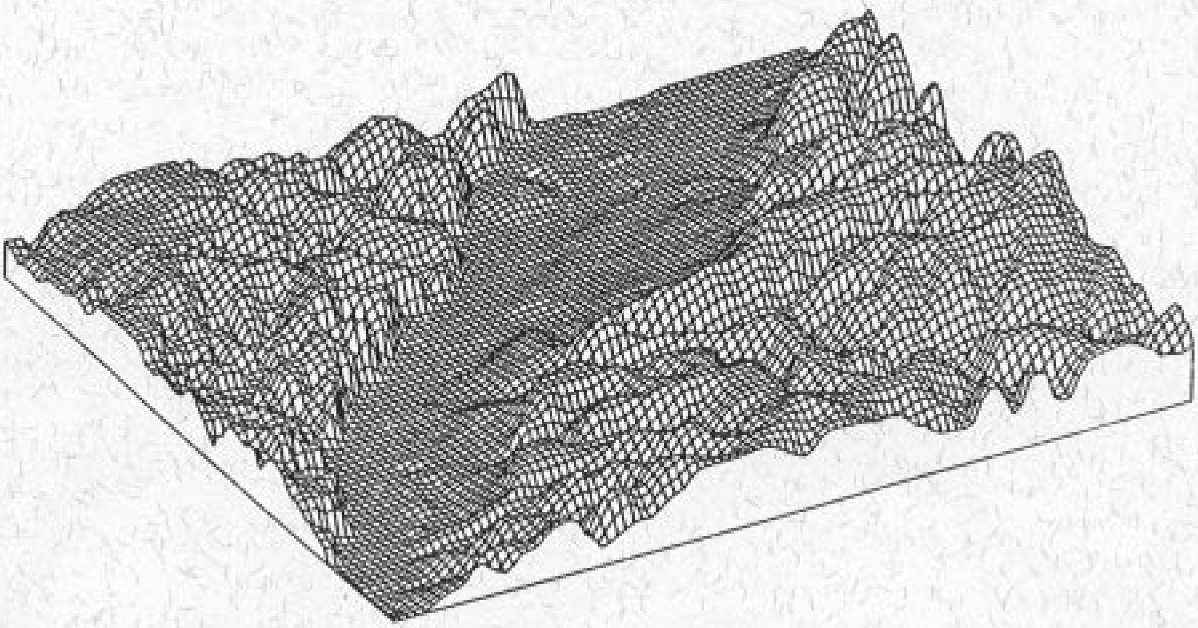
Geological Investigations of the Central Savannah River Area, South Carolina and Georgia

edited by

Wallace Fallaw and Van Price



CAROLINA GEOLOGICAL SOCIETY

Field Trip Guidebook 1992

November 13-15, 1992

Augusta, Georgia

CAROLINA GEOLOGICAL SOCIETY
FIELD TRIP GUIDEBOOK

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GEOLOGICAL INVESTIGATIONS OF THE CENTRAL SAVANNAH RIVER AREA, SOUTH CAROLINA AND GEORGIA

edited by

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Front cover: Topography of the Central Savannah River Valley and surrounding area looking up-river.

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OUTCROPS IN THE VICINITY OF THE SAVANNAH RIVER SITE

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ROAD LOG

Saturday

Miles	Cumulative	
	0.0	Leave Radisson and go west on 9th Street
0.6	0.6	Turn left onto Walton Way
0.7	1.3	Turn right onto 5th Street
0.4	1.7	Bear right onto US 1, 78, 278 (Gordon Highway) and proceed west
2.8	4.5	Turn left onto Old Savannah Road
0.8	5.3	Turn left at stop sign, remaining on Old Savannah Road
2.0	7.3	Cross I 520 and continue south on GA 56
2.3	9.6	Cross Tobacco Road
8.5	18.1	McBean sign
1.3	19.4	McBean Creek
0.1	19.5	Turn left onto GA 56 spur toward Vogtle generating plant
0.3	19.8	**STOP 1, LOCALITY M: "MCBEAN" CARBONATE** (Figs. 1,2)
		Continue south on GA 56 spur toward Vogtle generating plant
5.1	24.9	Gut Creek
1.2	26.1	GA 56 spur ends; continue ahead on River Road
7.8	33.9	Turn left at entrance to Plant Vogtle
1.3	35.2	Plant Vogtle visitor's center
		STOP 2, LOCALITY B; EOCENE CARBONATES AT PLANT VOGTLE BLUFF
	0.0	Reset mileage, leave visitor's center, return to River Road
1.2	1.2	At plant entrance, turn left and go south on River Road
0.2	1.4	**STOP 3, LOCALITY D; TOBACCO ROAD SAND AT VOGTLE PIT**
		Turn around, proceed north on River Road
0.3	1.7	Turn left onto Ebenezer Church Road
4.0	5.7	Turn left onto GA 23
4.1	9.8	Road to Griffins Landing on left
0.8	10.6	Girard, GA
0.5	11.1	Turn left toward Allendale, SC, leaving GA 23, and then bear right toward US 301 on Stony Bluff Road
7.8	18.9	Turn left on unpaved road, remaining on Stony Bluff Road
0.3	19.2	FRAGMENTS OF OLIGOCENE CHERT ON ROAD
0.7	19.9	Turn right on unpaved road
0.5	20.4	NORTHERN END OF LARGE CAROLINA BAY ON RIGHT
3.9	23.8	Turn left onto paved road
4.1	27.9	Turn left onto US 301
1.4	29.3	Savannah River
2.8	32.1	Turn left toward Martin, SC
4.9	37.0	**STOP 4, LOCALITY A; TOBACCO ROAD SAND AND ALTAMAHA FORMATION**
		Continue ahead
3.6	40.6	Martin, SC
0.2	40.8	Turn left at stop sign onto SC 125 and cross Lower Three Runs
8.3	49.1	Enter Savannah River Site
17.0	66.1	Bear left at stop sign and exit Savannah River Site; proceed north through Jackson, SC on SC 125 toward Augusta, GA
14.4	80.5	Turn right into Augusta Sand and Gravel opera-

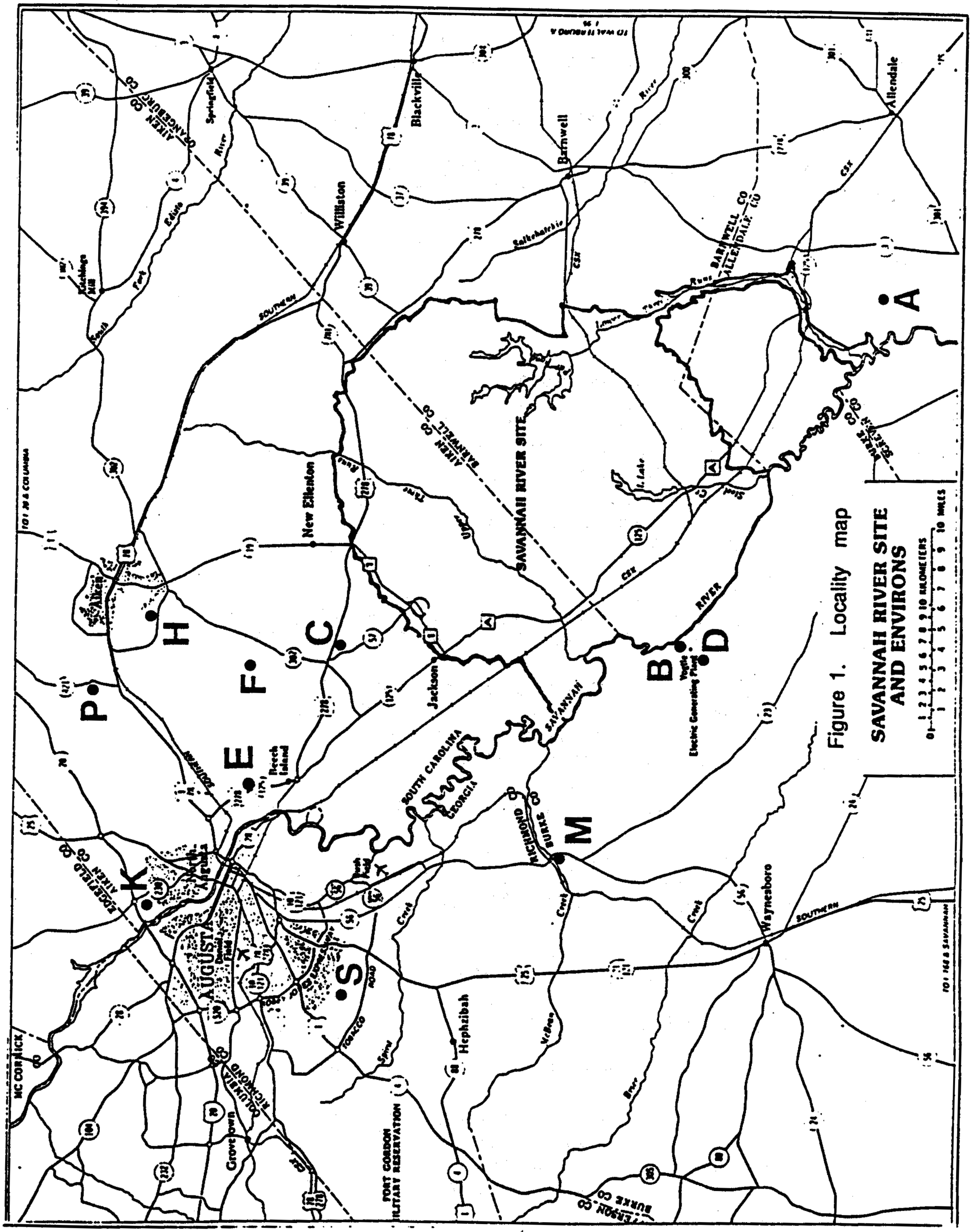


Figure 1. Locality map

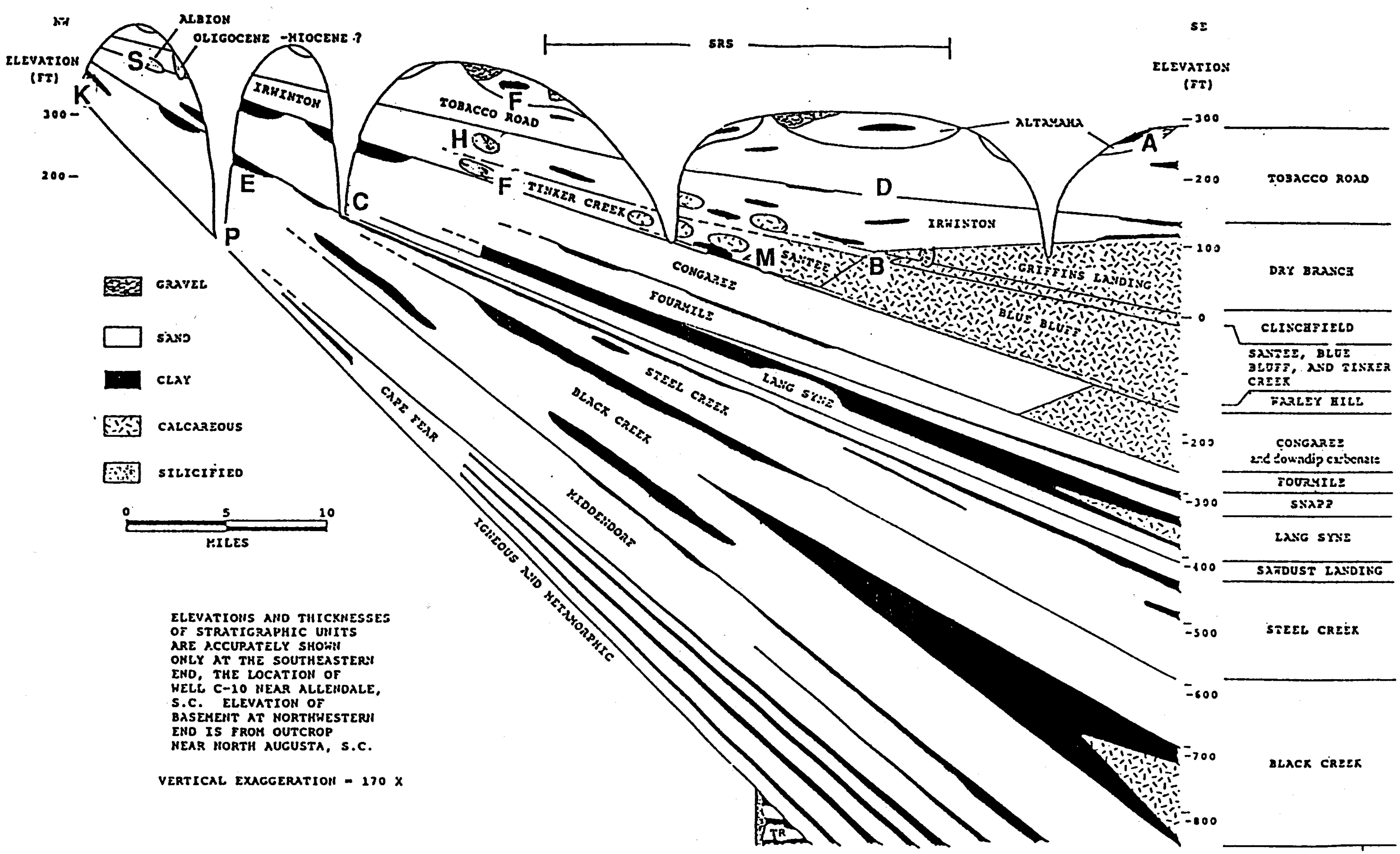


Figure 2. Generalized NW-SE cross-section, SRS and vicinity

tion

OPTIONAL STOP 5, LOCALITY E; CRETACEOUS

Return toward SC 125

0.2 80.7 Turn right onto SC 125

1.2 81.9 Cross US 1

2.1 84.0 Turn right onto SC 230

1.0 85.0 Turn left onto US 25 (Georgia Avenue)

1.5 86.5 Savannah River

0.2 86.7 Turn left onto Reynolds

0.4 87.1 Turn left to Radisson Hotel

Sunday

0.0 Leave Radisson and turn right onto Reynolds

0.8 0.8 Continue north on River Watch Parkway

4.3 5.1 Turn right onto I 20

1.1 6.2 Savannah River

1.0 7.2 Turn right onto SC 230

0.6 7.8 Turn right into Smile Gas station

STOP 1, LOCALITY K; CRETACEOUS ON METAMORPHICS

Turn right onto SC 230 and proceed south through North Augusta

3.0 10.8 Cross US 25 (Georgia Avenue)

1.0 11.8 Turn left onto SC 125 (Atomic Road)

2.0 13.8 Cross US 1

4.6 18.4 Beech Island, SC

0.1 18.5 Turn right to stay on US 278

0.2 18.7 Turn left to stay on US 278

6.2 24.9 Caution light at Petticoat Junction; cross SC 302

0.1 25.0 Hollow Creek

0.2 25.2 Pull off on right beyond store

STOP 2, LOCALITY C; CRETACEOUS (?), PALEOCENE (?), EOCENE

Turn around and go north on US 278

0.3 25.5 Cross Hollow Creek and turn right onto SC 302 (Silver Bluff Road) at Petticoat Junction

2.0 27.5 Gray Mare Hollow road on right; up this road, well C-2 was cored to basement

1.7 29.2 Turn left onto Good Hope Farms Road

0.4 29.6 Turn right at stop sign

0.1 29.7 **STOP 3, LOCALITY F; EOCENE AND ALTAMAHA FORMATION**

0.4 30.1 Continue around Good Hope Farms Road loop and return to SC 302

1.6 31.7 Turn left onto SC 302

4.6 36.3 Bear right at stop light onto Pine Log/Silver Bluff Road

0.5 36.8 Turn left at stop light onto SC 118 (Hitchcock Parkway)

0.8 37.6 Pull off on right

STOP 4, LOCALITY H; DRY BRANCH (?) SILICIFIED FACIES

Continue ahead

4.0 41.6 Turn left onto US 1 at stop light

3.2 44.8 Oxidized contact on right

1.8 46.6 Sudlow Lake Road

6.6 53.2 Bear right to return to Radisson Hotel via 4th Street bridge OR CONTINUE ON US 1 FOR LAST STOP

4.4 57.6 Bear right onto US 25

2.5 60.1 Turn right onto Windsor Spring Road

2.6 62.7 **STOP 5, LOCALITY S; ALBION MEMBER** (Buses may continue uphill beyond stop light and turn around in parking lot)

Turn around and return toward downtown Augusta on Windsor Spring Road

2.6 65.3 Turn left onto US 25 (Peach Orchard Road)

2.5 67.8 Join US 1 (Gordon Highway)

3.3 71.1 Turn left onto Walton Way

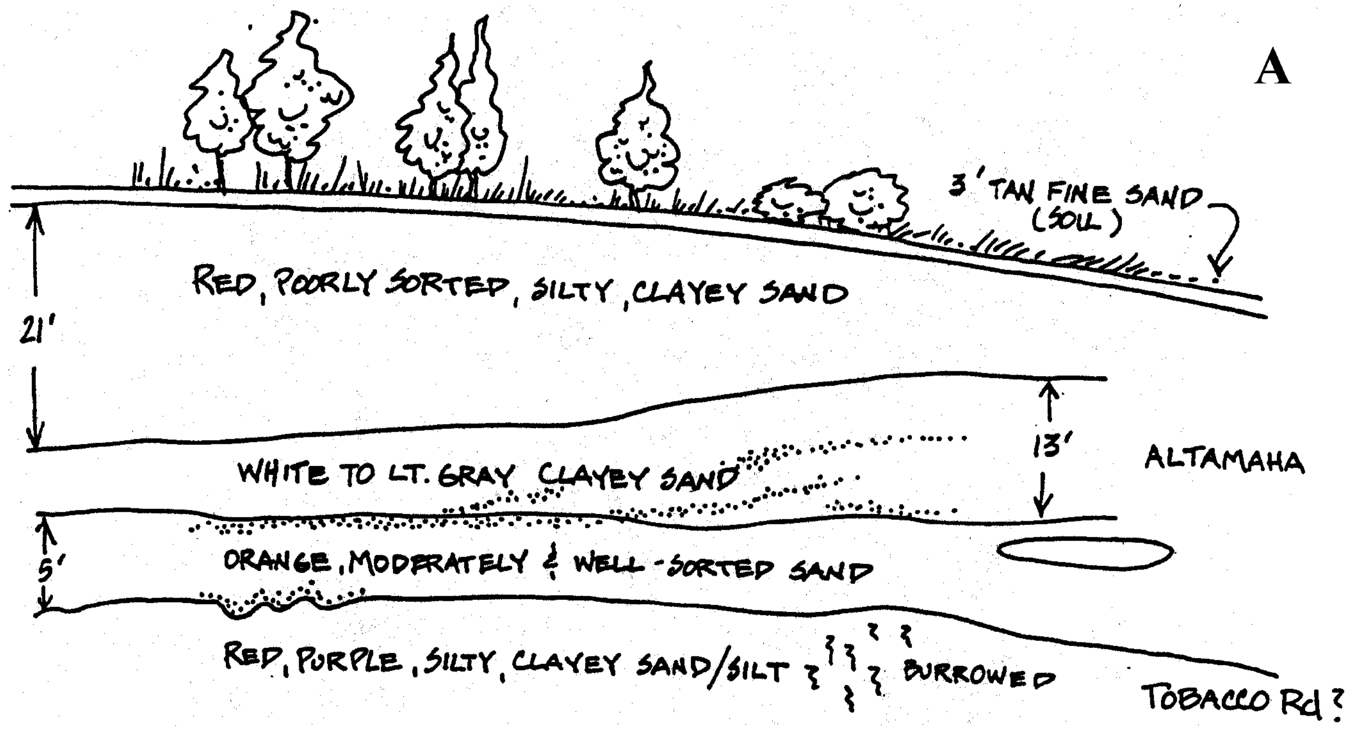
0.6 71.7 Turn right onto 9th Street

0.6 72.3 Turn left onto Reynolds; Radisson is on right

A. Roadcut on county road 102, 2 mi south of Martin, Allendale County, South Carolina; south of Smith Lake Creek; near the Sandoz plant. The section shown in the figure is on the western side of the road.

