unroofing. The metamorphic provenance proposed by Churnet (1993) for the entire Gizzard Group in southeastern Tennessee suggests a more advanced stage.

CONCLUSION

The Pennsylvanian Warren Point Sandstone of the Cumberland Plateau region of central Tennessee was deposited in a sand-rich, low sinuosity, braided, fluvial system. The channel bed was characterized by 2-D dunes with scattered shallow, relatively narrow, channels, Figure 9. Sediment transport was generally southwestward, although at specific localities, westward and southward transport was dominant. Although there is no widely accepted facies model for the braided, low sinuosity, fluvial system, the models of the Platte River (Miall, 1977) and the sand flat of the South Saskatchewan River (Cant and Walker, 1978) contain many facies units arranged in a similar assemblage to those of the Warren Point. The Warren Point facies units, especially the tabular cross-bedded cosets and facies sequence, closely resemble those of the Mesozoic Nubia Sandstone of southwestern Egypt. The Nubia contains a uniform distribution of medium-sized quartz grains, a large amount of plant fossils (imprints and casts), an overwhelming abundance of tabular cross-beds bounded by horizontal bedding planes, and interbeds of kaolinitic sand containing root traces (Klitzsch and others, 1979; Figure 5-7 in Harms and others, 1982). The facies sequence is a mudstone gravel lag, followed by tabular cross-beds, and capped with a kaolinitic, bioturbated sandstone containing root traces. The Nubia is also interpreted to have been deposited in a sand-rich, low sinuosity or braided, fluvial system characterized by 2-D dunes (Harms and others, 1982).

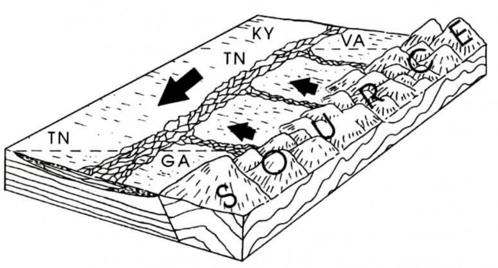

Figure 11. Block diagram illustrating the paleogeography of central Tennessee during deposition of the Warren Point Sandstone. The Warren Point is interpreted to have been deposited in an axial braid plain running parallel to the emerging southern Appalachians which were the sediment source. The northwest flowing streams draining the mountains proper have not yet been identified. However, the westerly transport directions locally found within the Warren Point may allude to this drainage. The Warren Point braid plain continued southwest into north central Alabama for, as yet, unknown distance; it extended northeast into Kentucky, Virginia, and West Virginia (Rice, 1984).

The Warren Point Sandstone is primarily a fine-grained quartz arenite, ranging to subarkose in central Tennessee and in the Chattanooga region (Chen and Goodell, 1964). However, the quartz population contains enough polycrystalline grains (Figure 10) to indicate a quartzose recycled orogen source rather than the craton interior, using the QmFLt diagram of Dickinson and others, (1983). This provenance interpretation suggests that the southeast adjacent Appalachian orogen is the source and, furthermore, during Warren Point deposition this orogen was in an early stage of unroofing.

The increased thickness of the Warren Point section encountered in the Chattanooga area is accompanied by an extremely thick Raccoon Mountain section. The Warren Point ranges 85-100 meters in thickness in the Chattanooga area (localities 13 and 14, Figure 4), whereas in the central Cumberland Plateau area, it ranges 7-18 meters thick. This increased vertical section has been proposed to be a result of localized subsidence (Bergenback, 1994), or possibly the sedimentation of an incised paleovalley.

Because the southwestern transport direction is parallel to the Appalachian orogen, the hypothesized source, the Warren Point probably represents an *axial* drainage system located some distance to the northwest of the Appalachians. Chesnut (1988) and Archer and Greb (1995) suggest that this axial or longitudinal drainage basin extended for thousands of kilometers, parallel to the emerging Appalachians and well up into eastern Canada (Gibling and others, 1992). We hypothesize that this axial drainage was fed primarily by northwest-flowing streams that came directly off the mountains (Figure 11). This paleogeographic reconstruction implies that further southwestward in north central Alabama there should be equivalent nearshore marine units, perhaps the beach and barrier deposits (Hobday, 1974, and Pfleeger, 1981) of the Boyles Sandstone.