Fine clastics up to about 10 ft thick exposed in the ditches and in the lower part of the outcrop have the characteristic color and the clay-lined burrows of the upper Eocene Tobacco Road Sand, although they are clayier than usual for the Tobacco Road. Several miles to the east, upper Eocene Carbonates of the Cooper Group (Colquhoun and others, 1983) or the Ocmulgee Formation (Huddlestun and Hetrick, 1986) become prominent at this stratigraphic position.

The contact between the Tobacco Road and the Miocene Altamaha Formation is very irregular and is marked by paleopotholes and rounded quartz pebbles in places. Heavy mineral concentrations are common in the coarser beds. The contact is obscure in much of the cut. The numerous facies changes in the upper part of the outcrop are typical of the



Altamaha and of fluvial deposits in general. A few miles to the east, the Altamaha is truncated by the Orangeburg scarp. Pliocene marine deposits occur to the east of the scarp (Colquhoun, 1988).

There is evidence of deformation in the sediments at the northern end of the cut. The deformed zone is several feet wide and strikes approximately north-south across the highway. Two northeasterly-striking, down-to-the-northwest faults have been mapped from subsurface control in Allendale County by Oldham (1981) and Colquhoun and others (1983). Is the Miocene Altamaha Formation affected by the deformation at this outcrop?

B. Bluffs along Savannah River and tributaries, Georgia Power Company Plant Vogtle, Burke County, Georgia, off River Road.

The "Blue Bluff" unit or member (Huddlestun and Hetrick, 1986, p.4), a middle Eocene carbonate cliff-former, crops out in bluffs along the river and in tributary valleys on the Georgia side. "Blue Bluff" sediments are light gray, and pale green and weather to gray, olive gray, and tan. They are mostly glauconitic calcilutite and calcarenite with thin layers and nodules of indurated limestone and quartz sand laminae. Shell layers occur sporadically. Cream colored carbonates (McBean facies") of the middle Eocene Santee Limestone also occur here. Outcrops of the "Blue Bluff" are at least 40 ft high in places.

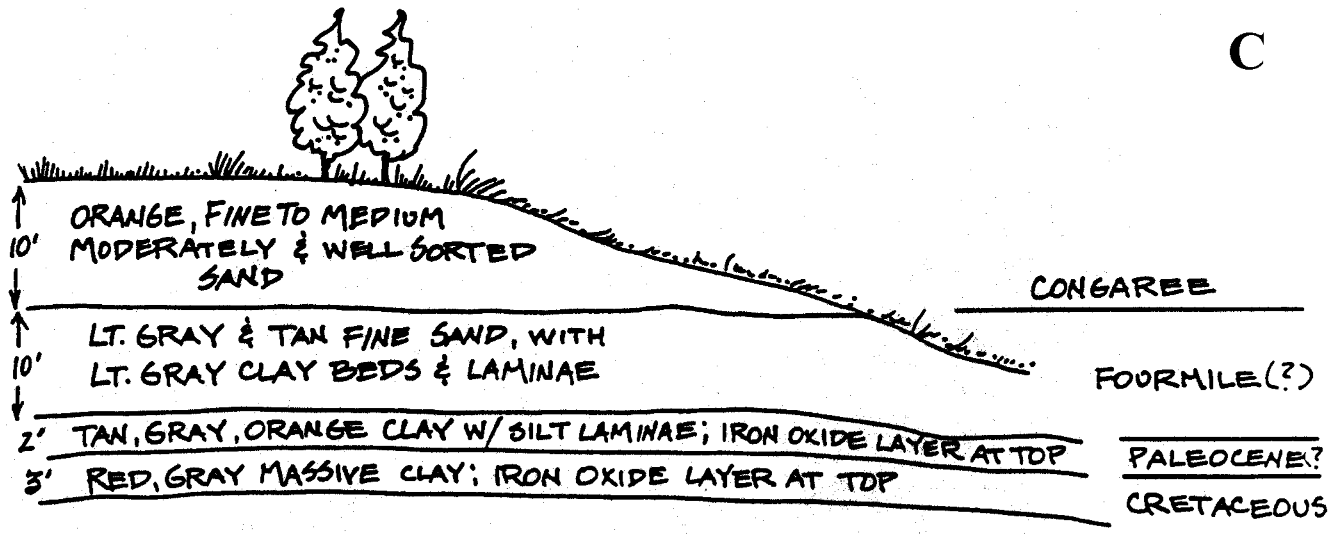
Slump blocks of the middle or upper Eocene Utley Limestone Member of the Clinchfield Formation and the upper Eocene Griffins Landing Member of the Dry Branch Formation occur at river level. The Utley is composed of indurated limestone, glauconitic in places, with abundant Periarchus (sand dollars) and molds of pelecypods and gastropods. Shells of *Crassostrea gigantissima* from the Griffins Landing are also common on the slopes.

C. Bank on the southwest side of US 278, 100 yd southeast of the intersection of US 178 and county road 57; southeast of Hollow Creek, 0.3 mi southeast of Petticoat Junction, Aiken County, South Carolina.

The massive, color-mottled clay at the base of the outcrop is similar to the oxidized clay found at the top of the Cretaceous in outcrops and in cores from SRS. It is tentatively assigned to the Upper Cretaceous.

A sample from a roadside ditch beside county road 57 a short distance southwest of the intersection with US 278 yielded an early Paleocene age (see Nystrom and others, 1991, p. 224). The thinly bedded or laminated, tan, red, and brown clay above the mottled clay at our outcrop is tentatively assigned to the Paleocene. It overlies the Cretaceous (?) clay with a sharp contact. Behind the nearby store, coarse, cross-bedded sand lies on the Cretaceous (?) mottled clay.

Several palynological samples from wells at SRS, about 4 mi to the southeast, indicate that late Sabinian (early Eocene) deposits of the Fourmile Formation lie between Paleocene strata and the early (and middle?) Eocene Congaree Formation. The interbedded sands, pebbly sands, and clays at this outcrop are tentatively correlated with the Fourmile on the basis of stratigraphic position. A quartz pebble



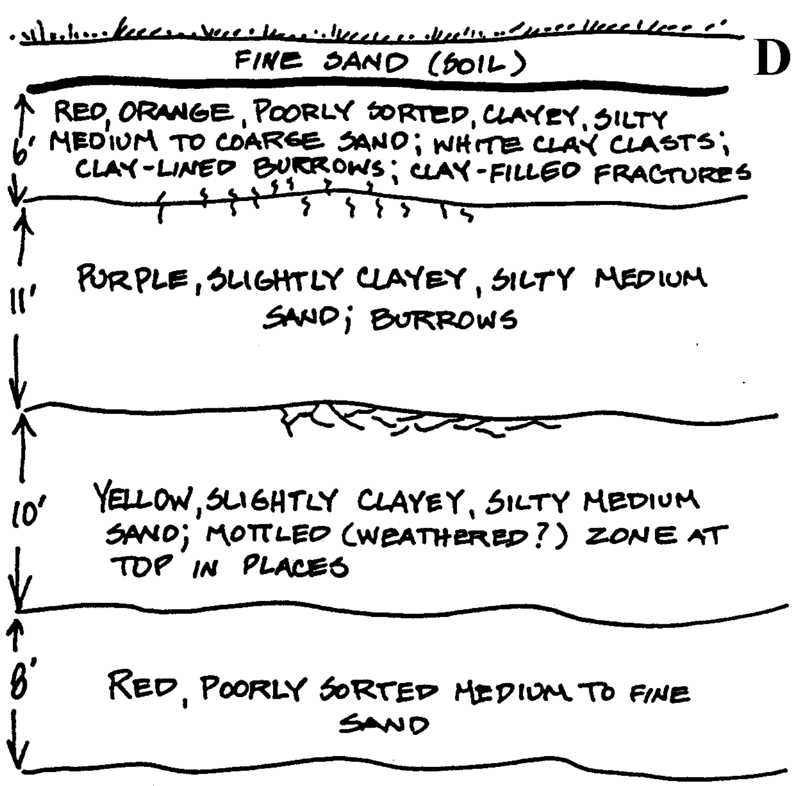
layer is at the base of the unit.

The orange sand in the upper part of the bank is typical of the lower (and middle?) Eocene Congaree formation.

D. Pit near River Road at Georgia Power Company Plant Vogtle, Burke County, Georgia; a few hundred years southeast of the main entrance to the plant and 40 yd northeast of River Road. The section shown in the figure is on the northeastern wall of the pit.

Most of the exposure is in the upper Eocene Tobacco Road Sand. The reddish purple, poorly to moderately sorted sands and silty sands in the upper part of the northeastern wall of the pit are overlain with sharp, eroded contact by coarser deposits. *Ophiomorpha* burrows are abundant in places near the top. The coarse deposits of the upper bed can be seen in the burrows in the underlying purple unit.

A sharp contact between purple sand above and yellow sand below is visible in several places on the northeastern



wall of the pit, suggesting exposure of the underlying upper Eocene Irwinton Member of the Dry Branch Formation. This yellow sand pinches out a short distance to the northwest and southeast, however, and a red sand occurs beneath it. Evidence for the presence of the Irwinton at or near the base of the pit are tan clay exposed in places in the floor of the excavation and a pebble bed several tens of feet wide on the southwest wall of the pit, possibly the flat-pebble bed which marks the base of the Tobacco Road in places. Above this pebble bed, the sands are red, orange, and yellow; below, yellow sands are more conspicuous.

The fairly clean, light colored sand several feet thick at the top is common in many places in the area. It may be leached soil horizon, but there has been some discussion of eolian influence.

The gray limestone which mimics an outcrop above the Tobacco Road on the northeast wall of the pit appears to be composed of pieces of the middle Eocene "Blue Bluff" unit or member (Huddlestun and Hetrick, 1986, p.4). We have found boards in the bedded clay and sands above the limestone, and angular pebbles of metamorphic rock are mixed with the limestone.

F. Roadcuts on the north loop of Good Hope Farms Road (county road 1956), off Silver Bluff Road (South Carolina highway 302); about 4 mi south of the intersection of Silver Bluff Road and Pine Log Road (county road 87) southwest of Aiken, South Carolina.

About 0.4 mi west of the intersection of Good Hope Farms Road and Silver Bluff Road, the extremely poorly sorted, cobbly facies of the Miocene Altamaha Formation is exposed. Rounded quartz cobbles and pebbles are in a matrix of and interbedded with red clayey sand with weathered feldspar grains.

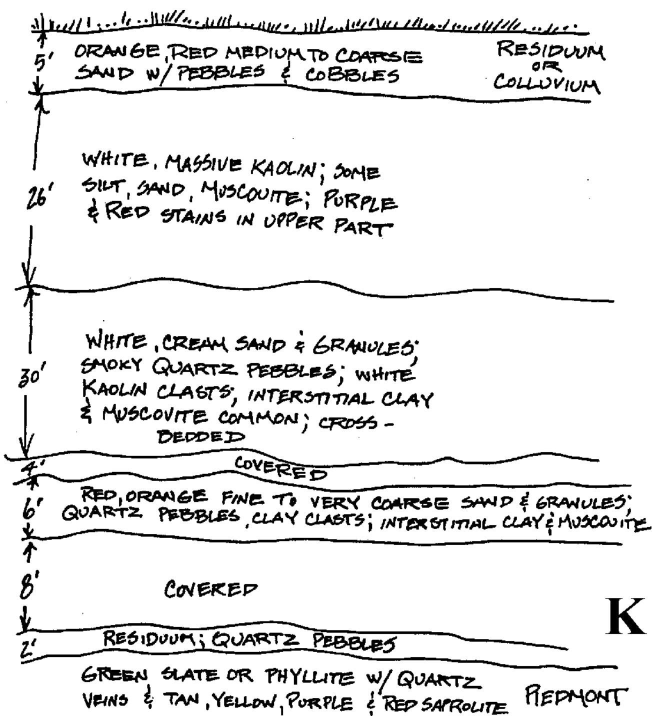
Down the road (to the west), cuts expose red and orange, clayey, silty, poorly sorted medium and coarse sand of the upper Eocene Tobacco Road Sand. Cross-beds, clay-filled fissures, burrows, and white clay clasts occur in places. The sand overlies bedded tan clays typical of the upper Eocene Dry Branch Formation and a massive, tan, light gray, and pink clay which may be the top of the "Huber Formation". About 0.9 mi west of the intersection of Good Hope Farms Road and Silver Bluff Road is an outcrop of well-sorted, very fine and fine, burrowed sand with clay laminae (see figure). In cores and outcrops at SRS, fine and very vine sands with clay laminae and burrows in places are common in the middle Eocene Tinker Creek Formation, interbedded with and updip from the middle Eocene Santee Limestone. These fine sands overlie the Congaree and Warley Hill formations. The fine, well-sorted sand in this outcrop is thought to be the Tinker Creek.

The iron oxide-rich quartz pebble conglomerate and coarse sand above the Tinker Creek sand appears to be the same unit as the coarser sand to the east and up the road assigned to the Tobacco Road. If it is, the Dry Branch Formation is missing at this outcrop. Another possibility is that the coarse nit is a facies of the Oligocene (to Miocene?) channels described by Zullo and others (1982) and Willoughby and others (1984).

H. Outcrop on north side of Hitchcock Parkway (South Carolina Highway 478) on the south side of Aiken, South Carolina, about 0.8 mi west of the intersection of Hitchcock and Pine Log Road (county road 87).

Light gray to tan, silicified, pebbly, coarse sandstone with prominent burrows crops out on the hillside. Light gray, yellowish and tan clay lies beneath the sand. Silicified shell fragments that appear to be Crassostrea gigantissima occur here. This may be the upper Eocene Dry Branch Formation, similar to facies described by Nystrom and others (1986, p. 17). It could also be a facies of the Oligocene (to Miocene?) channels described by Zullo and others (1982) and Willoughby and others (1984).

K. Ditch and cut at the Smile gas station in the southern corner of the intersection of South Carolina Highway 230 and Interstate 20, 0.3 mi southeast of Interstate 20; a few miles northwest of North Augusta, South Carolina. The figure is modified from Nystrom and others (1986, p. 43-47).



At the Fall Line contact, coarse, basal Coastal Plain sediments overlie crystalline rocks, probably metavolcanics of the Belair belt (Crickmay, 1952; Prowell and O'Conner, 1978). A Campanian palynological date has been obtained from outcropping sediments along strike on Interstate 20 northwest of Aiken (see Nystrom and Willoughby, 1982, p. 86; Nystrom and others, 1986, p. 7), and there are Santonian through Maestrichtian palynological dates from cores at SRS. The precise age of the Cretaceous at this locality is unknown.

A detailed description of the outcrop is in Nystrom and others (1986, p. 43-47).

M. Gully near McBean, Georgia on south side of River Road (highway 56 spur or 56c), about 0.3 mi east of intersection of highway 56 and 56 spur, Burke County, Georgia; about 0.5 mi east-southeast of McBean.

A few feet of cream-colored calcilutite and calcarenite, with a few small shell fragments, of the middle Eocene Santee Limestone are exposed among the poison ivy. This is part of the type section of the "McBean Formation" of Veatch and Stephenson (1911, p. 237-251). The term "Santee" is used here for these sediments in the vicinity of SRS because of priority (Sloan, 1908, p. 459-460). Silicified limestone float is common in the area.

P. Spillways of Flat Rock Pond, 200 to 300 yd west of South Carolina Highway 191, about 1 mi north of the center of Graniteville, Aiken County, South Carolina.

Granitic rock of the Kiokee belt (Circkmay, 1952; Prowell and O'Connor, 1978) crops out in an inlier in the valley of Horse Creek. Weathering, especially visible in the foliated zones, is converting feldspar to the kaolin which is abundant in much of the updip Coastal Plain section. Cretaceous sediments can be seen in the railroad cut a short distance east of South Carolina Highway 191 (Nystrom and others 1982, p. 116).

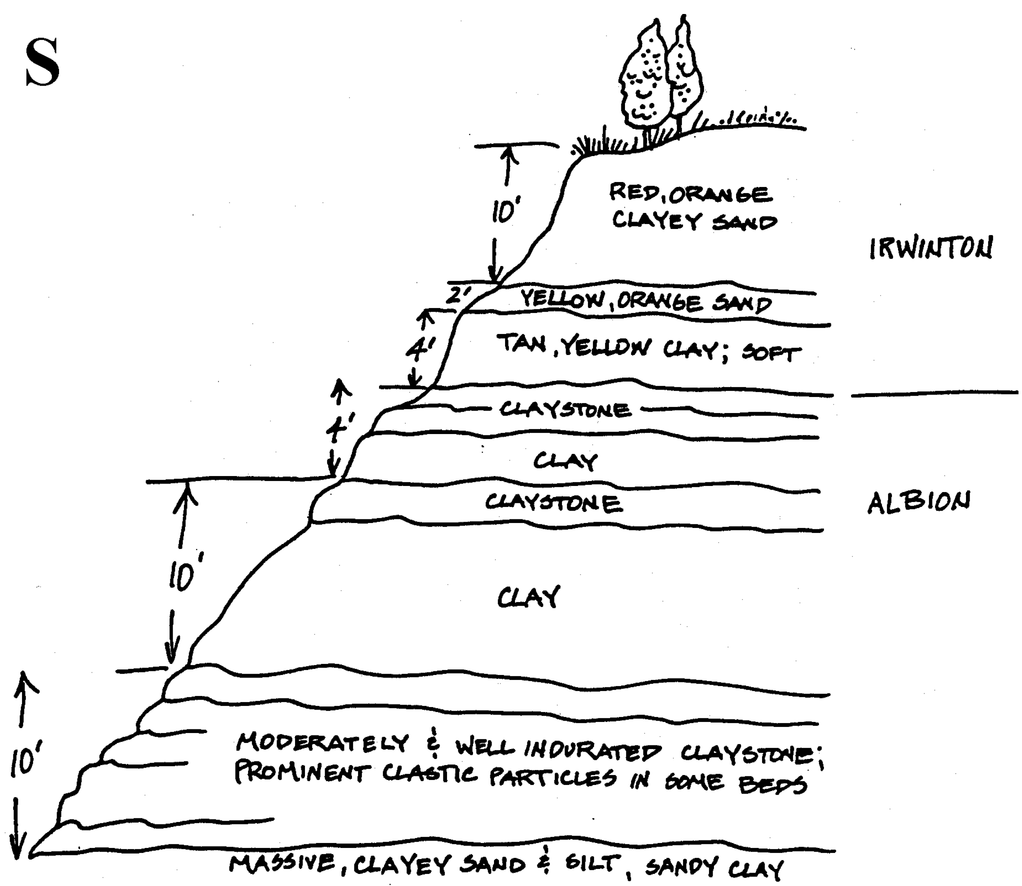
S. Roadcut on Windsor Spring Road about 2.2 mi southwest of the intersection of Interstate 520 and Windsor Spring Road, in the southwestern suburbs of Augusta, Georgia. The section shown in the figure, modified from Huddlestun and Hetrick (1986, p. 19), is on the eastern side of the road.

Sponge spicules and opal cement are common in the Albion Member (Carver, 1972). Some of the indurated spiculite in the lower part of the section resembles volcanic rock. A detailed description of the outcrop is in Huddlestun and Hetrick (1986, p. 19, 59-61).

Huddlestun and Hetrick (1986) tentatively placed the Albion in the Clinchfield Formation (middle or upper Eocene), but it could be part of the upper Eocene Dry Branch Formation. Tan clay beds above the spiculite are typical of the Dry Branch.

According to Huddlestun and Hetrick (1986, p. 31), the Albion also occurs in Aiken County, South Carolina.

S



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CAROLINA GEOLOGICAL SOCIETY
Guidebook for 1992 Annual Meeting
Pages 11-15

Observations on General Allo-Stratigraphic and Tectonic Framework of the Southeastern Atlantic Coast Regional Cross Section (DNAG E-5 Corridor) Georgia and South Carolina as they Relate to the Savannah River Side

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INTRODUCTION

Allostratigraphic units were mapped in the northwestern Upper Coastal Plain of South Carolina and Georgia along the Southeastern Atlantic Coast Regional Cross Section (Colquhoun and others, 1991A) (SACRCS) and the Decade of North American Geology Continent – Ocean Transect E-5 (DNAG E-5) (Hatcher and others, in press) within the Upper, Middle and Lower Coastal Plains. The picks followed concepts stated in Colquhoun and others, 1983; Jordana, 1984; Colquhoun and Steele, 1985; Colquhoun and others, 1986; McClelland, 1987; Colquhoun and Muthig, 1988; Muthig, 1990; Muthig and others, 1992; and Colquhoun and others, 1992.

The SACRCS, which includes the Savannah River Site extends Southeast from the Fall Line near Augusta GA to southeast of the Atlantic Ocean near Savannah GA, and about 25 miles either side of the Savannah River in SC and GA. Aspects of the geomorphology, petrology, allo- litho- and seismic stratigraphy, regional magnetics and gravity, structure and age are presented in Colquhoun and others, 1991A and Hatcher and others, in press.

PURPOSE AND SCOPE

Regional mapping (Coastal Plain and Continental Shelf) of allostratigraphic units has been undertaken to characterize and to date stratigraphic units occurring within the Coastal Plain. This is particularly important in the Upper Coastal Plain where *surficial* sediments usually are heavily weathered and leached such that normal fossil dating is often deficient. Microfossil and palynological dating is accomplished easily in the Lower Coastal Plain and Shelf because of preservation. In addition, because of faunal setting, such dating can be compared with Universal Stage Zonation through Deep Sea Drilling investigations, resulting in refined dates for correlation.

Dates obtained from micropaleontologic, palynologic and absolute dating of artifacts are assigned between bounding surfaces of groups of siliciclastic and carbonate sedimentary depositional units. Representative facies are alluvial, deltaic, shallow, deep and carbonate shelf in origin. These smaller wedge-shaped stratigraphic bodies representing submergence, erosion and deposition and emergence, are assigned to Universal Stages.

Bounding surfaces mapped statewide which enclose these smaller stratigraphic wedges include:

1. Pre-Upper Cretaceous Piedmont-Turonian/Coniacian Stage (Upper Cretaceous) (Piedmont-Cape Fear of authors).
2. Turonian/Coniacian-Santonian Stage (Upper Cretaceous) (Cape Fear-Middendorf of authors.
3. Santonian Stage-Campanian Stage (Upper Cretaceous) (Middendorf-Black Creek of Colquhoun and others, 1983).
4. Campanian stage-Maestrichtian Stage (Upper Cretaceous) (Black Creek-Peedee Formation of Colquhoun and others, 1983).
5. Maestrichtian Stage (Upper Cretaceous) – Danian Stage (lower Paleocene) (Midwayan).
6. Danian Stage (lower Paleocene) – Thanetian Stage (upper Paleocene) (Sabinian).
7. Thanetian Stage (upper Paleocene) – Ypresian Stage (lower Eocene).
8. Ypresian Stage (lower Eocene) – Lutetian Stage (middle Eocene).
9. Lutetian Stage (middle Eocene) – Priabonian/Bartonian Stage (upper Oligocene).
10. Priabonian/Bartonian Stage (upper Eocene) – Chattian Stage (upper Oligocene).
11. Chattian Stage (upper Oligocene) – Serravallian middle Miocene).

In addition to these mapped surfaces (Colquhoun and others, 1983; Jordana, 1984) and others not regionally mapped within and between these depositional unit groups, bounding unconformities between Upland Unit and Tertiary, various Pliocene, Pleistocene and Holocene units have been mapped in more local settings both in South Carolina and elsewhere; Colquhoun and others, 1991B and references therein).

REGIONAL TECTONIC FRAMEWORK OF DEPOSITION

Contours drawn on these surfaces and isopach maps constructed of thickness between these surfaces show regional tilting and downwarping as well as growth faulting and distortion.

A stable shelf (Marion) exists between the Fall Line and the Bamberg Warp (Colquhoun and others, 1991) in the vicinity of the northwest boundary to the Dunbarton Basin (Marine and Siple, 1974). The Bamberg Warp swings from a northeast to a southeast trend near Bowman SC where it joins the Charleston Fault trend extending toward Summerville SC (Muthanna, 1998; Colquhoun and others, 1992). The boundaries define the Southeast Georgia Embayment structure to the southeast and southwest.

Tectonic downwarping rates from late Cretaceous through Holocene associated with the development of the Southeast Georgia Embayment structure can be measured along the SACRCS. The rate of dip of the bounding surfaces can be plotted against absolute time associated with universal stages (as depicted on Haq and others, 1987, for example). These rates are compared with depositional unit groups within the Savannah River Site (SRS) for dating purposes where fauna are deficient, and to reinforce assigned ages where collections are present.

STRATIGRAPHY ALONG THE SOUTHEAST ERNATLANTIC REGIONAL CROSS SECTION

Stratigraphic surfaces 1, 3, 4, 5, 6, 8, 9, 10, 11 and the base of the UPLAND UNIT have been useful regionally to depict distortion through time within and in the vicinity of the SRS. Table 1 lists unconformities and their dip for ten surfaces measured from Colquhoun and others, 1991 (SACRCS).

Figure 1 illustrates similar data developed from Colquhoun and others, 1983. Regional dip of unconformity surfaces as expressed on structure contour maps is plotted against age in millions of years before present as reported in Haq and others, 1987. Black boxes are constructed which illustrate variation in age assigned in mybp for the stages in a horizontal dimension and variation in regional dip in a vertical dimension.

STRUCTURE

Coastal Plain sediments are expressed as a wedge of late Cretaceous to Holocene age siliciclastics and carbonates deposited above Paleozoic and Mesozoic rocks along the SACRCS. The Atlantic Continental Margin of this area is stable structurally generally, with gentle downwarping reflected in the rate of dip of the boundaries separating the depositional unit groups making up the wedge, and outlining the Marion Shelf and Southeast Georgia Embayment development through time. The youngest cyclic groups (Holocene) exhibit the least downwarping (unmeasurable), while the oldest (late Cretaceous) express the highest dip (about 30 feet per mile for the Coastal Plain – Piedmont boundary).

Within and near the SRS, the present divide areas of the Aiken Plateau (Cooke, 1936) in the Upper Coastal Plain are inclined seaward about 7.8 feel per mile. The associated oldest UPLAND sediments (Citronelle Formation of Doering, 1960, or Hawthorne Formation of Siple 1967), also are inclined about 7.8 feet per mile. The underlying base of the late Eocene/Jacksonian – middle Eocene unconformity is inclined about 11.4 feet per mile, while the seaward, overlying, base of the Chattian (Oligocene) unconformity dips about 5.5 feet per mile. The Chattian is overlain by an early-middle Miocene thin (10 feet) but laterally extensive "Tampa" limestone, that dips about 3 feet per mile. Deeply incised Pliocene and Pleistocene sediments are inclined at less than 2 feet per mile at the surface (Figures taken fro Table 1).

Figure 1 indicates almost linear distortion for coastal plain sediments from the base of the Santonian through the basal Thanetian stages (Late Cretaceous through early middle Paleocene) and from the base of the late Eocene through early middle Miocene. Middle Miocene through Holocene dips are slightly less. Late Paleocene sediments through to the base of the late Eocene show a much lower rate of dip.

AGE OF THE SRS NON-FOSSILIFEROUS SEDIMENTS

Non-fossiliferous sediments within and near the SRS can be assigned to depositional unit groups which are subdivided by regional unconformities or bounding surfaces. Such units are allostratigraphic in nature and can be correlated regionally within units that can be dated by conventional means. In general such units grade seaward from fluvial erosional unconformiteis to marine erosional (ravinement) unconformities with overlying alluvial and marginal marine depositional unit groups grading to shallow to deep siliciclastic and carbonate shelf lithofacies. Such groups may oscillate over underlying marine lithofacies, reflecting changes in sea level or sediment supply. Many stratigraphic terms recorded in the literature have proved to be lithofacies or members, which, when mapped, do no express generally, either regional tectonic distortion nor logical sedimentary variation.

Where correlation is difficult or impossible because of variation in lithology or lack of regional evidence, rate of dip vs. time can be used to limit ages. For example, the age of the oldest UPLAND sediments in the western coastal plain of South Carolina and Georgia is confined between 23 and 30 million years b.p. based on changes in regional dip of associated unconformities when plotted against time (Figure 1). A few highly corroded pollen have been found in UPLAND Unit samples from cores obtained from the Savannah River Site; however, these pollen are so weathered and degraded that identification is impossible.

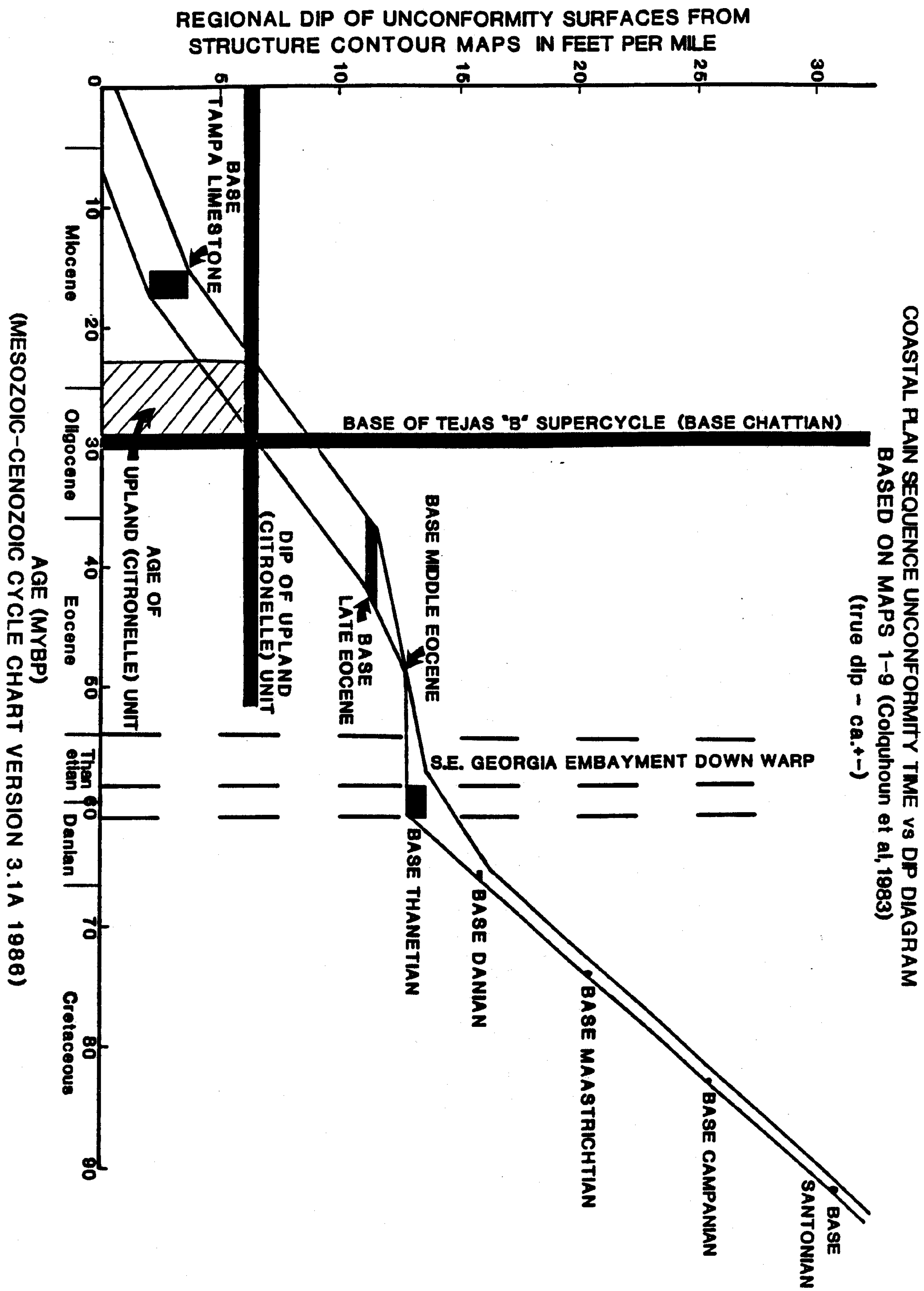
"UPLAND" – like lithologies that occur at elevations

Table 1. Time vs. dip table based on measurements on unconformities between sequences in AAPG South Atlantic Coast cross-section.

UNCONFORMITY	ELEVATION CHANGE AND DISTANCE		DIP (APPARENT)
Base Coastal Plain Turonian/Coniacian	2800’ in 93 miles		30.10
Base Campanian	2120’ in 93 miles		22.79
Base Maestrichtian	1800’ in 53.6 miles		18.65
Base Tertiary	1350’ in 53.6 miles		12.12
Base Paleocene			
Base Danian			
Base Wilcoxian			
Base Thanetian	1005’ in 53.6 miles		9.60
Base Sabinian			
Base Middle Eocene	325’ in 53.6 miles		6.34
Base Lutetian	780’ in 93.0 miles		8.38
Base Claibornian	790’ in 93.0 miles		7.83
		Average	(7.51)
Base Late Eocene	390’ in 53.6 miles		7.27
Base Priabonian/	760’ in 93.0 miles		8.06
Bartonian	890’ in 93.0 miles		8.01
Base Jacksonian		Average	(7.78)
Base Upland Unit”	450’ in 59 miles		7.62
Base Citronelle Fm	400’ in 49 miles		8.16
		Average	(7.89)
Base Oligocene	200’ in 32 miles		5.55
Base Chattian			

NOTE: Base Miocene (Hawthorne Group) is a buried land surface and variable, hence a thin persistent limestone is used. The “Tampa Limestone” lies below the Serravallian (Ernissee, 1977) Coosawhatchie Clay

Base “Tampa Limestone”	40’ in 20 miles		2.00
Base Serravallian	110’ in 29 miles		3.79
(circa)		Average	(2.89)



COASTAL PLAIN SEQUENCE UNCONFORMITY TIME vs DIP DIAGRAM
BASED ON MAPS 1-9 (Colquhoun et al, 1983)
(true dip - ca.+-)
REGIONAL DIP OF UNCONFORMITY SURFACES FROM
STRUCTURE CONTOUR MAPS IN FEET PER MILE
0
5
10
15
20
25
30
BASE
TAMPA LIMESTONE
BASE OF TEJAS "B" SUPERCYCLE (BASE CHATTIAN)
AGE OF
UPLAND (CITRONELLE) UNIT
DIP OF UPLAND
(CITRONELLE) UNIT
BASE
LATE EOCENE
BASE MIDDLE EOCENE
S.E. GEORGIA EMBAYMENT DOWN WARP
BASE THANETIAN
BASE DANIAN
BASE MAASTRICHTIAN
BASE CAMPANIAN
BASE
SANTONIAN
10
20
30
40
50
60
70
80
90
Miocene
Oligocene
Eocene
Than-
etian
Danian
Cretaceous
AGE (MYBP)
(MESOZOIC-CENOZOIC CYCLE CHART VERSION 3.1A 1986)

lower than those of the Aiken Plateau often are associated within the Upper Coastal Plain or terraces in the Middle Coastal Plain. Both predate or are coeval with early-middle Pliocene sediments in other areas of the coastal plain. Such lithologies generally are not as clayey nor as indurated as the UPLAND although many contain gravels similar in size. These sequences support very complex sea – level change events contributing to coastal plain development between the Oligocene and the Pleistocene. These changes are yet to be understood.

ACKNOWLEDGEMENT

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OUTLINE OF STRATIGRAPHY AT THE SAVANNAH RIVER SITE

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INTRODUCTION

The sediments of the Atlantic Coastal Plain in the vicinity of the Savannah River Site (SRS) are quartz sand, clay, limestone, and conglomerate ranging in age from Late Cretaceous to Holocene. The Coastal Plain sedimentary sequence thickens from zero at the Fall Line to more than 4000 ft at the coast (Chowns and Williams, 1983). Composed of siliciclastics at and near the Fall Line, the section becomes calcareous downdip. Regional dip is to the southeast and south-southeast, although beds dip and thicken locally in other directions.

This progress report discusses the stratigraphic framework the authors are now using at SRS. Sediments updip form the Site, such as the undifferentiated Upper Cretaceous and the undifferentiated lower Tertiary, are only briefly described. The stratigraphic interpretation will evolve as more data are analyzed. A stratigraphic column (Fig. 1) and a generalized cross-section (Fig. 2) summarize the stratigraphy as currently understood by the authors. Figure 3 shows the major geographic features of the area.

PREVIOUS WORK

A stratigraphic framework for updip Coastal Plain stratigraphy in South Carolina was established by Sloan (1908), who examined many outcrops in the study area. Veatch and Stephenson (1911), Cooke (1936, 1943), Cooke and Shearer (1918), and Cooke and MacNeil (1952) included the are in their investigations of the geology of the South Carolina and Georgia Coastal Plain. Snipes (1965), Smith (1979), Smith and Kite (1982), Mittwede (1982), Nystrom (1986), Nystrom and Willoughby (1982, 1992), and Nystrom and others (1982, 1986, 1989, 1991, 1992) investigated outcrop and shallow subsurface stratigraphy in the general area of SRS. LaMoreaux (1946 a, b), Pickering (1970), Carver (1972), Herrick (1972), Huddlestun (1986) helped develop the stratigraphic framework for the upper Eocene. Newell and others (1980) discussed geomorphological features in the area.

Siple (1967) initiated detailed subsurface stratigraphic analysis at SRS. Colquhoun and co-workers (Colquhoun and others, 1982, 1983; Colquhoun and Muthig, 1991; Oldham, 1981; Bishop, 1982; Steele, 1985; McClelland, 1987) presented subsurface data, correlating sediments in the study area with strata in other parts of the Coastal Plain. Faye and Prowell (1982) published structural and stratigraphic subsurface data. Prowell and others (1985 a, b) presented lithologic and paleontologic subsurface information and correlated SRS strata with deposits in Georgia and with formations elsewhere in the Atlantic and Gulf coastal plains. Logan and Euler (1989) discussed stratigraphic and hydrologic data.

Outcrop and shallow subsurface stratigraphy near the center of SRS has been discussed recently by Dennehy and others (1989), Nystrom (1989), Nystrom and others (1991, 1992), Nystrom and Dockery (1992), and Snipes and others (1992). Laws and others (1987) and Harris and Zullo (1988, 1992) analyzed the Tertiary section from the point of view of sequence stratigraphy, and Harris and Fullagar (1992) discussed radiometric dates.

Thayer and others (1988), Robertson and Thayer (1992), Robertson (1990), and Smith and others (1992) made detailed lithologic analyses of Tertiary sediments from cores at SRS. Studies emphasizing paleontology in the last few decades include those by Cushman and Herrick (1945), Herrick (1960, 1964), Scrudato and Bond (1972), Tschudy and Patterson (1975), Zullo (1984), Zullo and Kite (1985), Laws (1988, 1992), Lawrence (1988), Lucas-Clark (1988, 1992), Steele and others (1986, 1988), Edwards (1992), Frederiksen (1991), and Edwards and Frederiksen (1992). Among hydrologic investigations are those of Siple (1967), Colquhoun and others (1985), Gorday (1985), Logan and Euler (1989), Logan (1992), Aadland (1992), Aadland and Bledsoe (1992), and Harris and others (1992). We have presented some preliminary results of our work (Fallaw and others, 1988, 1989, 1990, 1991, 1992; Price and others, 1992).

Numerous studies not in the public domain have also been done at SRS and at Georgia Power Company Plant Vogtle in Georgia.