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PARTICLE SIZE DISTRIBUTION ALONG A PLEISTOCENE TERRACE ON THE FLORIDA PANHANDLE GULF COAST

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ABSTRACT

Although studies of sedimentary deposition and the spatial distribution of grain size have been made on Holocene beach and dunal deposits along the Florida Panhandle Gulf Coast, and definite relationships shown between sediment distribution and grain size and wave conditions and longshore transport, no studies have examined the spatial distribution of particle size in the region's terraces topographically above the Recent beach/dual sequence. The purpose of this research is to examine the spatial variation of grain size distribution in soils formed from sediments of Pleistocene strand lines in the Florida Panhandle region. The approach examines existing particle size data from three commonly occurring soil series in the study area. The data, averages of particle size classes weighted by soil horizon thickness in the upper 2 m, were gathered from soil characterization reports in six counties along the Florida Gulf Coast, extending eastward over 320 km from the Alabama/Florida line to Lighthouse Point. The soils range from 81.2 to 96.3 percent fine and medium sand fraction. Results of regression trend analyses indicate that medium sand abundance increases (R^2=0.75), that fine sand decreases (R^2=0.66), and the mean size of the sediment (in phi units) decreases (R^2=0.71), indicating a general coarsening of texture westward across the study area. The trend of coarsening of particle size on low Pleistocene terraces along the Florida Panhandle Gulf Coast westward from Franklin to Escambia County is similar to that for Holocene beach and dune sediments, which results from a westward increase in wave energy. The similarity in particle size trend suggests a similarity in geologic substrate and developmental geomorphic processes, particularly wave energies along shorelines of different ages.

INTRODUCTION

Eight ancient marine shorelines and terraces were originally mapped along the Florida coast by Cooke (1939, 1945) and later by Healy (1975). These surfaces increase in age and elevation inland from the modern coastline starting with the Holocene Silver Bluff terrace (0-3 m above MSL) and ending with the Pliocene Hazlehurst terrace (45-85 m above MSL) (Healy, 1975). The second of these strand lines and the one studied herein, the Pamlico, is mid- to late-Pleistocene and is generally 3-11 m above MSL (MacNeil, 1950; Healy, 1975). The study of grain size along the Florida Panhandle Gulf Coast has centered mostly on the Silver Bluff terraces and Recent beach/dual formations (Tanner, 1960; Stone and others, 1992).

Sorenson and Psuty (1978) examined sediment particle size distribution across a series of three strand lines in the Tampa Bay, Florida vicinity along the Peninsular Gulf Coast. They noted that characteristics of soils formed from sediments in these features varied markedly with landscape position. Using the methods of

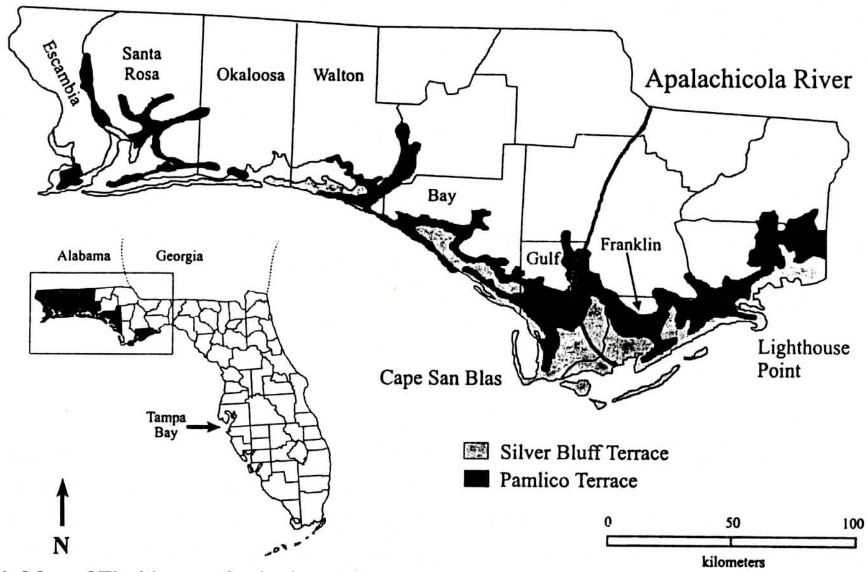

Figure 1. Map of Florida counties in the study area.