BASEMENT ROCKS

Igneous and metamorphic rocks of the Piedmont and Blue Ridge provinces are the source of the Coastal Plain sediments. They are Precambrian and Paleozoic and formed under the influence of several orogenic episodes in the Appa-

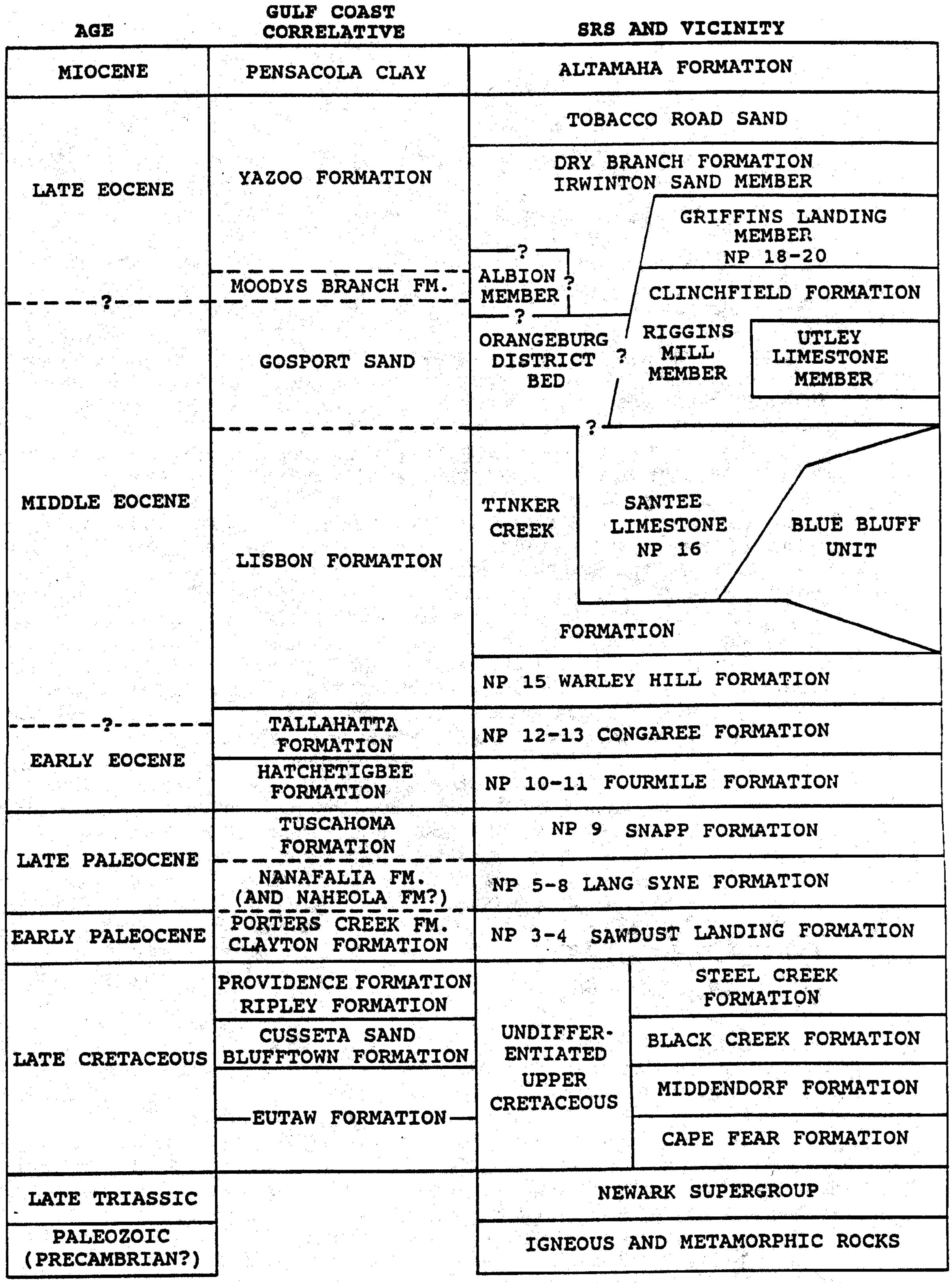

Figure 1. Stratigraphic column for Savannah River Site and vicinity. No vertical scale. NP zones are from most common age calls.

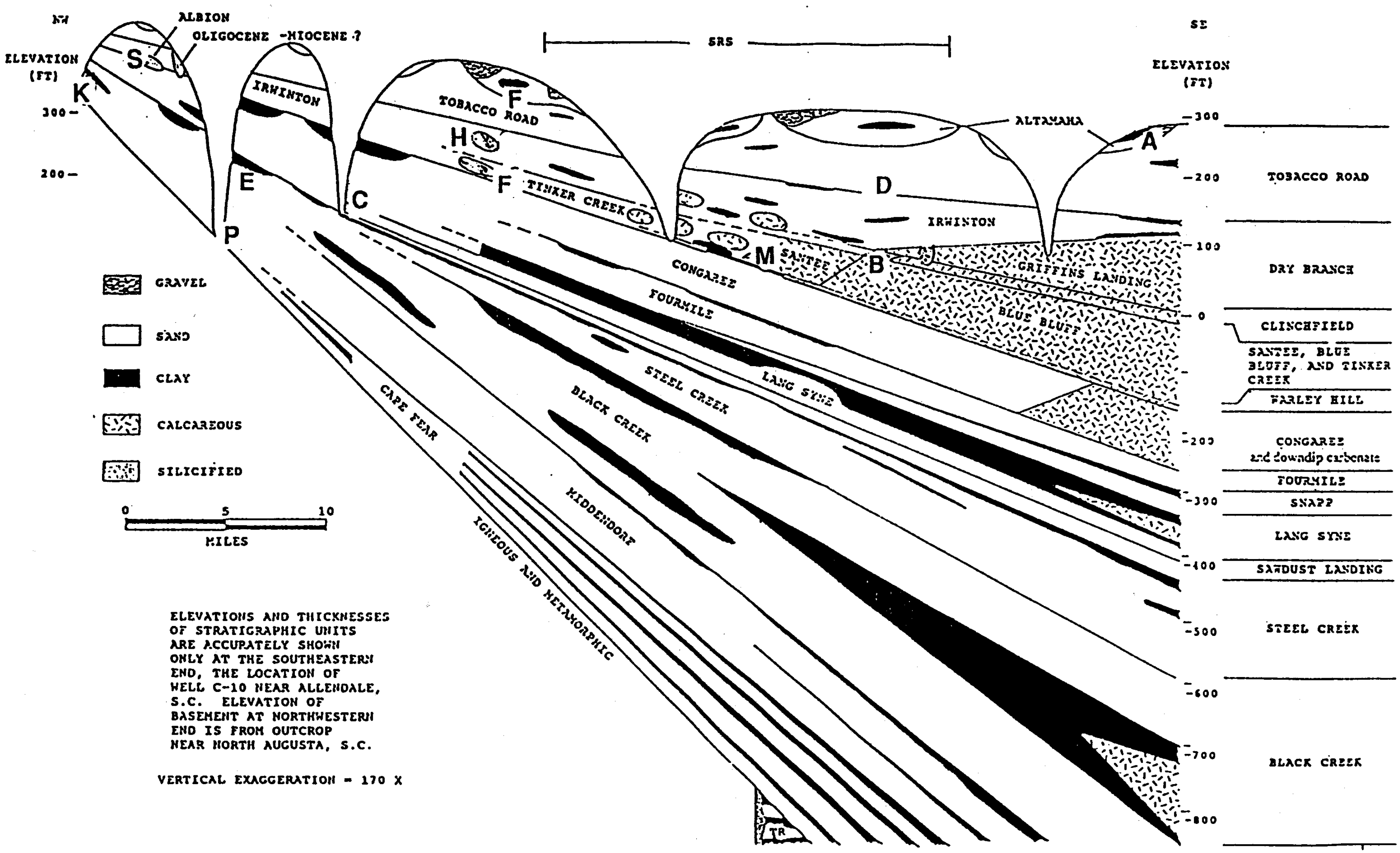

Figure 2. Generalized NW-SE cross-section, SRS and vicinity.

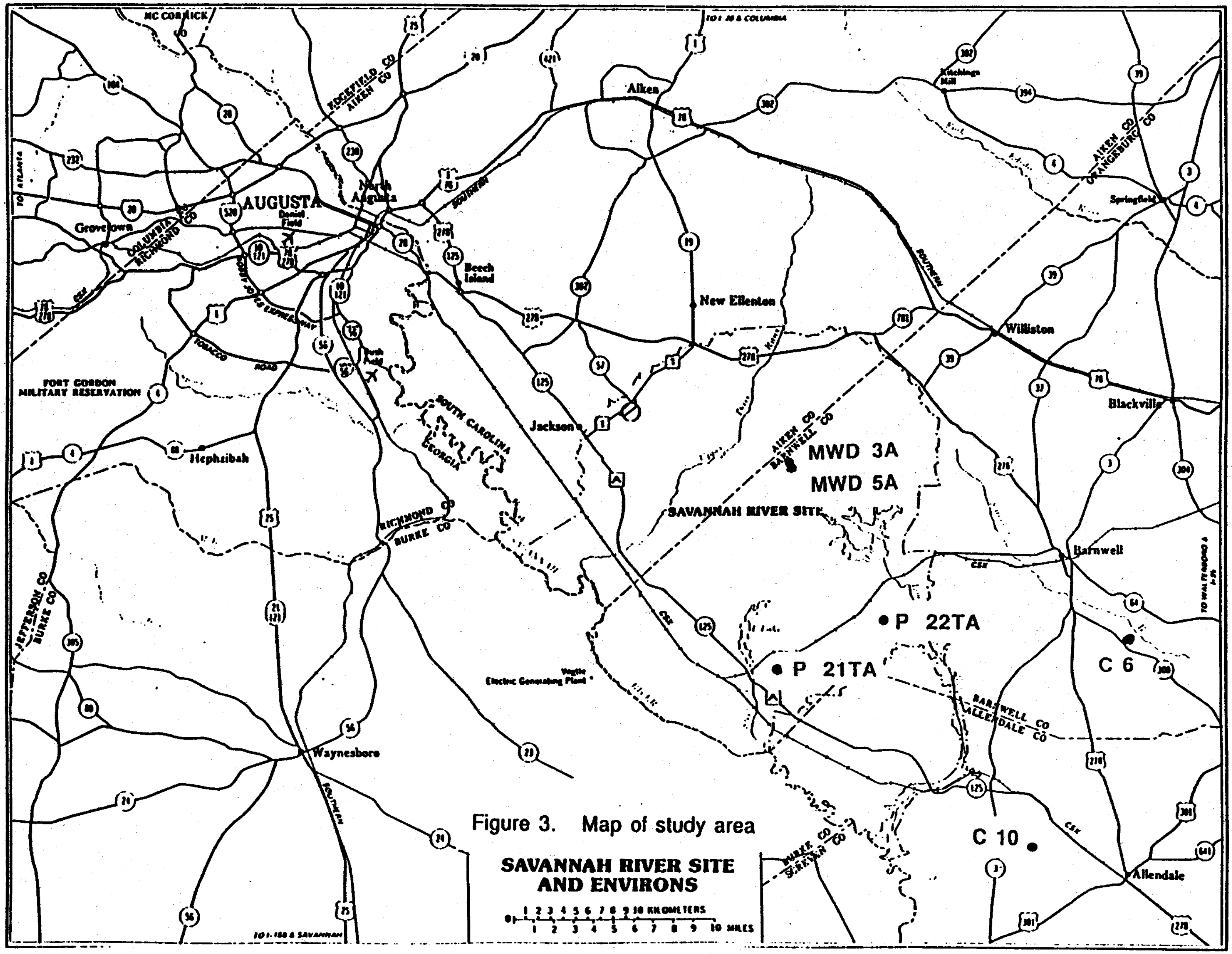

Figure 3. Map of study area.

lachians. They include slate, phyllite, schist, gneiss, volcanics and metavolcanics, granite, and some mafic bodies. The rocks are generally rich in feldspar, providing a source for the kaolinite which is abundant in much of the updip Coastal Plain section.

Rocks similar to those exposed in the Piedmont lie beneath the Coastal Plain sediments within most of SRS. The southeastern part of the Site is underlain by mudstones, sands, and conglomerates of the Triassic Newark Supergroup in the Dunbarton basin (Siple, 1967, p. 22 – 23; Marine and Siple, 1974). The basement surface, the sub-Cretaceous unconformity, dips at about 50 ft/mi to the southeast at SRS.

UPPER CRETACEOUS

Outcropping Upper Cretaceous

Lithology and stratigraphic terminology.

Outcropping Cretaceous sediments consist mostly of medium to very coarse, poorly sorted grayish sands with common to abundant kaolinite and muscovite. Pebbly sands and gravel layers are common, as are clay clasts. Bedding is irregular with facies changes occurring over short distances. Cross-bedding is well developed in places. Clay laminae are common within the sands, and large lenses of “soft” kaolin are mined in the area (Buie and Schrader, 1982, p. 5 – 12). Detailed descriptions of the outcropping Cretaceous are in Nystrom and Willoughby (1982) and Nystrom and others (1986).

The exposed Cretaceous strata have been mapped as Hamburg and Middendorf by Sloan (1908), Middendorf by Cooke (1926) and Snipes (1965); Middendorf and Black Creek by Colquhoun and others (1983); Tuscaloosa by Cooke (1936), Lang (1940), Siple (1967), and Prowell and O’Conner (1978). Christopher (1982) observed that the Cretaceous sediments in the area were younger than the type Tuscaloosa, and the use of the term in the area as a formal formation name has declined. Nystrom and Willoughby (1982) and Nystrom and others (1986) mapped the deposits as simply “Cretaceous”.

Much of what was included before 1970 as Cretaceous strata in Georgia and South Carolina updip from SRS is now assigned to the Tertiary based on paleontologic data (Scrudato and Bond, 1972; Abbott and Zupan, 1975; Tschudy and Patterson, 1975; Buie, 1978) and detailed mapping (see Nystrom and Willoughby, 1982; Nystrom and others, 1986, 1991.

Paleontology, age and correlation

Fossils are rare in the outcropping Cretaceous. Leaves have been found (Berry, 1914), and pollen from an outcrop of dark clay on Interstate Highway 20 near Aiken indicated a late Campanian age (see Nystrom and Willoughby, 1982, p. 86; Nystrom and others, 1986, p. 7), correlative with the Black Creek Formation which crops out in northeastern South Carolina, and the Blufftown and Cussetta formations of Alabama. There are probably older and younger sediments within the exposed Upper Cretaceous Series in Aiken County.

Environment

Most the sands were probably deposited in fluvial and deltaic environments. The large clay bodies suggest deposition in oxbow lakes or in interdistributary bays.

SUBSURFACE UPPER CRETACEOUS

Introduction

The Cretaceous section in the subsurface at SRS is divided from older to younger into the Cape Fear, Middendorf, Black Creek, and Steel Creek formations. The thickness of the Cretaceous section is about 400 ft at the northwestern boundary of SRS and 800 ft at the southeastern boundary. Siple (1967) assigned all the Cretaceous strata in the vicinity of SRS to the Tuscaloosa Formation, the type locality of which is in Alabama. They type Tuscaloosa is now thought to be Cenomanian or Turonian (Christopher, 1982; Valentine, 1984; Sohl and Smith, 1985). Fossil age determinations from SRS are younger. Colquhoun and others (1985a) subdivided the subsurface Cretaceous in the SRS area.

Cape Fear Formation

Lithology and stratigraphic terminology.

The basal unit of the Coastal Plain stratigraphic section at SRS is composed of poorly sorted, silty to clayey quartz sands and interbedded clays. The sands are commonly medium and coarse. They are arkosic in places and pebbly zones are present in many parts of the section. Gray, yellow, orange, red, brown, tan, and blue colors are common. The Cape Fear Formation is more indurated than the other Cretaceous formations because of high clay content and abundance of cristobalite in the matrix (Prowell and others, 1985a, p.8). In general, bedding thickness varies from about 5 to 20 ft, with sands being thicker than clays. Lithologic similarity and fossils indicate a correlation with the type Cape Fear Formation in southeastern North Carolina. Prowell and others (1985a) assigned these sediments to their UK1 unit.

The Cape Fear is about 30 ft thick at the northwestern SRS boundary and thickens to about 200 ft near the southeastern boundary. Regional dip of the upper surface is about 35 ft/mi to the southeast. In the northwestern and central parts of SRS, the Cape Fear lies nonconformably on metamorphic rocks of the Appalachian orogen. In the southeastern part of the Site, it lies on red mudstones, conglomerates, and sands of the Triassic Newark Supergroup.

Paleontology, age, and correlation

Only plant fragments, spores, and pollen have been found at SRS. A few palynological assemblages have a similar age range as those from the type Cape Fear and suggest a Santonian age. Prowell and others (1985a) correlated palynological assemblages in their UK1 unit with the type Cape Fear. The Cape Fear in the type area is probably late Turonian to Santonian (Sohl and Owens, 1991). The unit appears to correlate with the lower part of the Eutaw Formation of Alabama.

Environment

The paucity of marine fossils, the poor sorting, and the high degree of oxidation indicate that the sediments were deposited in fluvial and delta plain environments.

Middendorf Formation

Lithology and stratigraphic terminology

The Middendorf Formation is composed mostly of tan, gray, and yellow, medium and coarse quartz sand. Sorting is generally moderate to good. Pebbly zones are common within the sand, and clay clasts occur in places. Some parts of the unit are feldspathic, and micaceous and lignitic zones occur. Cross-bedding is well developed in the lower part of the section in some areas. Over much of SRS, a kaolinitic clay or a clay-and-interbedded-sand zone up to 50 ft thick forms the top of the unit. In the southeastern part of the Site, this clayey interval is micaceous and lignitic. Another clay-rich zone occurs near the middle of the formation in places. Most of the clays are oxidized. In the northern part of SRS, the formation is highly colored sand with only a few thin clays. The Middendorf has been traced from its type area in northern South Carolina by Sloan (1908), Cooke (1926), and Snipes (1965). Prowell and others (1985a) assigned the sediments at SRS to their UK2 unit.

In most wells the contact between the Middendorf and the underlying Cape Fear is sharp and often marked by a pebbly zone. The younger unit has cleaner sands and lacks the repetitive sand-clay sequences of the Cape Fear. It contains less feldspar, is not as well indurated, and the color is less variable. The Middendorf is approximately 100 ft thick near the northwestern boundary of SRS and thickens to about 180 ft near the southeastern boundary.

Paleontology, age, and correlation.

Wood fragments, spores, pollen, and rare dinoflagellates occur in the unit. A few palynological assemblages suggest a Santonian age, indicating a correlation with the upper part of the Eutaw Formation in Georgia and Alabama. Prowell and others (1985a) correlated their UK2 unit with the Middendorf.

Environment.

The scarcity of marine fossils, the presence of wood fragments, and the discontinuous nature of the bedding indicate that the sediments of the Middendorf Formation probably were deposited in fluvial and deltaic environments.

Black Creek Formation.

Lithology and stratigraphic terminology

The Black Creek Formation consists of quartz sands, silts, and clays. It is generally darker, more micaceous, and more lignitic than the other Cretaceous units. The lower part of the formation consists of tan and light gray, fine to coarse sand with moderate to poor sorting. The sand is micaceous and becomes lignitic in the central and southeastern parts of SRS. Layers of pebbles and clay clasts are common and feldspathic zones occur locally. A thick, oxidized, kaolinitic clay lens occurs within the lower Black Creek in the western part of the Site, suggesting an unconformity within the formation, at least in the updip part of SRS. In the central and downdip part of SRS, a southeastwardly-thickening wedge of dark, fissile, lignitic, pyritic, micaceous clay with dark, interbedded sands and silts occur in the middle and upper parts of the formation; this facies is slightly calcareous in well C 6 near Barnwell, South Carolina, and well C 10 near Allendale, South Carolina (Fig. 3). The upper part of the formation consists mostly of tan and light gray sands.

In many wells tan sands of the Black Creek lie on oxidized clay beds at the top of the Middendorf. Where the clays are missing, it is difficult to pick a contact, but a pebbly zone occurs in some wells. In general, the Black Creek contains more dark clays, lignite, and muscovite than the Middendorf. The oxidized clays and the presence of a pebbly layer suggest that the contact is unconformable, but the time gap may be small. The Black Creek is about 200 ft thick at the northwestern boundary of SRS and thickens to about 300 ft at the southeastern boundary.

The Black Creek appears to be the UK4 and UK5 units of Prowell and others (1985a). Except for the variegated clay bodies, the sediments are lithologically similar to the Black Creek in the type area in northeastern South Carolina, and numerous palynological assemblages from SRS confirm the correlation.

Paleontology, age, and correlation

Wood fragments, some quite large, and pollen and spores are common, as are dinoflagellates. A few mollusks were found in the deep well near Allendale, South Carolina. The Black Creek in and near the type area (Sloan, 1908) in northeastern South Carolina is early Campanian to early Maestrichtian according to Sohl and Owens (1991). Numerous fossil dates of Campanian and Maestrichtian age have been obtained from palynological assemblages in the unit at SRS. Prowell and others (1985a) correlated their UK4 and UK5 units with the type Black Creek. The Black Creek appears to correlate with the Blufftown and Cusseta formations, and perhaps the lower part of the Ripley formation, of

Georgia and Alabama.

Environment

Light-colored sands and large, oxidized clay lenses suggest delta plain conditions in the lower Black Creek in the northwestern part of SRS. The dark clays and sands abundant in the southeastern part of the Site appear to have been deposited in delta front and prodelta environments.