Folk (1980), they found fine textures were typical in depressional/lagoonal positions and coarse textures on ridge/barrier bar positions. They also found that particle size generally coarsened inland from youngest to oldest features. In extreme northwest Florida, Goldin and Collins (1996) showed that landscape position and terrace age on the Silver Bluff and Pamlico terraces influence soil chemical and mineralogical properties, but found no significant difference between them in particle size. Both of these studies focused on grain size variability across strand line features (perpendicular to the coastline) rather than along them (parallel to the coastline).

In the interpretation of the environment of deposition, sedimentologists must make increasing use of clues provided by studies of modern depositional environments (Andrews and van der Lingen, 1969). Hsu (1960) found that most of the Gulf Coast Holocene beach sands are similar to the Pleistocene sands in grain size and morphology. Goldin and Collins (1996) found little difference in particle size distribution between soils on Holocene and Pleistocene terraces in Escambia County, Florida.

Studies of sedimentary deposition and the spatial distribution of grain size (Martens, 1931; Johnson, 1956; Stewart and Gorsline, 1962; Kofoed and Gorsline, 1963; Nordstrom, 1977) have been made on Holocene beach and dunal deposits along the Florida Panhandle, and some have shown definite relationships with wave conditions and longshore sediment transport (Price, 1954; Tanner, 1960; Balsillie, 1975; Stone and others, 1992). No studies, however, have examined the spatial distribution of grain size in the Pleistocene terraces topographically above the Recent beach/dunal sequence along the Florida Panhandle Gulf Coast.

The purpose of this paper is to determine the coast-wise grain size relationship within sediments of the Pleistocene strand lines in the Florida Panhandle region from the analysis of existing soil particle size data. These data are available for three commonly occurring soils in each county in the region. Particular attention is given to the trends in grain size distribution and their possible relationships with coastal processes, such as wave energy and longshore transport of sediment.

DESCRIPTION OF THE GEOLOGY AND SOILS OF THE STUDY AREA

Age and terrace elevations have been

Table 1. Determination of weighted average for representative Leon pedons in Santa Rosa and Franklin counties.

Size Fraction (mm) → Horizon and County ↓	2.0-1.0	1.0-.5	.5-.25	.25-.1	.1-.05	.05-.002	<.002
SANTA ROSA CO.							
A - 0 to 5 cm	0.1	6.7	68.3	16.2	0.8	3.1	2.0
E - 5 to 40 cm	0.0	5.8	72.2	17.8	0.1	3.5	0.6
Bh1- 40 to 53 cm	0.0	4.9	63.9	17.8	0.2	7.9	5.3
Bh2 - 53 to 64 cm	0.0	5.5	66.3	17.3	0.2	5.9	4.8
BC - 64 to 81 cm	0.0	5.0	65.6	20.8	0.2	5.2	3.2
C - 81 to 200 cm	0.0	5.0	68.7	22.3	0.2	2.7	1.2
Weighted avg.	**0.0**	**5.2**	**68.6**	**20.7**	**0.2**	**3.6**	**1.7**
FRANKLIN CO.							
Ap - 0 to 20 cm	0.3	13.3	45.5	37.3	1.8	1.7	0.1
E - 20 to 56 cm	0.2	11.0	42.4	41.0	2.0	0.2	3.2
Bh1 - 56 to 102 cm	0.3	12.8	45.4	36.6	1.7	2.1	1.1
Bh2 - 102 to 183 cm	0.4	13.3	45.5	37.9	1.4	1.0	0.5
C - 183 to 203 cm	0.0	5.0	37.2	54.0	1.2	0.2	2.4
Weighted avg.	**0.3**	**12.1**	**44.2**	**39.5**	**1.6**	**1.1**	**1.2**

closely correlated in the Panhandle region (Cooke, 1939, 1945; MacNeil, 1950; Marsh, 1966) (Figure 1). The Pamlico terrace has been regarded as mid-Wisconsinan by Cooke (1945), MacNeil (1950) and Vernon (1951) among others, while Flint (1942), Doering (1956), and Richards (1962) favor a Sangamon age, according to Schnable and Goodell (1968). The Silver Bluff terrace has been assigned a mid-Wisconsinan age by Cooke (1945) and Doering (1956), whereas MacNeil (1950) and Fairbridge (1961) favor a Recent age, as summarized by Schnable and Goodell (1968).