Steel Creek Formation—a new formation

Lithology and stratigraphic terminology

The type section of the Steel Creek Formation, a quartz sand and interbedded kaolinitic clay sequence, is described in the appendix from core from SRS well P 21TA in Barnwell County, South Carolina (Fig. 3). Cretaceous beds of Maestrichtian age overlying the Black Creek are light-colored quartz sands and mostly oxidized, kaolinitic clays. The sediments in the lower part of the formation consist of tan, light to dark gray, orange, and yellow, poorly to well-sorted, fine to coarse quartz sand and silty sand, in places very micaceous. Concentrations of feldspar and lignite occur. Pebbly zones are common, as are layers with clay clasts. The upper part of the Steel Creek in most places at the Site is oxidized, kaolinitic clay, with orange, red, gray, purple, and yellow coloring, interbedded with sands in places. The clay is up to 60 ft thick but absent in some cores. Fining-upward sands are interbedded with the clay in some cores, as in the type well.

In general, the Steel Creek has fewer and much thinner dark clays and less lignite than the Black Creek and has more oxidized clays. In most wells, the basal contact can be placed at the bottom of a coarse sand below which are sands interbedded with dark clays and above which are sands interbedded with variegated clays. Basal Steel Creek tends to be pebble-rich, suggesting an unconformity.

The Steel Creek is about 60 ft thick at the northwestern SRS boundary and 140 ft thick at the southeastern boundary. The dip of the upper surface is to the southeast at approximately 30 ft/mi. The unit occurs throughout SRS and is present downdip in the deep wells near Barnwell (C 6) and Allendale (C 10), South Carolina.

Steel Creek sediments were assigned to the Middendorf and Middendorf (?)-Black Creek(?) by Oldham (1981) and to the Black Creek by McClelland (1987). Colquhoun and others (1983) and Steele (1985) place them in the Black Creek updip from Lower Three Runs and in the Peedee Formation to the southeast. Logan and Euler (1989) included them in the Peedee. The Steel Creek appears to be the UK 6 unit of Prowell and others (1985a).

Paleontology, age, correlation

Wood fragments, spores, pollen, and rare dinoflagellates have been found in SRS wells. Dinoflagellates and pollen suggest a Maestrichtian age and correlation with the Peedee Formation or the Black Creek Formation. The Peedee in the type area in northeastern South Carolina is dark silt and sand, glauconitic in places, with marine fossils. The type Black Creek contains thick black, lignitic clays. Neither of these lithologies is common in the Steel Creek at SRS. In the type area the Peedee is middle Maestrichtian (Sohl and Owens, 1991). Prowell and others (1985a) assigned Steel Creek sediments to their UK6 unit, reporting Peedee-correlative fossil assemblages. Sohl and Owens (1991) have recently redefined the Black Creek/Peedee contact in the Cape Fear arch area. If the Steel Creek is the same age as the redefined Peedee, it correlates with the middle and upper Ripley and Providence formations of Georgia and Alabama.

Environment

The few marine fossils, the irregular bedding, and the large bodies of oxidized clay suggest that the sediments were deposited in delta plain environments.

UNDIFFERENTIATED LOWER TERTIARY

Updip from SRS, sediments between the Cretaceous strata and the upper Eocene Dry Branch Formation consists of sands and clays which are difficult to correlate with strata to the southeast. The sediments are mostly light-colored, kaolinitic, coarse, cross-bedded quartz sands, micaceous sands, with kaolin beds of “hard clay” (Buie, 1978, p. 5; Buie and Schrader, 1982, p. 5-12) which are mined, at the top. According to Nystrom and Willoughby (1982, p. 88-92) and Nystrom and others (1986, p. 8-10), the lower part of the Tertiary northwest of SRS consists of fine to medium, moderately well-sorted, loose, micaceous quartz sand interbedded with thinly laminated to thinly bedded clays. Heavy minerals are abundant. Burrows and shark and ray teeth have been found (Kite, 1982; Nystrom and Willoughby, 1982). The upper part of the undifferentiated Tertiary section is typically orange, cross-bedded quartz sand, fine to coarse, poorly sorted, micaceous, and clayey in places. Clay clasts are common. Bedding is not as well developed as in the lower part. A massive, light-colored, “hard” kaolin bed, locally pisolitic, is commonly observed at the top and is mined in the area (Buie and Schrader, 1982; Nystrom and Willoughby, 1982; Nystrom and others, 1986).

Buie (1978) proposed the term “Huber Formation” for the post-Cretaceous, pre-Jacksonian deposits in the districts where kaolin is mined northeast of the Ocmulgee River in Georgia, with the type area in Twiggs County. The “Huber” probably consists of Paleocene, early Eocene, and middle Eocene sediments deposited near the Fall Line, perhaps including age equivalents of the Warley Hill and Santee or “McBean” (Scrudato and Bond, 1972; Abbott and Zupan, 1975; Tschudy and Patterson, 1975; Buie, 1978; McClelland, 1987).

The term “Huber” has been used in the study area by Oldham (1981), Buie and Schrader (1982), Kite (1982), Mittwede (1982), Nystrom and Willoughby (1982), Colquhoun and others (1983), Steele (1985), McClelland (1987), and Nystrom and others (1986, 1991). A few molluscan fossils have been found in the upper part of Georgia. Eocene diatoms (Abbott and Zupan, 1975), middle Eocene fossil leaves (Hutchenson, 1978), and lower middle Eocene pollen (Nystrom and others, 1986, p. 8) have been reported.

The updip lower Tertiary was probably deposited in fluvial, deltaic, and marginal marine environments.

LOWER PALEOCENE

Sawdust Landing Formation

Lithology and stratigraphic terminology

The Sawdust Landing consists of yellow, orange, tan, moderately to poorly sorted, micaceous quartz sands in some wells in the northwestern part of SRS. In other wells it is composed of gray, poorly and moderately sorted, micaceous, silty and clayey quartz sands and pebbly sands with interbedded, gray clays. It is locally feldspathic, and iron sulfides and lignite are common in the darker parts of the section. The clays are fissile in places and contain micaceous silt and fine sand laminae. The darker, poorly sorted, micaceous facies is dominant in the southeastern part. There appear to be two fining-upward, sand-to clay sequences in the downdip part of the Site.

Basal sands, often pebbly, of the Sawdust Landing lie with a sharp, unconformable contact on oxidized clays of the Steel Creek in most wells at SRS. In general, the Sawdust Landing has more feldspar and iron sulfide than the Steel Creek, is darker, and sorting is poorer. The clays of the Sawdust Landing are more fissile than those of the Steel Creek. Where the oxidized clay at the top of the Steel Creek is missing, it is difficult to pick the contact. Where the Sawdust Landing in these places is better sorted and lighter in color than is typical, it is similar to tan, moderately to well-sorted sands in the Steel Creek. In some cores, the sands of the Steel Creek are micaceous, poorly sorted, and dark, similar to typical Sawdust Landing sands. A pebbly layer occurs in the base of the Sawdust Landing in some of the problem wells.

The Sawdust Landing is about 10 ft thick near the northwestern boundary of the Site and thickens to about 40 ft near the southeastern boundary. It crops out about 4 mi northwest of SRS in the valley of Hollow Creek (Prowell and others, 1985b, p. A63; Nystrom and others, 1991, p. 224).

We consider the basal Paleocene quartz sands and clays at SRS to be a facies of the Sawdust Landing Formation, the type locality of which is to the north in the Congaree River valley (Padgett, 1980; Colquhoun and others, 1983; Howell, 1985; Muthig and Colquhoun, 1988; Colquhoun and Muthig 1991; Nystrom and others, 1991). The Sawdust Landing appears to be the lower part of the “Ellenton Formation” as used by Oldham (1981); of the “Ellenton Formation” and the “Rhems Formation” as used by Colquhoun and others (1983); of the “Ellenton member of the Rhems Formation” as used by Steele (1985); and of the “Rhems Formation” as used by McClelland (1987). The Sawdust Landing is the lower part of unit P1 of Prowell and others (1985a).

We believe that the term “Ellenton” should be abandoned because the sediments named by Siple (1967) consist of two different sedimentary sequences with different lithologies deposited during separate cycles of deposition. An alternative to the use of the term “Sawdust Landing” for the basal Paleocene at SRS is to restrict the “Ellenton” of Siple to the lower sequence. Most of the type section of the “Ellenton”, however, appears to be upper Paleocene Lang Syne Formation. We use the term “Sawdust Landing” for the lower Paleocene strata rather then “Rhems”, because the lithology at SRS is more similar to the type Sawdust Landing in central eastern South Carolina (Padgett, 1980; Colquhoun and others, 1983; Howell, 1985; Muthig and Colquhoun, 1988; Colquhoun and Muthig, 1991; Nystrom and others, 1991) than it is to the type Rhems in eastern South Carolina (Sloan, 1908; Van Nieuwenhuise, 1978; Van Nieuwenhuise and Colquhoun, 1982).

Paleontology, age, and correlation

When Siple (1967) named and described the “Ellenton Formation” from well cuttings at SRS, he thought that the age was either Cretaceous or Paleocene. Prowell and others (1985b) reported early Paleocene fossils from the lower part of the “Ellenton” but were not able to obtain dates from the upper part. Since that time, late Paleocene palynomorphs have been recovered from the upper part, coming from sediments above a glauconitic sand which appears to be the transgressive system tract of a depositional sequence younger than the Sawdust Landing. Harris and Zullo (1992) also considered the “Ellenton” of Siple (1967) to be both early and late Paleocene. Frederiksen (1991) dated the “Ellenton” at SRS as late Paleocene.

In its type area, the Sawdust Lading is thought to be early Paleocene (Colquhoun and Muthig, 1991; Nystrom and others, 1991). A few palynological dates from SRS indicate assignment to the calcareous nannoplankton zonation of Martini (1971) of NP 3 to 4 and perhaps older. The Midwayan Sawdust Landing at SRS appears to correlate with the early Paleocene Rhems Formation in central eastern South Carolina (Van Nieuwenhuise and Colquhoun, 1982), a more marine facies. It also appears to correlate with the Clayton and Porters Creek formations in the Gulf Coastal Plain (lower and middle Midwayan; Danian).

Environment

Upper delta plain deposits composed of light-colored, moderately to poorly sorted, micaceous quartz sands, feldspathic in places, are common in the northwestern part of SRS, with darker, poorly sorted, micaceous lower delta plain facies becoming dominant in the southeastern part.

UPPER PALEOCENE

Lang Syne Formation

Lithology and stratigraphic terminology

At SRS the Lang Syne typically consists of dark gray and black, lignitic clays and poorly and moderately sorted, micaceous, lignitic, silty and clayey quartz sands and pebbly sands interbedded with dark gray clays. Iron sulfides are common in the darker parts of the section. Both sands and clays are glauconitic in places, especially in the southeastern part of the Site. The basal unit is a green sand in places. The clays tend to be fissile and contain micaceous silt and fine sand laminae, often glauconitic. Cristobalite is common in some cores. Deposits composed of yellow, orange, tan, moderately to poorly sorted, micaceous quartz sands are comm in the northwestern part of SRS, with darker, poorly sorted, micaceous facies becoming dominant to the southeast. In some wells, clean, moderately to well-sorted sands occur near the top of the unit.

Basal sands which are glauconitic in places lie on dark clays or dark, moderately and poorly sorted sands of the Sawdust Landing. A pebbly zone is common at the contact. In general the Lang Syne contains more glauconite, muscovite, lignite, and iron sulfide than the Sawdust Landing, and the clay beds are much thicker. It tends to be darker and to contain less feldspar. It is difficult to pick the contact where the basal sand is not glauconitic. The Lang Syne appears to be sporadic in the northwestern part of SRS and is about 80 ft thick near the southeastern boundary. It is somewhat calcareous in the deep well near Allendale, South Carolina.

The type locality of the Lang Syne is in central eastern South Carolina (Sloan, 1908; Padgett, 1980; Colquhoun and others, 1983; Howell, 1985; Muthig and Colquhoun, 1988; Colquhoun and Muthig, 1991; Nystrom and others, 1991). At SRS, it appears to be the upper part of the “Ellenton Formation” of Siple (1967) as used by Prowell and others (1985b) and Logan and Euler (1989); of the “Black Mingo Formation” as used by Oldham (1981); of the “Ellenton Formation” and the “Rhems Formation” as used by Colquhoun and others (1983); of the “Ellenton member of the Rhems Formation” as used by Steele (1985); and of the “Rhems Formation” as used by McClelland (1987). The term “Lang Syne” is applied here rather than “Rhems”, because our palynological data indicate that the Lang Syne (upper “Ellenton”) strata at SRS and vicinity are late Paleocene (Thanetian or Selandian) rather than early Paleocene (Danian). The Rhems has been dated as Danian (Van Nuiewenhuise and Colquhoun, 1982). The Lang Syne at SRS is the upper part of unit P1 of Prowell and others (1985a).

Paleontology, age, and correlation

The Lang Syne has yielded numerous palynoligical assemblages which indicate an assignment to calcareous nannoplankton zones NP 4-8 or 5-8. A nannofossil assemblage from the Lang Syne in the deep Allendale well was given a late Paleocene age by Laws (1992, p. 112). Frederiksen (1991) dated several samples from the “Ellenton” at SRS as late Paleocene. Muthig and Colquhoun (1988) assigned the Lang Syne in the type area to the lower Paleocene, but Nystrom and others (1991) believed it to be upper Paleocene, citing age determinations from dinoflagellates, calcareous nannofossils, and mollusks. It probably correlates with the Naheola and Nanafalia formations of the Gulf Coastal Plain (upper Midwayan and lower Sabinian; lower and middle Thanetian or Selandian).

Environment

Upper delta plain deposits composed of light-colored, moderately to poorly sorted, micaceous quartz sands are common in the northwestern part of SRS, with darker, poorly sorted, micaceous lower delta plain and prodelta facies becoming dominant in the southeastern part. Glauconitic sands probably represent transgressive deposits.

Snapp Formation—A New Formation

Lithology and stratigraphic terminology

The type section of the Snapp Formation, composed of quartz sand and interbedded kaolinitic clay, is described in the appendix from core from SRS well P 22TA in southern Barnwell County, South Carolina. Typically, the sediments are light gray, tan, orange, and yellow, silty, micaceous, medium to coarse quartz sands and pebbly sands interbedded with kaolinitic clays. The micaceous sands have a powdery appearance in some wells. Sorting in the sands is generally poor, but well-sorted sands are present. Dark, micaceous, lignitic sands also occur. The clays are oxidized in some places but dark in others.

In most wells basal, light colored, micaceous Snapp sands lie on dark clays, glauconitic in places, of the Lang Syne. Snapp sands are usually lighter in color than Lang Syne sands, and the unit contains less lignite, iron sulfide, and glauconite. In the middle of SRS, a few cores contain sands of both formations which are better sorted and lighter in color than is typical, making it difficult to pick a contact. The sharpness of the contact in most cores suggests and unconformity, but the time gap may be small.

The Snapp is well developed in the southeastern part of SRS, where there are two fining-upward sequences. Only one sequence occurs in the center of the Site, and the Snapp appears to pinch out updip in the vicinity of Upper Three Runs. It is about 70 ft thick near the southeastern boundary of SRS and is present downdip in well C 10 near Allendale, South Carolina. A glauconitic sand occurs in this part of the section in well C 6 near Barnwell.

The Snapp has been referred to in the study area as

"Williamsburg Formation" by Colquhoun and others (1983), Steele (1985), and McClelland (1987). It appears to correspond roughly to at least part of the "Black Mingo Formation" as used by Logan and Euler (1989). A new formation is established here because the lithology is not similar to that of the type Williamsburg in eastern South Carolina (Sloan, 1908; Van Nieuwenhuise, 1978; Van Nieuwenhuise and Colquhoun 1982), and chronologic relationships between the Snapp and the Williamsburg are uncertain. The Snapp is probably unit P2 of Prowell and others (1985a).

Paleontology, age and correlation

Fossils are rare in the Snapp. There are not many age determinations; judging from a few palynological assemblages, and well-dated strata above and below, it is probably in zone NP 9, middle Sabinian, perhaps correlating with the upper part of the Williamsburg Formation (Van Nieuwenhuise and Colquhoun, 1982; Colquhoun and others, 1983) of eastern South Carolina and the Tuscahoma Sand of the Gulf Coastal Plain (middle Sabinian; upper Thanetian or Selandian).

Environment

The near absence of marine fossils, the generally poorly sorted sands, and the oxidized clays indicate that the environment of deposition was probably mostly delta plain.

LOWER EOCENE

Fourmile Formation—A New Formation

Lithology and stratigraphic terminology

The type section of the Fourmile Formation, composed of quartz sand with some interbedded clays, is described in the appendix from core from well MWD-3A in northwestern Barnwell County, South Carolina. The Fourmile is mostly orange, green, gray, yellow, and tan, moderately to well-sorted, fine to coarse quartz sand with green and gray clays a few feet thick in the middle and at the top in places. There appear to be two fining-upward sequences. Glauconite, muscovite, and iron sulfide are common accessories. Dark clays rich in organic matter tend to be more abundant in the northwestern part of SRS, and glauconitic clays are more common to the southeast. Clay laminae occur in the sands locally.

In the northwestern part of SRS, the Fourmile overlies the dark clays and sands of the Lang Syne Formation. In the southeast, the underlying unit is the Snapp. The basal contact is sharp in both areas. In general, going upward across the Lang Syne contact, the sands become cleaner, iron sulfide and lignite content decreases, colors become lighter, and clay bed thickness decreases. Going upward across the Snapp/ Fourmile contact, sands become cleaner, glauconite increases, and clay bed thickness decreases. Oxidized clays at the top of the underlying Snapp indicate that the contact is an unconformity. On geophysical logs, gamma ray counts are markedly lower in the Fourmile than in the underlying sediments.

Fourmile sediments probably crop out northwest of SRS. The upper surface of the Fourmile dips to the southeast at about 25 ft/mi across the Site. The unit is about 30 ft thick in the northwestern part of the Site and appears to thin to the southeast and toward the Savannah from the center of SRS. Edwards and Frederiksen (1992) noted the absence of early Eocene fossils in a well in Burke County, Georgia, near the Savannah River. The Fourmile occurs in wells C 6 and C 10 near Barnwell and Allendale, South Carolina.

The unit seems to be the lower part of the Congaree (?) Formation as used by Siple (1967) and the lower Congaree as used by Logan and Euler (1989). It roughly corresponds to the lower part of the lower "Bamberg" and lower "Neeses" as used by Oldham (1981) and Colquhoun and others (1983) and to the lower parts of the "McBean", "Neeses", and "Aiken formations as used by Steele (1985). The Fourmile is the E1 unit of Prowell and others (1985a), who noted the presence of beds in the area of units possibly equivalent to the Fishburne.

Paleontology, age, and correlation

The only well-preserved fossils recovered from the Fourmile are palynomorphs. Age determinations fro dinoflagellates indicate that the Fourmile is within zones NP 10 to NP 11, early Eocene, late Sabinian (early Ypresian). It is a correlative of the Fishburne Formation, a calcareous unit found in wells near the coast in South Carolina (Gohn and others, 1983). The western Gulf Coastal Plain correlative is the Hatchetigbee Formation.

Environment

The glauconite, the abundant dinoflagellates, and the moderate to good sorting indicate that the environment of deposition was shallow marine, with dark clays in the northwestern part of SRS probably forming in bays or lagoons, and glauconitic clays in the southeastern part being deposited in neritic conditions.

Congaree Formation

Lithology and stratigraphic terminology

The Congaree consists of orange, yellow, tan, gray and greenish gray, moderately and well-sorted, fine to coarse quartz sands. Thin clay laminae are present in places. In some cores, quartz grains are rounder than in other parts of the section. There appear to be at least two fining-upward sequences. In a few places at SRS, the unit is slightly calcareous. The abundant indurated clays which are common in the type area in central eastern South Carolina (Sloan, 1908; Nystrom and others, 1991) are absent at SRS.

The Congaree is similar to the Fourmile. In most wells, going upward across the contact, glauconite decreases, muscovite decreases, clay beds and laminae become less common, sorting becomes better, pebble content decreases, and colors become lighter. The presence of a silicified zone at the top of the Fourmile, and the occurrence of pisolitic structures near the top in one well, suggest that the contact is unconformable.

The Congaree crops out in stream valleys in the northeastern part of SRS. Correlative sediments northwest of SRS have been mapped as part of the "Huber Formation" (Nystrom and Willoughby, 1982). The "Huber" is more micaceous and poorly sorted in places and indicates more fluvial and deltaic influence. The Congaree is about 60 ft thick at the northwestern boundary of SRS and about 80 ft thick near the southeastern boundary. Across the river from SRS in Georgia it appears to be thinner and more argillaceous and micaceous. Sediments downdip from SRS are more calcareous, and a carbonate occurs in this part of the section in the deep Allendale well (C 10) where another formation name would be appropriate. Typical Congaree is present in well C 6 near Barnwell.

The Congaree was traced in outcrop from its type area in central eastern South Carolina by Sloan (1908) and Cooke and MacNeil (1952), and has been described at SRS by several authors including Siple (1967), Denehy and others (1989), and Nystrom and others (1992). The unit corresponds in stratigraphic position to part of the lower "Bamberg" and "Neeses" as used by Oldham (1981) and Colquhoun and others (1983), and to parts of the "McBean" and "Aiken" formations as used by Steele (1985). The Congaree appears to be units E2 and E3 of Prowell and others (1985a).

Paleontology, age, and correlation

A few molluscan shell fragments, usually silicified, have been found in the Congaree at SRS. In the type area of the Congaree in central eastern South Carolina, the pelecypod Anodontia augustana, an index fossil found in the Tallahatta Formation of the Gulf Coastal Plain, occurs (Cooke and MacNeil, 1952; Nystrom and others, 1991). We have a few palynological dates from the lower and middle parts of the Congaree; judging from these and by age determinations from below and above, it is probably in zones NP 12 to NP 14, early Claibornian (late Ypresian and possibly early Lutetian), equivalent to the Tallahatta Formation. The latter unit is mostly early Eocene according to Bybell and Gibs (1985). The upper part of the Congaree may be early middle Eocene.

Environment

The well sorted sands, the occurrence of glauconite, and the dinoflagellate assemblages indicate shallow marine and barrier environments.

MIDDLE EOCENE

Warley Hill Formation

Lithology and stratigraphic terminology

A fine to medium, poorly to well-sorted quartz sand and muddy quartz sand, glauconitic in places and a few inches to approximately 15 ft thick, occurs above the Congaree in many cores at SRS. The sand fines upward, and locally a clay, a few inches to 2 ft thick, occurs at the top. Common colors are brown, green, gray, yellow, tan, and orange. The top of the Congaree is picked at the top of a clean sand sequence. Going upward in many wells, the overlying Warley Hill sands become coarser, then finer, sorting becomes poorer, silt and clay content increases, glauconite becomes more common, and colors are darker. In some cores, the top of the Congaree is cemented with silica, indicating that the contact may be unconformable.

Sloan (1908) apparently assigned outcrops along Tinker Creek within SRS to his "Warley Hill phase", correlating with his type area in central eastern South Carolina where it is very glauconitic. Siple (1967) noted the possible occurrence of the Warley Hill at SRS. The unit is sporadic and difficult to identify at SRS. The possible occurrence of *Cubitostrea lisbonensis* at Blue Bluff on the Savannah River indicates that the unit, or a time-equivalent, may crop out there, although at least most of that exposure is younger. The unit is most distinct in cores and outcrops in the central part of SRS and appears to become calcareous in the downdip part, making it difficult to distinguish from overlying carbonates. It appears to be missing from the northwestern part of SRS. Steele (1985) and McClelland (1987) applied the ter "Warley Hill" to calcareous facies in the downdip part of the study area. At least part of unit E4 of Prowell and others (1985a) may be the Warley Hill.

Paleontology, age, and correlative

Dinoflagellates, spores, and pollen have been recovered from the unit at SRS. Samples from two wells have dinoflagellate assemblages indicating a correlation with zone NP 15 and the lower Lisbon Formation of the Gulf Coastal Plain, which is middle Claibornian (lower Lutetian).

Environment

Glauconite and dinoflagellates suggest shallow marine conditions, with the muddier sands indicating lower energy levels than those prevailing when the Congaree was deposited. The high mud content could have also been caused by flocculation at the fresh water/salt water interface.

Santee Limestone

Lithology and stratigraphic terminology

Above the Warley Hill, most of the middle Eocene section consists of three laterally gradational units: the Santee

Limestone, the informally named "Blue Bluff" unit or member (Huddlestun and Hetrick, 1986, p. 4), and the Tinker Creek Formation.

A cream-colored calcareous facies composed of calcarenite and calcilutite with indurated calcareous nodules is common at SRS. This is the typical "McBean" carbonate lithology. Indurated, moldic limestone similar to that in the type area of the Santee (Moultrie Member of Ward and others, (1979) also occurs in many SRS cores and outcrops, and in exposures in the type area of the "McBean" (Sloan, 1908, p. 271-272; Veatch and Stephenson, 1911, p. 244-246). In places the carbonate has been replaced by silica. The Santee is approximately the E5 unit of Prowell and others (1985a). The Santee is best developed in a northeasterly trending zone across the middle of SRS, It is sporadic in the vicinity of Upper Three Runs and rare to the northwest. To the southeast it interfingers with and grades into the "Blue Bluff". Judging from Sloan's (1908, p. 271) lithologic descriptions, the Santee is at least 60 ft thick at Shell Bluff in Burke County, Georgia.

"McBean Formation" of many authors and "McBean member of the Lisbon Formation" (Huddlestun, 1982; Huddlestun and Hetrick, 1986, p. 4) have been applied in the past to these sediments at SRS and vicinity. The "McBean Formation" at its type locality on McBean Creek in Georgia (Veatch and Stephenson, 1911, p. 237-244) consists of carbonates overlain by clay and quartz sand. Most of the siliciclastics are apparently of Jacksonian age according to Huddlestun and Hetrick (1982, p. 25), although Nystrom and Dockery (1992) suggested that at least some of them are correlative with the Claibornian Gosport Sand in Alabama. The original concept of the unit also included carbonates exposed on the Savannah which are now known to be upper Eocene (Veatch and Stephenson, 1911, p. 243; Huddlestun and Hetrick, 1986).

Huddlestun (1982) and Huddlestun and Hetrick (1986) suggested restricting the term "McBean" to calcareous facies and informally used the term "McBean member of the Lisbon Formation". Because of the confusion involved in the use of the term, we are currently not using "McBean" and are using "Santee Limestone" for the calcareous sediments rather than "McBean Formation", "Lisbon Formation", or "McBean member of the Lisbon Formation" for these reasons:

1. Sloan (1908, p. 459-460) applied the term "Santee" at SRS and vicinity before the "McBean Formation" was defined by Veatch and Stephenson (1911).
2. Although the calcareous facies of the type "McBean" consists mostly of slightly to moderately indurated sediment with a "marly" texture, beds of moderately to well-indurated biomoldic limestone similar to the Moultrie Member of the Santee occur in the "McBean" type area (see Sloan, 1908, p. 271; Veatch and Stephenson, 1911, p. 242-243).
3. "McBean" as used in the updip Coastal Plain by Cooke and MacNeil (1952) and Siple (1967) consists mostly of siliciclastics. In some places, "McBean" has been mapped where no calcareous sediments are present.
4. Two names have been used by most workers for this part of the section: "Santee" for calcareous sediments and "McBean" for calcareous sediments and siliciclastics. We believe that it is more logical to have a name for the calcareous deposits and another for the siliciclastics.

Discussions of the confusing usage of the ter "McBean" are in Huddlestun (1982) and Huddlestun and Hetrick (1986). We await a more precise and useful definition of "McBean", at which time it may be incorporated into our stratigraphic column.

Paleontology, age, and correlation

Microfossils and megafossils are abundant in the Santee. From the outcrops at McBean Creek, Georgia, Cushman and Herrick (1945) described many species of foraminifers, mostly benthonic. The benthic foraminiferal species Cibicides westi appears to be a marker for the Santee in this area (Huddlestun and Hetrick, 1986, p. 15). Zullo (1985) analyzed barnacle assemblages from the "McBean". Veatch and Stephenson (1911, p. 239-240) listed numerous species identified by T. W. Vaughan, including gastropods, pelecypods, a coral, and a scaphopod. *Cubitostrea sellaeformi* and *Pteropsella lapidosa*, characteristic of the upper Lisbon, have been found at many places. Among other groups common to abundant in the Santee are sponges, foraminifers, ostracodes, bryozoans, and barnacles. Calcareous nannoplankton, palynomorph assemblages, and other fossils indicate a zone NP 16 age assignment (late Lutetian, middle Claibornian).

Veatch and Stephenson (1911, p. 237) suggested a possible correlation for the upper part of the "McBean" with the Gosport Sand of late Clabornian age in the Gulf Coastal Plain, and Toulmin (1977) correlated the upper part of the "McBean" with the Gosport. Ostracodes from Santee carbonates in one well at SRS indicate the presence of Claibornian strata slightly younger than the *Cubitostrea sellaeformis* zone, probably equivalent to the Gosport (J. E. Hazel, personal communication). This part of the section appears to correlate with strata in the central eastern South Carolina Coastal Plain described by Dockery and Nystro (1992). The deposits there contain abundant silicified molluscan shells and are unconformably separated from the underlying C. sellaeformis zone. [This is probably at or near Sloan's locality.] Dockery and Nystrom (1992) informally named these sediments the "Orangeburg District bed". The Gosport-correlative deposits may be an updip facies of the Utley Limestone and other parts of the Clinchfield Formation (Nystrom and Dockery, 1992; see also Harris and Zullo, 1992) and may also correlate with the upper part of the Santee Limestone (see Ward and others, 1979; Powell and

Baum, 1982; Dockery and Nystrom, 1991; Harris and Zullo, 1991) in central eastern South Carolina.

Environment

The environment of deposition was probably mostly inner to middle neritic.

"Blue Bluff" unit

Lithology and stratigraphic terminology Calcareous strata occur for many miles along the Savannah River valley in the same stratigraphic position as the Santee Limestone but with sufficient areal extent, thickness, and distinctiveness in lithology to warrant recognition as a separate unit. Huddlestun and Hetrick (1986, p. 4) informally used "Blue Bluff member of the Lisbon Formation". The unit is a cliff-former and is exposed at several bluffs one the Georgia side of the Savannah opposite SRS (see Veatch and Stephenson, 1911, p. 249-250). The "Blue Bluff" is gray and pale green, clayey, laminated calcilutite, calcarenite, and calcareous silts and clays, with shell layers, indurated nodules, thin indurated limestone lenses, calcareous muds, and quartz sand laminae in places. Brantley (1916, p. 54) reported an analysis from the exposure at Blue Bluff with a carbonate content of 56%. Much of the sediment form SRS cores has more than 75% (Paul Thayer, personal communication). Thin, phosphatic crust in SRS well P 21TA suggests that the basal contact is unconformable. On geophysical logs, the "Blue Bluff" is characterized by having high gamma ray counts and low resistivities compared to sediments above and below.

"Blue Bluff" sediments are widespread in the southern part of the Savannah River Site. They interfinger and are gradational with the cream-colored Santee facies, and, in general, tend to be more common in the lower part of the calcareous section than the lighter-colored carbonates. The "Blue Bluff" lithology appears to extend as thin beds as far northwest as McBean, Georgia, judging from the subsurface descriptions of McLelland (1987); it extends to the southeast at least as far as the deep wells near Barnwell and Allendale, South Carolina. The "Blue Bluff" is about 90 ft thick at the southeastern boundary of SRS.

The "Blue Bluff" has been assigned to the "McBean Formation" or Santee Limestone by most workers in the area. Colquhoun and others (1983), Steele (1985), McClelland (1987), and Logan and Euler (1989) used the terms "Santee" downdip and "McBean" updip for carbonates within the study area. The "Blue Bluff" may be part of the E4 unit of Prowell and others (1985a); most is unit E5.

Paleontology, age, and correlation

The benthic foraminiferal species Cibicides westi appears to be a marker for the Santee and "Blue Bluff" in this area (Huddlestun and Hetrick, 1986, p. 15). Cubitostrea sellaeformis and Pteropsella lapidosa, characteristic of the upper Lisbon, occur in the "Blue Bluff" with numerous other molluscan taxa. Calcareous nannoplankton, palynomorphs, and other taxa indicate an approximate zone NP 16 age assignment (late Lutetian, middle Claibornian).

Environment

Sediments and fossils in the "Blue Bluff" suggest a lower energy environment than that of the Santee.

Tinker Creek Formation—A New Formation

Lithology and stratigraphic terminology

The Tinker Creek consists of quartz sands, silts, and clays which, in general, occur updip form the Santee. The type section is described in the appendix from core from well MWD-5A in northwestern Barnwell County, South Carolina. In general, the sands of Tinker Creek are finer than the sands above and below, contain more heavy minerals, and are more likely to contain glauconite, although glauconite is often found in the Warley Hill. Yellow, tan, and white sands are common, and pale green sands occur in the center of SRS. Clay beds and laminae are underlying and overlying units. The clays of the Tinker Creek tend to be illite/smectite rather than kaolinitic as in other parts of the section (Dennehy and others, 1989). Tan clays are more prominent in the overlying Dry Branch Formation while green clays are common in the Tinker Creek. Silica cemented zones occur in many places. Burrows of the *Ophiomorpha* type are abundant in some outcrops of the Tinker Creek. Most burrows are less than 1 inch in diameter and have thin walls of white clay. Although very fine and fine sands are typical of some of the Tinker Creek, medium and coarse sands are common in SRS wells, especially updip. The fine sand facies can also be found many miles updip. An exposure of very fine, well-sorted, burrowed sand on Good Hope Farms Road in Aiken County, about 0.9 mi west of Silver Bluff Road (South Carolina Highway 302), appears to be the Tinker Creek. A similar exposure is in a borrow pit-landfill on the north side of Herndon Dairy Road, about 1.3 mi west of Silver Bluff Road. The fine, well-sorted, burrowed sand here is topped by massive clay. These sediments were assigned to the "Huber Formation" by Nystrom and others (1982, p. 121).

The clay between 187 and 190 ft in the type section is part of the "green clay interval" (Dennehy and others, 1989; Snipes and others, 1992), a series of clay beds and clayey sands ranging for the upper part of the Congaree Formation through the lower part of the Tinker Creek. A fossiliferous section of the Tinker Creek "green clay" several feet thick is exposed in a road cut on the east side of Upper Three Runs were SRS road 2-1 crosses the creek. Molluscan molds, including Pteropsella lapidosa, occur here. Outcrops of green caly, green clayey sand, and the fine, well-sorted, burrowed sand facies occur in northwesterly-flowing tributaries to Upper Three Runs at SRS. In a few cored wells near the center of SRS, part of Tinker Creek consists of light tan to buff, low density silt.

Where the Warley Hill is missing and the Tinker Creek overlies the Congaree, going upward in the section colors become darker, grain size decreases, sorting becomes poorer, green clay and/or glauconitic sand become more common, and heavy minerals become abundant. Where the Tinker Creek overlies the Warley Hill, the contact is more obscure, but Tinker Creek stands tend to be finer and cleaner than the underlying sand. A pebbly zone occurs at the base of the Tinker Creek in places.

On geophysical logs, the gamma ray count for the Tinker Creek is usually higher than for overlying and underlying units, especially where the "green Clay" facies is well developed at or near the base of the unit. In general, resistivities are low in the Tinker Creek, especially in comparis with the overlying unit.

The Tinker Creek grades downdip into the carbonates of the Santee and, perhaps, the "Blue Bluff". Northwest of Upper Three Runs within SRS, we know of only one well which encountered calcareous sediments. Outcrops of silicified limestone north of SRS in the Tinker Creek part of the section suggest that some of the siliciclastic facies developed by solution of calcareous deposits. Trending southwest-northeast through the middle of SRS, the Tinker Creek and Santee are gradational and interfingering. Some wells with calcareous sediments are surrounded by wells a few hundred feet away containing only siliciclastics, and vice versa. For mapping purposes, the contact is defined in the transition zone where 25% of the section is composed of calcium carbonate. (Although the North American Stratigraphic Code recommends boundaries be drawn at 50%, we believe that 25% is a significant amount of carbonate).

The Tinker Creek is about 40 ft thick at the northwestern boundary of SRS, and the "Blue Bluff" is about 90 ft thick at the southeastern boundary. Dip of the upper surface of the Tinker Creek-Santee "Blue Bluff" is about 20 ft/mi to the southeast across SRS.

The Tinker Creek is some of the siliciclastic parts of the "McBean Formation" as used by many workers; the upper part of the "Aiken formation" as used by Colquhoun and others, (1982, 1983). Bishop (1984), and Steele (1985); some of the upper part of the "Huber Formation" as used by Nystrom and Willoughby (1982); and part of the "Neese formation" as used by Oldham (1979). It is the "Tims Branch" of Fallaw and others (1992).

Paleontology, age and correlation

Palynomorphs and silicified shells and molds of mollusks have been found in the Tinker Creek. A few palynomorph assemblages indicate zone NP 16, and Pteropsella lapidosa, characteristic of the upper Lisbon (middle Claibornian; upper Lutetian), occurs in the unit. Nystrom and Dockery (1992) considered some of the red sands described by Sloan (1908) as his "Barnwell phases", and other sands containing silicified fossils at SRS, to be Gosport equivalents.

Environment

The environment of deposition was probably mostly barrier, shallow marine, and lagoonal.

MIDDLE OR UPPER EOCENE

Clinchfield Formation

Lithology and stratigraphic terminology

The Clinchfield, type locality in central Georgia (Pickering, 1970), consists mostly of quartz sand and clay, calcareous in places, and carbonates. The quartz sand of the Clinchfield at SRS may be the Riggins Mill Member, defined in central Georgia (Huddlestun and Hetrick, 1986, p. 26-29, 63-65). It is tan and yellow, poorly to well-sorted, and fine to coarse. The Utley Limestone Member, type locality at Plant Vogtle in Burke County, Georgia near SRS (Huddlestun and Hetrick, 19 86), is an indurated, bioclastic and biomoldic, glauconitic limestone in some places, and in others a calcareous sand and calcarenite. The Clinchfield appears to be unit E6 of Prowell and others (1985a). The Utley is exposed in places on the Georgia bank of the Savannah opposite SRS at least as far downstream as several hundred feet southeast of Griffins Landing. Approximately 30 ft thick in the southeastern part of the SRS, the Clinchfield pinches out or becomes unidentifiable updip in the middle of the Site.

In places the lower contact of the Clinchfield is marked by a change from calcareous sediments of the Santee and "Blue Bluff" to poorly to well-sorted sand of the Riggins Mill Member. In some wells, the Riggins Mill contains coarse quartz pebbles. The Utley Limestone tends to be more indurated and coarsely glauconitic than the underlying carbonates, and it contains abundant specimens of the sand dollar Periarchus lyelli. In general, there are fewer heavy minerals and more manganese-stained sediments above the contact.

Paleontology, age, and correlation

Huddlestun and Hetrick (1986) reported the presence of the pelecypod *Chlamys* cf. *C. membranosa* and *Crassostrea gigantissima*, the sand dollar *Periarchus lyelli*, and benthonic foraminifers in Georgia. *P. lyelli* has been identified by the Utley at SRS. We do not have good fossil dates from the Clinchfield. The most common age determinations in the immediately underlying strata are zone NP 16, and in overlying strata, NP 18-20. The abundance of *P. lyelli* suggests that the Clinchfield correlates with the "*Scutella*" abundance zone of the Gulf Coast, making it a correlative of the Gosport Sand (late Claibornian) and/or the Moodys Branch Formation (early Jacksonian). Huddlestun and Hetrick (1986, p. 26) discussed the age problem and tentatively assigned the Clinchfield to the Jacksonian. Harris and Zullo (1992) favored a correlation with the Claibornian Gosport Sand.

Environment

The concentrations of sand dollars in the carbonates and the sorting of the sands suggest a littoral and inner neritic environment.

Albion Member (of the Clinchfield Formation?)

Lithology and stratigraphic terminology

A distinctive unit with spiculitic (containing sponge spicules) sediments has been encountered in several places in Georgia and in Aiken County, South Carolina (Huddlestun and Hetrick, 1986, p. 31). It consists of spiculite, and spiculitic mudstones and sandstones, cemented with opal in places (Carver, 1972). Maximum known thickness is 22.5 ft in the Windsor Spring roadcut south of Augusta, Georgia (Huddlestun and Hetrick, 1986, p. 31).