Modern and ancient beaches along the Florida Panhandle are composed of predominantly quartz with few accessory minerals (Gorsline, 1966; von Drehle, 1973; Stone and others., 1992; Goldin and Collins, 1996). The original source of the sands that make up the barrier islands and off-shore sandy shelf is the Appalachian Piedmont to the north. These coastal sands represent multicycle, extensively reworked coastal plain sediments that have been deposited and redeposited at successively lower stands of sea level (Schnable and Goodell, 1968).

The soils studied on the Pamlico terrace are the Leon, Resota, and Kureb series, which fit a predictable hydrosequence of poorly drained, moderately well drained, and excessively drained sandy soils, respectively. These correspond to depressional, intermediate, and ridge/dunal positions in the landscape (Carlisle and others, 1981, 1985, 1988, 1989; Sodek and others., 1990; Goldin and Collins, 1996).

The region in modern times is a low- to medium-energy coast as defined by Price (1954). East of Cape San Blas, wave energy levels are minimal and west of the Cape, wave heights and energy increase markedly (Tanner, 1960; Gorsline, 1966; Balsillie, 1975).

METHODS

Data were derived from eighteen pedons representing three soils in a toposequence for each of the six counties along the Florida Panhandle Gulf Coast. All pedons were located within 1.5 km of the present coast except one Leon pedon, which was 40 km inland in Bay County. Seven classes of grain size from coarse sand to clay were determined for each horizon sampled, and the mean of the sediment (in phi units) was calculated from the grain size data according to the methods outlined in Folk

Table 2. Amount of each particle size class by weight for three soils in six counties in Florida.

Size Fraction(mm) → Soil and County ↓	2.0-1.0	1.0-.5	.5-.25	.25-.1	.1-.05	.05-.002	<.002	mean phi
LEON SERIES								
Escambia	0.0	8.9	67.2	17.1	0.0	5.6	1.2	3.50
Santa Rosa	0.0	5.2	68.6	20.7	0.2	3.6	1.7	3.34
Okaloosa	0.1	4.8	61.1	29.6	0.3	2.2	1.9	3.19
Walton	0.6	8.3	58.5	27.6	0.9	2.4	1.7	3.40
Bay	0.0	9.9	54.7	26.5	2.7	5.0	1.2	3.29
Franklin	0.3	12.1	44.2	39.5	1.6	1.1	1.2	2.50
RESOTA SERIES								
Escambia	0.0	7.9	70.3	17.2	0.1	3.8	0.7	3.54
Santa Rosa				Not Sampled				
Okaloosa	0.2	7.5	61.0	26.4	0.7	2.7	1.5	3.35
Walton	0.2	8.1	40.7	43.5	3.2	2.9	1.4	2.96
Bay	0.0	1.6	46.2	48.7	0.6	1.8	1.1	2.71
Franklin	0.0	0.7	40.6	55.7	0.4	0.6	2.0	2.55
KUREB SERIES								
Escambia	0.0	4.1	75.7	18.0	0.0	1.3	0.9	3.46
Santa Rosa	0.0	4.1	73.1	19.0	0.1	2.5	1.2	3.39
Okaloosa	0.0	5.6	60.5	29.5	0.7	2.2	1.5	3.22
Walton	0.0	1.6	58.2	36.2	0.5	2.2	1.3	2.94
Bay	0.0	0.9	45.6	49.4	0.7	1.9	1.5	2.65
Franklin	0.0	3.1	41.4	53.4	1.0	0.2	0.9	2.73

(1980). Although the data set includes only 18 points (three soil series sampled in each of six counties), the pedons were selected in the original studies because they are typical of the three soils in their respective counties (Carlisle and others, 1981, 1985, 1988, 1989; Sodek and others, 1990).

In the comparison of Pleistocene sediments with those from the Holocene, it would be appropriate to use a similar sampling technique, namely from the upper few cm of sediment. However, such a sample cannot be collected from unaltered Pleistocene sediments since they have been differentiated pedologically since that time. Because these soils show clear pedological development with translocation of iron, aluminum, organic matter, and clay, the upper 2m of soil material were treated as a weighted average for each particle size class, weighted by horizon thickness. This decision was made to offset the effects of soil formation on these sediments. Thus, for each of the eighteen soils for which data are presented, the average grain size represents 4 to 7 samples from the horizons identified in these soils by the researchers who originally collected them (Tables 1 and 2).