The type locality is the Albion Kaolin Mine in Richmond County, Georgia (Carver, 1972).

Paleontology, age, and correlation

The unit was tentatively placed in the upper Eocene by Carver and in the Clinchfield Formation by Huddlestun and Hetrick (1986), but its precise age is unknown. In addition to marine sponge spicules, some diatoms, radiolarians, and plant fragments have been found which could be used for accurate age determination (Huddlestun and Hetrick, (1986).

Environment

Carver (1972) suggested an extremely nearshore, perhaps tidal pool, environment for the Albion.

UPPER EOCENE

Dry Branch Formation

Lithology and stratigraphic terminology

The Dry Branch Formation includes the Twiggs Clay Member, dominant west of the Ocmulgee River in Georgia, type locality in central Georgia (Shearer, 1917, p. 158-174); the Irwinton Sand Member, dominant from the Ocmulgee River eastward, type locality in central Georgia (Lamoreaux, 1946a, 1946b); and the Griffins Landing Member, type locality across the Savannah from SRS (Huddlestun and Hetrick, 1986, p. 43-46, 72-73). The Dry Branch has been correlated in outcrop from its type locality in central Georgia (Huddlestun and Hetrick, 1986, p. 34-46, 66-67) to SRS (Nystrom and Willoughby, 1982). Siple (1967) appears to have assigned all the Irwinton and some of the Griffins Landing to his “McBean Formation”. The Dry Branch includes unit E7 and probably part of E8 of Prowell and others (1985a).

The Twiggs Clay Member is not a mappable unit at SRS, although lithologically similar beds occur at various horizons in the formation. The Griffins Landing Member is at least 50 ft thick in the southeastern part of SRS. Calcilutite, calcarenite, bioclastic and biomoldic limestone, calcareous sand, and shelly, calcareous clay occur in the member. The large oyster Crassostrea gigantissima, abundant in the Griffins Landing at its type locality, is found in many SRS cores. Siple (1967) assigned some C. gigantissima-bearing beds to his “Barnwell Formation”, but placed all limestones at SRS in the lower part of his “McBean”. The Griffins Landing occurs sporadically in most of the Site and is not known to be present northwest of Upper Three Runs within the Site boundaries, but it has been encountered in the subsurface north of SRS (Zullo and Kite, 1985).

At SRS, the Griffins Landing contains less glauconite that the carbonates of the underlying Utley and Santee. It lacks the concentrations of Periarchus lyelli and generally contains abundant Crassostrea gigantissima. Where Griffins Landing carbonates overlie the sands of the Riggins Mill Member, the contact is obvious. A thin quartz sand visible on outcrop between the Griffins Landing and the Utley at Griffins Landing is interpreted as a transgressive deposit. A pebbly layer at the contact occurs in some cores. Pisolitic structures were found at the contact in one well at SRS.

The remainder of the Dry Branch Formation within SRS is made up of the Irwinton Sand Member. It is composed of yellow, tan, and orange, moderately sorted quartz sand, with interlaminated and interbedded clays, typically tan, abundant in places. Pebbly layers and zones rich in clay clasts occur. Glauconite is rare. In general, the Griffins Landing grades updip and upseciton into the Irwinton.

In places as far north of the Site as Aiken, outcrops of clay and silicified sandstone with what appears to be C. gigantissima occur. Nystrom and others (1986, p. 17) cited several occurrences of fossiliferous, silicified sand apparently within the Dry Branch, one of which is northwest Aiken.

The Dry Branch Formation is about 50 ft thick near the northwestern SRS boundary and about 80 ft near the southeastern boundary.

Paleontology, age, and correlation

Aggregations of Crassostrea gigantissima in living position are prominent in parts of the Griffins Landing. Herrick (1960, 1964) described foraminiferal assemblages fro Shell Bluff and Griffins Landing, Georgia, near SRS. Zullo and Kite (1985) and Steele and others (1986) reported foraminifers, barnacles, crabs, bryozoans, starfish, crinoids, shark and ray teeth, and fish bones from the member of several localities in the vicinity of SRS. *Ophiomorpha*, palynomorphs, and silicified *C. gigantissima* have been found in the Irwinton Sand Member. Palynological and calcareous nannoplankton assemblages from SRS cores suggest a correlation with zones NP 18 to NP 20 and the lower part of the Yazoo Formation of the Gulf Coastal Plain, which is middle Jacksonian (middle Pribonian).

Environment

Common planktonic Foraminifera in one SRS core sample from the Griffins Landing indicate some open ocean influence. Some of the *Crassostrea* and *Brachiodontes*-bearing calcareous clay beds contain foraminiferal genera indicating bay or lagoonal environments. Irwinton sands are probably inner neritic and barrier deposits. The clays of the Irwinton probably formed in lagoons or bays.

Tobacco Road Sand

Lithology and stratigraphic terminology

The Tobacco Road Sand consists of moderately to poorly sorted, red, brown, tan, purple, and orange, silty, clayey quartz sands and quartz sands. A few thin clay beds are present in some places. In general, the sands of the Tobacco Road are muddier, more micaceous, and more highly colored than those of the Dry Branch. The base of the Tobacco Road is marked in places by a coarse layer that contains flat quartz pebbles. The unit has been traced in outcrop from its type locality in Richmond County, Georgia, to SRS (Huddlestun and Hetrick, 1978, 1986; Nystrom and Willoughby, 1982). The "Barnwell Formation" of Siple (1967) seems to correspond roughly to the Tobacco Road.

The formation is exposed in much of the southwestern South Carolina Coastal Plain, including SRS. Its upper surface is irregular because of incision that preceded deposition of the overlying Altamaha Formation. The thickness varies considerably because of the eroded upper surface, but it is at least 60 ft thick in places.

Paleontology, age and correlation. No datable fossils have been recovered from the Tobacco Road at SRS, but Ophiomorpha burrows can be seen in many outcrops, and silicified shell fragments occur in places. Crassostrea gigantissima has been reported from the sand in Georgia, and the Sandersville Limestone Member in central Georgia contains C. gigantissima, Turritella, molluscan molds, and the echinoid *Periarchus quinquefarius* (Huddlestun and Hetrick, 1986). Based on evidence in central Georgia, Huddlestun and Hetrick (1986) assigned the Tobacco Road to the Jacksonian (late Eocene), correlating it with the upper part of the Yazoo Formation in the Gulf Coastal Plain, which is upper Jacksonian (upper Priabonian).

Environment

Marine fossils and glauconite have been found in the Tobacco Road in central Georgia, indicating a shallow neritic environment. The occurrence of clay laminae and beds, especially in the upper part, suggest that some of the Tobacco Road was deposited in a transitional, low energy environment, such as a tidal flat or shallow lagoon.

OLIGOCENE (TO MIOCENE?)

Zullo and others (1982), Willoughby and others (1984), and Nystrom and others (1991) described partially silicified, barnacle-bearing, quartz sand channel deposits of Oligocene (to Miocene?) age in several localities in Aiken County (*Lophobalanus baumi* beds). The channels cut into the "Huber" and Dry Branch formations. Barnacles, echinoids, Foraminifera, worm tubes, and pectenids occur in the sediments, and the interpretation is a valley-fill sequence or a basal part of the Miocene "upland" unit (Nystrom and others, 1991, p. 236).

Fossiliferous chert of Oligocene age [King's Creek phase of Sloan (1908); Flint River formation of Cooke (1936) and Cooke and MacNeil (1952) crops out along the Savannah about 5 mi downstream from SRS and 14 mi downstream from Plant Vogtle in Georgia.

MIOCENE

Altamaha Formation ("Upland" Unit)

Lithology and stratigraphic terminology

The "upland" is an informal term applied to deposits that occur at higher elevations in many places in the southwestern South Carolina Coastal Plain (Nystrom and Willoughby, 1982; Nystrom and others, 1986, 1991; Colquhoun and others, 1983; Steele, 1985; McClelland, 1987; Logan and Euler, 1989). It may be a facies of unit M1 of Prowell and others (1986a). The sediments are red, purple, gray, orange, yellow, and tan, poorly sorted, clayey and silty, fine to coarse sands, with lenses and layers of gravels, pebbly sands, and oxidized, massive clays. Clay clasts are abundant. Cross-bedding is prominent in places, and muscovite and flecks of weathered feldspar are locally abundant. Clay-filled fissures, probably caused by weathering, are numerous in places. The unit is an extension of the Altamaha Formation of Georgia (Nystrom and Willoughby, 1992), type locality in southeastern Georgia (Dall and Harris 1892, p. 82; Huddlestun, 1988, p. 101).

The Altamaha occurs at the surface at higher elevations in many places around and within SRS but appears to be missing from some high elevation SRS wells. It is up to 70 ft thick in parts of SRS. The lower surface of the unit is very irregular because of erosion of underlying deposits. In a few SRS cores, the Altamaha lies on Dry Branch sediments rather than on the Tobacco Road. In general, going upward across the base of the Altamaha, sorting becomes poorer, weathered feldspar grains become larger and more common, clay beds become more abundant and thicker, sand become more argillaceous and indurated, pebbles are larger, and, in places, muscovite increase.

Much of the "Hawthorn Formation" of Siple (1967) corresponds to the Altamaha, but the Miocene Hawthorne Group in its type area is phosphatic and dolomitic (Huddlestun, 1988). Siple's "Hawthorn" apparently included some of the underlying Tobacco Road, as he considered the occurrence of *Ophiomorpha* (="*Halymenites*"), common in that formation, to be typical of his "Hawthorn" rather than his

"Barnwell Formation". Other terms which have been applied to the Altamaha deposits in the area are "Lafayette" (McGee, 1891; Sloan, 1908, p. 479) and "Citronelle" (Doering, 1960, 1976; Smith and White, 1979).

Paleontology, age and correlation

Very few fossils have been reported from the Altamaha and its equivalents. Ophiomorpha burrows were observed in what appears to be the Altamaha at one locality at SRS. Siple (1967, p. 61) reported benthic Foraminifera from his "Hawthorn Formation" in a well at SRS indicating a correlation with the Duplin Marl, then considered Miocene but no assigned to the Pliocene. In southeastern Georgia, the Altamaha appears to grade laterally into the Parachucla and Coosawatchie formations of the Hawthorne Group, both of Miocene age (Huddlestun, 1988, p. 30), making it Aquitanian and Serravallian. According to Nystrom and Willoughby (1992), the Altamaha is late middle to early late Miocene and unconformably overlies the Coosawatchie. Downdip from SRS, the Altamaha is truncated by the Orangeburg scarp. Pliocene marine deposits occur to the east of the scarp (Colquhoun, 1988).

Environment

The conglomerates, poorly sorted sands, and clay lenses have the characteristics of fluvial sediments. The possible occurrence of rare Ophiomorpha suggests that there may have been occasional transitional marine influence.

YOUNGER DEPOSITS

Stream terrace deposits, colluvium, and alluvium are common at lower elevations (Siple, 1967; Newell and others, 1980; Dennehy and others, 1989). There has been some informal discussion of a possible eolian origin for clean sands found at higher elevations in parts of the area.

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APPENDIX—TYPE SECTIONS

Steel Creek Formation

The type section of the Steel Creek Formation, a quartz sand and interbedded kaolinitic clay sequence, is described below from core from SRS well P21TA in Barnwell County, South Carolina, Site coordinates north 24675 and east 40739, or approximately 33°9'28"N and 81°35'25"W (Fig. 3). Steel Creek is a tributary to the Savannah about 2.4 mi west of the well. The core is stored at SRS.

Feet below ground surface

Sawdust Landing Formatio

450-452 Sand, coarse, clayey, very poorly sorted, angular; slightly indurated; gray

452-452.3 Sand, very coarse, pebbly, angular; slightly indurated; gray

452.3-453 Missing core

Steel Creek Formation

453-460 Clay, becoming sandy toward base; micaceous; moderately indurated; mottled grayish red

460-464 Sand and clayey sand, medium, poorly sorted, angular; micaeous; slightly to moderately indurated; light gray

464-472 Clay, sandy at base; moderately indurated; mottled yellowish and tannish gray

472-484 Sand, medium, poorly and moderately sorted; angular and subangular; clayey at top; micaceous; iron sulfides in places; slightly indurated; gray

484-486 Sand, medium, pebbly, clayey very poorly sorted, subangular; slightly indurated; gray

486-488 Missing core

488-488.4 Sand, coarse, pebbly, very poorly sorted, subangular; slightly indurated; tan

488.4-500 Clay, moderately indurated; gray, yellow, brown

500-518 Sand, medium, clayey at top, poorly sorted; micaceous; slightly lignitic in places; gray, light brown at base

518-540 Clay, sandy at base, moderately indurated; mottled gray, red, yellow, orange

540-552 Sand, medium, moderately and poorly sorted; micaceous; gray

552-574 Clay, moderately indurated; mottled reddish gray

574-575 Missing core

575-577 Clay, moderately indurated; dark gray

577-578 Missing core

578-586 Clay, moderately indurated; dark gray

586-588 Missing core

588-589 Sand, fine, poorly sorted, slightly indurated; micaceous; gray

589-592 Missing core

592-594 Sand, very coarse, somewhat pebbly, poorly sorted; slightly indurated; light gray

Black Creek Formation

594-600 Sand, medium, moderately sorted, clayey and lignitic at base; tan and light gray

Snapp Formation

The type section of the Snapp Formation, composed of quartz sand and interbedded kaolinitic clay, is described below from core from SRS well P 22TA in southern Barnwell County, South Carolina, about 2 mi west of Lower Three Runs, a tributary to the Savannah River, and 2 mi south of Par Pond. SRS coordinates of the well are north 20593 and east 73555, or approximately 33^{o}12'14"N and 81^{o}31'25"W. The ground elevation is 215 ft above mean sea level. The core is stored at the Savannah River Site. "Snapp" is the name of an old railroad stop in the southeastern part of the Site.

Fourmile Formation

296-300 Sand, coarse, clayey in places, moderately to well sorted, subrounded; slightly indurated; trace glauconite; light green

300-310 Missing core

Snapp Formation

310-319 Clay, becoming sandy toward base, micaceous in places; slightly to moderately indurated; light yellowish gray (The geophysical log indicates that the top of the clay is at a depth of 305 ft, within the interval of missing core).

319-323 Sand, coarse, clayey, poorly sorted, subrounded; slightly indurated; light gray and yellowish gray

323-324 Clay, slightly to moderately indurated; medium gray

324-327 Sand, coarse, clayey, poorly sorted, subrounded; slightly indurated; light gray

327-331 Clay, sandy, micaceous in places; slightly to moderately indurated; pebbly at base

331-337 Clay, moderately indurated; light gray

337-347 Sand, medium and coarse, clayey, poorly sorted, subangular to subrounded; micaceous in places; moderately indurated; light yellowish orange and gray

347-349 Sand, very coarse and coarse, moderately sorted, subrounded; slightly indurated; clayey and darker at base; light yellowish gray

349-354 Missing core

354-357 Sand, coarse, moderately sorted, subangular; heavy minerals common in places; trace lignite; slightly indurated; light yellowish gray

357-358 Missing core

358-360 Sand, very coarse, slightly pebbly, moderately sorted, subangular; slightly lignitic at base; slightly indurated; light gray

Lang Syne Formation

360-364 Clay; moderately indurated; medium gray

Fourmile Formation

The type section of the Fourmile Formation, composed of quartz sand with some interbedded clays, is described below from core for well MWD-3A in northwestern Barnwell County, South Carolina, near the Aiken County line, southeast of Tinker Creek and west of Mill Creek. Savannah River Site coordinates are north 69839 and east 75756, or approximately 33^{o}18'9"N and 81^{o}36'23"W. The ground elevation is 328 ft above mean sea level. Fourmile Branch is a Savannah River tributary which rises in the center of SRS. In June of 1992, the core was located at the University of South Carolina at Aiken.

Feet below ground surface

Congaree Formation

252-256 Sand, very coarse, slightly pebbly, moderately sorted, subrounded; slightly indurated; orange

Fourmile Formation

256-257 Sand, fine, moderately sorted, subangular; fissile; burrowed; lignitic; green and gray clay laminae

257-258 Sand, medium, poorly sorted, subangular; trace iron sulfides and glauconite; light gray

258-259 Sand, very fine, well sorted, subangular; tan clay laminae; somewhat micaceous; slightly indurated; medium gray

259-260 Clay, silty, slightly to moderately indurated; somewhat micaceous; dark gray

260-261 Missing core

261-265 Sand, very coarse, moderately sorted, subrounded; slightly indurated; tan and orange

265-271 Sand, fine poorly and moderately sorted, clayey in places, subangular; green and gray clay laminae; somewhat micaceous; common heavy minerals in places; some glauconite grains and trace iron sulfide; slightly indurated; green and gray

271-278 Sand, coarse and very coarse, poorly sorted, somewhat pebbly, clayey in places, subrounded; greenish gray clay laminae; sulfides and glauconite becoming more abundant toward base; cemented sands and pebbles at base; grayish green

Lang Syne Formation

278-284 Clay and silty clay, micaceous; lignitic in places; moderately indurated; fissile; dark gray

Tinker Creek Formation

The Tinker Creek consists of quartz sands, silts and clays, which, in general, occur updip from the Santee. The type section is described below from core well MWD-5A in northwestern Barnwell County, South Carolina, near the Aiken County line, southeast of Tinker Creek and west of Mill Creek. Savannah River Site coordinates are north 69235 and east 75491, or approximately 33 °18'7"N and 81°36'10"W. The ground elevation is 322 ft above mean sea level. In June of 1992, the core was located at the University of South Carolina at Aiken.

Feet below ground surface

Irwinton Member of Dry Branch Formation

154-158 Sand, medium to coarse, moderately sorted, subrounded; slightly indurated; tan, yellow, orange, white with black oxide stains

Tinker Creek Formation

158-158.5 Sand, fine, clayey, poorly sorted, subangular; slightly indurated; yellowish tan

158.5-159 Interbedded medium sand and clay with lignitic (?) laminae; slightly indurated; dark tan

159-160 Sand, fine to medium, well sorted, subangular; slightly indurated; tan

160-162 Sand, fine to medium, subangular, slightly clayey and with a few clay laminae, moderately to well sorted; slightly indurated; light green and brown

162-165 Sand, fine to medium, moderately and well sorted, subangular; slightly indurated; heavy minerals common; yellow

165-166 Missing core

166-170 Sand, very fine, well sorted, subangular; heavy minerals common; slightly indurated; yellow

170-172 Sand, very fine, well sorted, subangular; slightly clayey and with light green clay laminae; slightly indurated; yellow, orange

172-174 Sand, very fine, subangular; nodules of cemented sand; moderately indurated; yello

174-180 Sand, very fine, slightly clayey, moderately sorted, subangular; heavy minerals common; slightly indurated; yellow, orange

180-181 Missing core

181-185 Sand, very fine and fine, moderately to well sorted; subangular; slightly clayey and with white clay laminae; heavy minerals common; yellow orange

185-187 Sand, fine, moderately sorted, subangular; many green clay laminae; slightly indurated; orange

187-187.5 Clay with fine sand laminae; slightly indurated; yellow and green

187.5-188 Sand, coarse, very clayey, silty, very poorly sorted; slightly indurated; brown

188-190 Clay, green, with many laminae and thin beds of yellow, fine to coarse sand; slightly indurated

190-190.5 Sand, very fine, slightly clayey; slightly indurated yellow

190.5 – 191 Missing core

Warley Hill Formation

191-192 Sand, medium, poorly sorted, subangular, clayey and with green clay laminae; slightly indurated; trace glauconite; orange

192-193 Sand, medium and coarse, slightly clayey, poorly sorted, subangular; slightly indurated; orange

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STRATIGRAPHIC RELATIONSHIPS IN EOCENE OUTCROPS ALONG UPPER THREE RUNS AT THE SAVANNAH RIVER SITE

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Upper Three Runs, which flows southwest along strike of the sedimentary strata toward the Savannah River, is the major stream draining the Savannah River Site (SRS). Relief is relatively low on its northwestern side but is up to about 200 ft on the southeast, perhaps because of migration of the stream down the regional dip (Siple, 1967, p. 14). Eocene sediments are exposed along northwesterly-flowing tributaries to Upper Three Runs, in bluffs along Upper Three Runs, and along the railroad paralleling the stream near F area and C road (Figure 1). Sloan (1908) described sections along Tinker Creek, a tributary to Upper Three Runs north of the area studied in this report, and Siple (1967) mentioned outcrops along Tinker Creek and Upper Three Runs. Exposures in the area have been discussed recently by Dennehy and others (1989), Nystrom (1989), Nystrom and others (1989, 1990, 1991), and Nystrom and Dockery (1992).