The particle size data were taken from soil survey characterization reports for Escambia, Santa Rosa, Okaloosa, Walton, Bay, and Franklin counties (Carlisle and others, 1981, 1985, 1988, 1989; Sodek and others, 1990) and from Goldin and Collins (1996). These data were derived using standard particle size analytical techniques (Soil Survey Laboratory Staff, 1992). Characterization data were not collected for the three soils in Gulf County, therefore that county was excluded from this study. Linear regression was used to evaluate the trends of particle size changes in the averaged data across the Florida Panhandle Gulf Coast (Lindman, 1991).

RESULTS AND DISCUSSION

The soils are comprised of 81.2 to 96.3 percent fine and medium sand and their texture be-

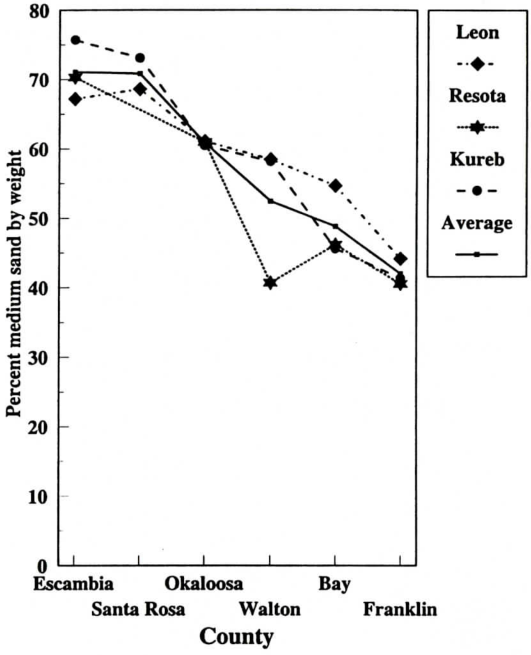

Figure 2. Distribution of the medium sand grain size fraction in the six counties along the Florida Panhandle Gulf Coast.

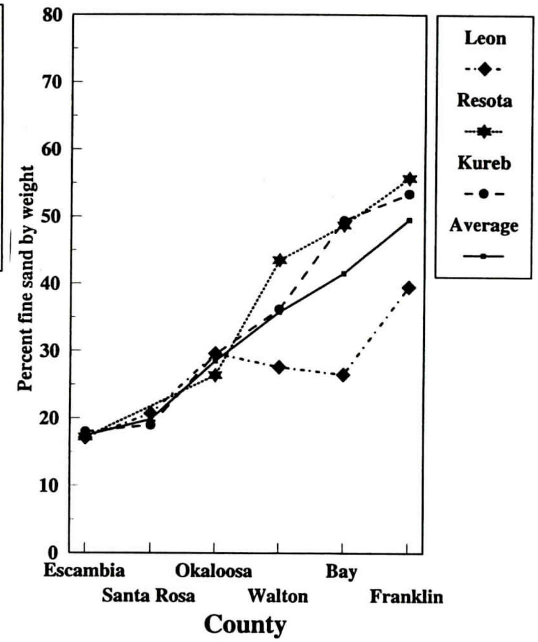

Figure 3. Distribution of the fine sand grain size fraction in the six counties along the Florida Panhandle Gulf Coast.

comes progressively coarser toward the west (Table 2). The regression trend analyses compare the amount of medium and fine sand, and the mean grain size, with the distance of each data point eastward from the north-south Alabama-Florida state line. Results of these analyses, shown in Figures 2-4, indicate that medium sand decreases (R^2=0.75), that fine sand increases (R^2=0.66), and that mean grain size of the sediment (in phi units) increases (R^2=0.71) with increasing distance from the Alabama-Florida line. The three regression lines are significant at $P < 0.001$. The mean grain size values are comparable to other studies in North America (Table 3).

The particle size trends for each of the three soils across the Panhandle were not significantly different ($P < 0.001$) from each other in each respective county, indicating that pedogenesis, resulting from differential translocation of iron, aluminum, organic matter and clay, has not affected the overall particle size distribution in the upper 2 m (Goldin and Collins, 1996).The lack of any significant difference among soils in the three drainage classes does not concur with Sorenson and Psuty (1978) in the Tampa Bay area along the Florida Peninsular Gulf Coast, who found that particle size was closely correlated

Table 3. Range of sediment sizes in different beach faces in North America

Location	Range of Size (phi)	Sources
Coburg Peninsula, B.C.	-0.27-0.32	McLaren and Bowles (1985)
Florida and SE Alabama	1.7-2.4	Stone et al. (1992)
Hook Spit, New York Bay	1.17-1.42	Nordstrom (1977)
Western Florida Panhandle	1.22-1.79	Balsillie (1975)
Tampa Bay, Florida	1.8-3.0	Sorenson and Psuty (1978)
Florida Panhandle	1.48-2.00	This study

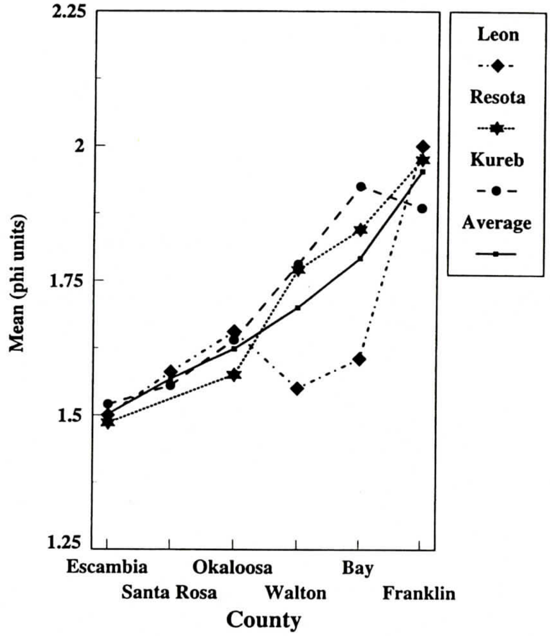

Figure 4. Distribution of the mean grain size in three soils by county in the Florida Panhandle

with geomorphic position. In their study grain size allowed precise identification of individual foreshore, beach, dune and lagoonal facies of sediments. Such was not the case here

The data clearly indicate a coarsening of particle size on the Pleistocene terrace along the Florida Panhandle Gulf Coast westward from Franklin to Escambia County. This trend is similar to that on the Holocene beach and dune sediments, which results from a westward increase in wave energy (Tanner, 1960; Gorsline, 1966; Balsillie, 1975; Stone and others, 1992). Our findings of similarity in soils/sediments among Holocene and Pleistocene surfaces in the Panhandle region suggests their parent material and developmental processes, including wave energies, were also similar throughout these time periods. That is, the finer sediments are found in lower energy, depositional zones, whereas coarser sediments are associated with high-energy erosive zones (Trask and Hand, 1985; Dubois, 1989; Guillen and Jimenez, 1995).

Net longshore transport of modern sediment along this coast has been interpreted as westward (Johnson, 1956; Gorsline, 1966; Balsillie, 1975; Walton, 1976), and the supply has been shown to originate from multiple sediment sources (Stone and others, 1992). Longshore variations of beach sediment are mainly related to variations in wave energy, selective transport rates, and the influence of different sediment sources along the beach (Komar, 1976; Nordstrom, 1981). Despite the coarsening westward trend in the Pleistocene sediments and the similarity of these trends with Holocene sediments, without knowing the littoral dynamics (transport cells, source of sediment, nearshore wave and energy conditions), sediment distribution alone is insufficient to adequately explain the dominant littoral processes. To relate sedimentary data with beach processes, a model that incorporates estimates of wave conditions and a representative transport scheme during the Pleistocene would have to be used, and such an endeavor is clearly beyond the scope of this study.

CONCLUSIONS

In this study the plots of particle size groups against geographic location of Panhandle counties from east to west indicate a coastwise trend of increasing grain-size westward across those counties. Even though complete understanding of sedimentation on the low terraces along the Florida Panhandle is dependent upon the interpretation of the nature of Late Pleistocene sea-level fluctuations (Schnable and Goodell, 1968), and may require sophisticated modeling assumptions for accurate reconstructions, we can infer from these data that wave energies increased from east to west and probably supported a westward longshore current during the Pleistocene, indicating that, based on grain size distribution patterns, wave and depositional conditions seem to have maintained similar trends over thousands of years.

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