The sections described in this report are exposed at Upper Three Runs Bluff, located about 2100 ft south of the railroad bridge over Upper Three Runs and about 50 ft east of the stream; in several outcrops along Waterfall Creek, a tributary which flows into Upper Three Runs about 1500 ft south of the bridge and extends upstream almost to F area; in several outcrops along Copperhead Creek, a tributary which passes under the railroad about 1800 ft northeast of the bridge; and in the railroad cut about 2500 ft northeast of the bridge (Figure 1). Thicknesses and elevations of the strata were estimated by Jacob staff and hand level, measuring from Upper Three Runs and the railroad. Composite sections were constructed along the two streams. The sections described in this report include the Congaree and Warley Hill formations, the Santee Limestone and equivalent siliciclastics, and the Dry Branch Formation, all of Eocene age, and Quaternary (?) colluvial and fluvial deposits (Figure 2).

The Congaree is exposed at one place along the lower part of Waterfall Creek where about 5 ft of orange, moderately to well-sorted, fine to medium sand can be seen. The thickness of the formation could not be determined. The Congaree is early (to middle?) Eocene and a correlative of the Tallahatta of the Gulf Coastal Plain.

The Warley Hill, a middle Eocene lower Lisbon correlative, is exposed at Upper Three Runs Bluff, Waterfall Creek, and Copperhead Creek. It consists of orange, poorly sorted, clayey and silty, medium to coarse sand with grayish clay laminae overlain by dark green glauconitic clay and clayey sand with very coarse sand, granules, and pebbles. The upper clay unit is a little less than 2 ft thick. The thickness of the formation is estimated to be about 15 ft.

The outcropping Santee Limestone (part of the "McBean Formation" of other workers), a middle Eocene upper Lisbon equivalent (and perhaps younger), occurs as a silicified facies containing shell fragments and external and internal molds of pelecypods and gastropods with Turritella being especially common. A layer about 1.5 ft thick holds up a waterfall about 2.5 ft high on Waterfall Creek and loose blocks of the facies are common in the railroad cut. Fragments of silicified limestone are also common in the strea bed above the waterfall.

The Santee-equivalent siliciclastics (part of the "McBean" of other workers) are interbedded with the silicified carbonate facies and consist mostly of fine and very fine, light gray, yellow, and orange well sorted sand with green, white, gray, yellow, and tan laminae and beds common in places. *Ophiomorpha* – type burrows approximately 0.5 inches to 1 inch in diameter, mostly vertically oriented and lined with white clay, are abundant at some outcrops. Silicified internal molds of Turritella are abundant, especially in one exposure in Copperhead Creek. Prominent in the lower part of the unit is a green glauconitic clay or very clayey sand about 2 ft thick. The clay can be distinguished from the dark green clayey bed of the underlying Warley Hill by a paucity of coarse sand, granules, and pebbles abundant in the older unit. In placed the two green clays are in sharp contact,

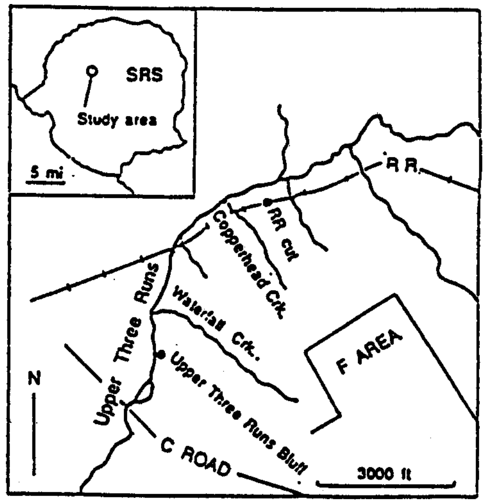

Figure 1. Location map.

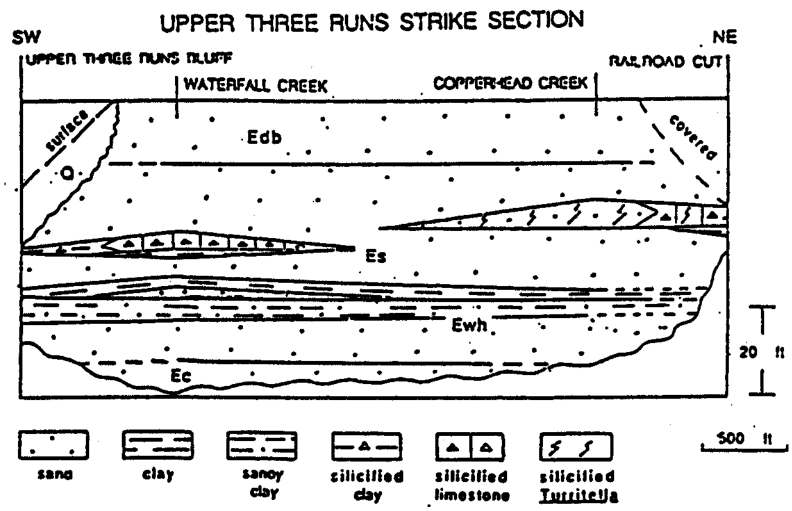

Figure 2. Cross-section along strike. EC=Congaree; Ewh=Warley Hill; Es=Santee and equivalent siliciclastics; Edb=Dry Branch. Upper Three Runs Bluff and the two creek sections are hung on top of Warley Hill. Railroad section is hung on base of silicified zone. The two creek sections are composites. Vertical exaggeration = 25x.

and in other places they are separated by a layer of fine, well-sorted, light gray to white sand up to 4 ft thick. Small shark teeth occur in both clays. The two clay layers are part of the "green clay interval" at SRS described by Root in internal SRS documents and discussed by Dennehy and others (1989) and Snipes and others (1992). A tan clay higher in the section at Upper Three Runs Bluff has been silicified. The upper part of the Santee and correlative siliciclastics may include sediments equivalent to the Gosport Formation of the Gulf Coast (Veatch and Stephenson, 1911; Toulmin, 1977; Nystrom and others, 1990, 1991; Nystrom and Dockery, 1992). The thickness of the Santee and correlative siliciclastics is approximately 35 ft.

Each of the sections contains a bed in the Santee interval which is at least partially silicified. The silicified facies was judged not to be a single key bed because it is not parallel with the Warley Hill-Santee and the Santee-Dry Branch contacts (Figure 2).

The upper Eocene Dry Branch Formation, a correlative of the Gulf Coastal Plain, is composed of yellow and orange, fine to coarse, moderately to well-sorted sand with abundant tan and yellow clay layers. Its thickness could not be determined.

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AN INITIAL GEOCHEMICAL AND ISOTOPIC STUDY OF GRANITE FROM CORE C-10, SAVANNAH RIVER SITE, SOUTH CAROLINA

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INTRODUCTION

The Savannah River Site is approximately 30 kilometers south of the Fall Line, which is the boundary between crystalline rocks of the Piedmont and the relatively unconsolidated sediments of the Atlantic Coastal Plain. Depth to crystalline basement in this area is approximately 0.5 kilometers. This brief note reports on the petrography, geochemistry, and possible age of a granite collected from a core as part of a study of the geology of the Site. The core site (C-10) is located at 33^{o}01'30"N and 81^{o}23'04"W. The granite sample utilized in this study was collected from a depth of 528.5 meters (1,734 feet) below the top of the drill hole. The granite will be called the "C-10" granite for the purposes of this paper.

PETROGRAPHY

The granite sampled in the core is coarse-grained (5-10 mm) and equigranular with a pinkish, medium-gray color. Laths of potassium feldspar and plagioclase have noticeable alignment suggesting a weak foliation. The medium-gray color of the granite is due to the dark gray color of quartz rather than the presence of mafic minerals. The modal composition of the sample (Table 1) indicates a leucogranite composition. Chlorite, which is the only significant mafic phase in the granite, appears to have formed by replacement of biotite. Apatite, sphene, and zircon are minor accessory phases.

Most of the quartz within the granite is composed of aggregated subgrains that have highly sutured contacts. Potassium feldspar is composed of vein-type perthite and some microcline. Locally, plagioclase is present as grains within the perthite and approximately 15 percent of the potassium feldspar grains have a Rapakivi texture formed by 0.1-1.0 millimeters rims of plagioclase. Plagioclase within the granite is extensively altered to grains that contain very fine aggregates of epidote and white mica. The altered nature of the minerals in the granite, plus the weak foliation suggests the granite has undergone greenschist facies metamorphic conditions.

GEOCHEMISTRY

The major and trace element chemistry of the C-10 granite is presented in Table 1. The chemical composition is typical of a calcalkaline granite; the sample is moderately peraluminous, with 0.99 weight percent normative corundum.

The granite is enriched in the light rare earth elements, with the concentration of the heavy rare earths having a

Table 1. Chemical and mineralogical composition of core sample C-10-1734

Major Elements (Wt. Percent)

SiO_2	$A1_2O_3$	CaO	MgO	Na_2O	K_2O	FeO	MnO	TiO_2	P_2O_5	LOI	Sum
72.9	14.0	0.79	0.46	4.22	4.62	1.84	0.05	0.32	0.08	0.85	100.1

Trace Elements (ppm)

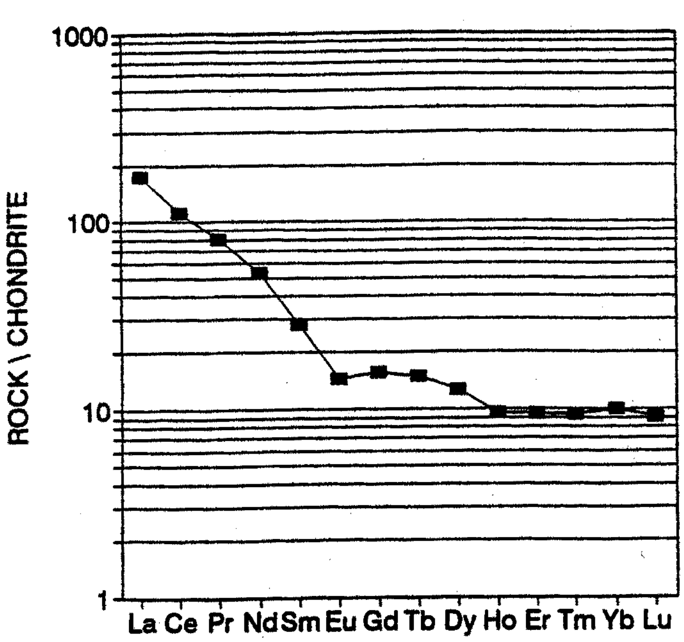
La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
102	34	9.8	34	5.5	1.06	4.1	0.7	3.8	0.75	1.9	0.3	2.2	0.31

Cr	Rb	Sr	Y	Zr	Nb	Ba	U	Th
24	166	150	24	246	23	623	3	16

Modal Composition (Volume Percent)

Quartz	Plagioclase	K-Feldspar	Chlorite	Epidote	Opaques
31.8	30.9	34.2	2.4	0.3	0.5

Major elements and selected trace elements analyzed by XRF;REE, U, and Th analyzed by ICPMS.



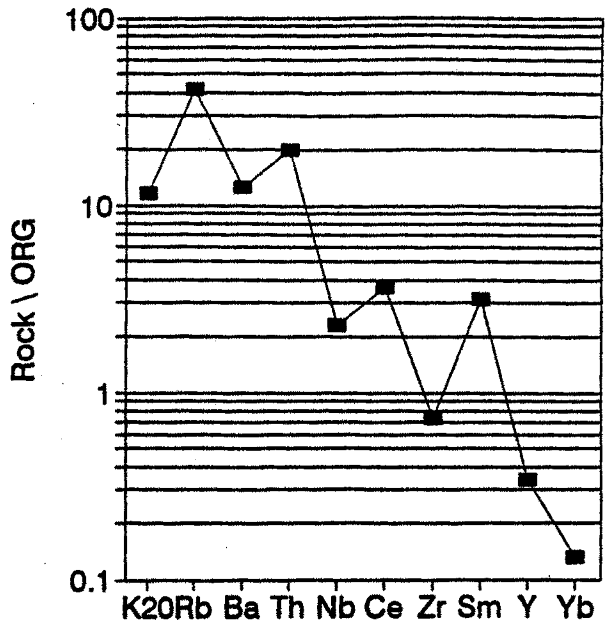


Figure 1a. Rare earth chondrite normalized plot for C-10 granite. Chondrite normalization values from Henderson, 1984 (Table 1.5, Column 1).
Figure 1b. Ocean ridge granite (ORG) normalized geochemical plot for the C-10 granite. Modified from Pearce and others, 1984. The elements Ta and Hf have been omitted from the plot.

nearly constant 10x enrichment relative to a chondritic average (Fig. 1a).

Trace element discrimination diagrams for granites (Pearce and others, 1984) can be utilized to evaluate the possible tectonic setting associated with granite formation. Utilizing these diagrams (e.g. Fig. 1b) the C-10 granite would be best characterized as a volcanic arc granite, however these diagrams are not unambiguous. For instance, post-collisional granites can have trace element signatures similar to volcanic arc granites.

GEOCHRONOLOGY

In order to place some limits on the age of the C-10 granite, Rb-Sr isotopic analyses were performed on whole-rock and potassium feldspar (Table 2). Both biotite (mostly chloritized) and plagioclase proved unsuitable for dating due to the highly altered nature of these minerals.

A date obtained from a whole-rock and potassium feldspar pair yields a value of 220$\pm$4 Ma (2 sigma). Because the granite appears to have been metamorphosed and altered, this age does not represent the time crystallization. Based upon K-Ar and Rb-Sr dating studies of K-feldspar elsewhere in the Appalachians, this age may represent the time when the rock cooled to temperatures below $100^{o} - 150\,^{o}C$. This condition could be associated with extensive erosion that took place following the end of Paleozoic orogenic activity.

A whole-rock model age may be calculated for the sample. For such a calculation an assumed initial $^{87}Sr/^{86}Sr$ value is used. For granitic rocks of the Piedmont (Fullagar, 1971; Fullagar and Butler, 1979; Kish, 1983) the most common range in $^{87}Sr/^{86}Sr$ initial ratio is 0.7040 to 0.7150. If the upper value (0.7150) is used in the age calculation a model age of 440 Ma is obtained; using the lower $^{87}Sr/^{86}Sr$ initial ratio the model age is 550 Ma. Since most granites in the Piedmont have relatively lo $^{87}Sr/^{86}Sr$ initial ratios, the older age (~550 Ma) is preferred as an estimate for the age of crystallization.

Table 2. Rb-Sr isotopic data for core sample C-10-1734.

	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Whole-rock	165.7	150.0	3.206	0.73826
K-Feldspar	353.0	161.0	6.374	0.75474

DISCUSSION

The C-10 drill site is in close proximity to the late Precambrian-Cambrian volcanic and plutonic terrane of the Carolina slate belt. Given the chemistry, probable age, and the metamorphosed nature of the C-10 granite, it is probable that the granite is a part of this terrane. Late Precambrian to Cambrian volcanic and plutonic rocks are also present in the Suwannee terrane, located across a major magnetic anomaly south of the Savannah River Site (Horton and others, 1984; Kish, 1992), however, these rocks are unmetamorphosed and overlain by undeformed early Paleozoic sedimentary rocks.

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PETROLOGY AND RESERVOIR CHARACTERISTICS OF MIDDLE AND LATE EOCENE CARBONATE STRATA IN DOWNDIP WELLS AT THE SAVANNAH RIVER SITE, SOUTH CAROLINA

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INTRODUCTION

Carbonate strata of middle and late Eocene age were continuously cored in two downdip wells at the Savannah River Site (SRS) (Fig, 1). Petrographic study of the core was done to: 1) delineate lithofacies, 2) assess the effects of diagenesis on pore system evolution, and 3) determine depositional environments.

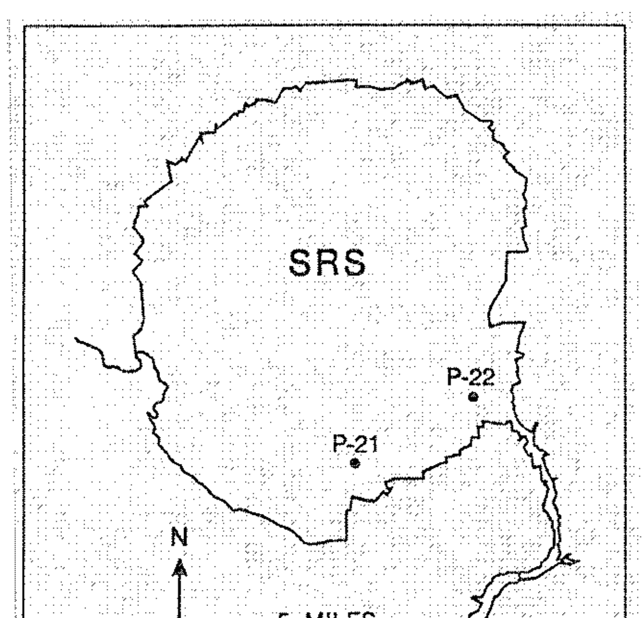

Figure 1. Location of wells used in this study.

Figures 2 and 3 are graphic logs showing the stratigraphy, lithology, fossils, and grain-size parameters of insoluble residues from carbonate intervals in SRS wells P-21TA and P-22TA. Figure 4 explains the symbols used in the graphic logs. Our stratigraphic terminology is modified slightly from Fallaw and others (1992). Stratigraphic relationships of Eocene carbonate strata in this region have been reviewed by Powell (1984), Huddlestun and Hetrick (1985), Prowell and others (1985), Gohn (1988), Nystrom and others (1991), Fallaw and others (1992), and Harris and Zullo (1992). Papers concerned with petrology of Eocene carbonate strata in this area include Powell and Baum (1981), Powell (1984), Thayer and Miller (1988), and Thayer and others (1988).

SANTEE LIMESTONE

The Santee Limestone unconformably overlies the Congaree Formation (Figs. 2 and 3). The basal contact occurs in an interval of missing core in well P-22. In P-21, the lower contact is marked by a phosphatic crust; the underlying Congaree sand is calcareous and contains thin silcrete layers. The top of the Santee is an unconformity, which Harris and Zullo (1992) identified as the 40 Ma type 1 boundary. Harris and Zullo (1992) assigned the Santee to the upper middle Eocene TA3.5/3.6 cycle and suggested that the lower part of the unit represented a transgressive systems tract and the upper part a highstand systems tract.

The Santee is usually moderately to well indurated, but is friable in sandy and muddy parts of both wells. Colors are yellowish-gray and light and very light gray, except in the upper third where grayish-green and greenish-gray predominate. Weight percent carbonate ranges from 14.7 to 97.7% ($\bar{x}$ = 64.2%, s = 24.1%) and is higher in P-22 ($\bar{x}$ = 70.2%, s = 19.5%) than in P-21 ($\bar{x}$ = 57.3%, s = 27.1%). Carbonate content decreases upward in P-21 with a concomitant increase in percent terrigenous mud (Fig. 2), whereas, P-22 shows no systematic trend (Fig. 3). Weight percent terrigenous mud (silt plus clay) averages 22.4% and is much higher in P-21 ($\bar{x}$ = 35.5%, s = 26.8%) than in P-22 ($\bar{x}$ = 10.2%, s = 6.2%). In fact, the Santee becomes a calcareous mud above 187 ft in P-21 (Fig. 2). Subangular quartz sand averages 13.6 weight percent and is more abundant in P-22 ($\bar{x}$ = 19.7%, s = 17%) than in P-21 ($\bar{x}$ = 7.1%, s = 10.1%).

Mean size of terrigenous quartz is lower fine sand in P-21 ($\bar{x}$ = 2.91ϕ, s = 0.73ϕ) and upper fine sand in P-22 ($\bar{x}$ = 2.18ϕ, s = 0.22ϕ). Maximum quartz size greatest near the base of the Santee and attains lower pebble size (-2.39ϕ) directly above the unconformity in P-21. Overall, quartz

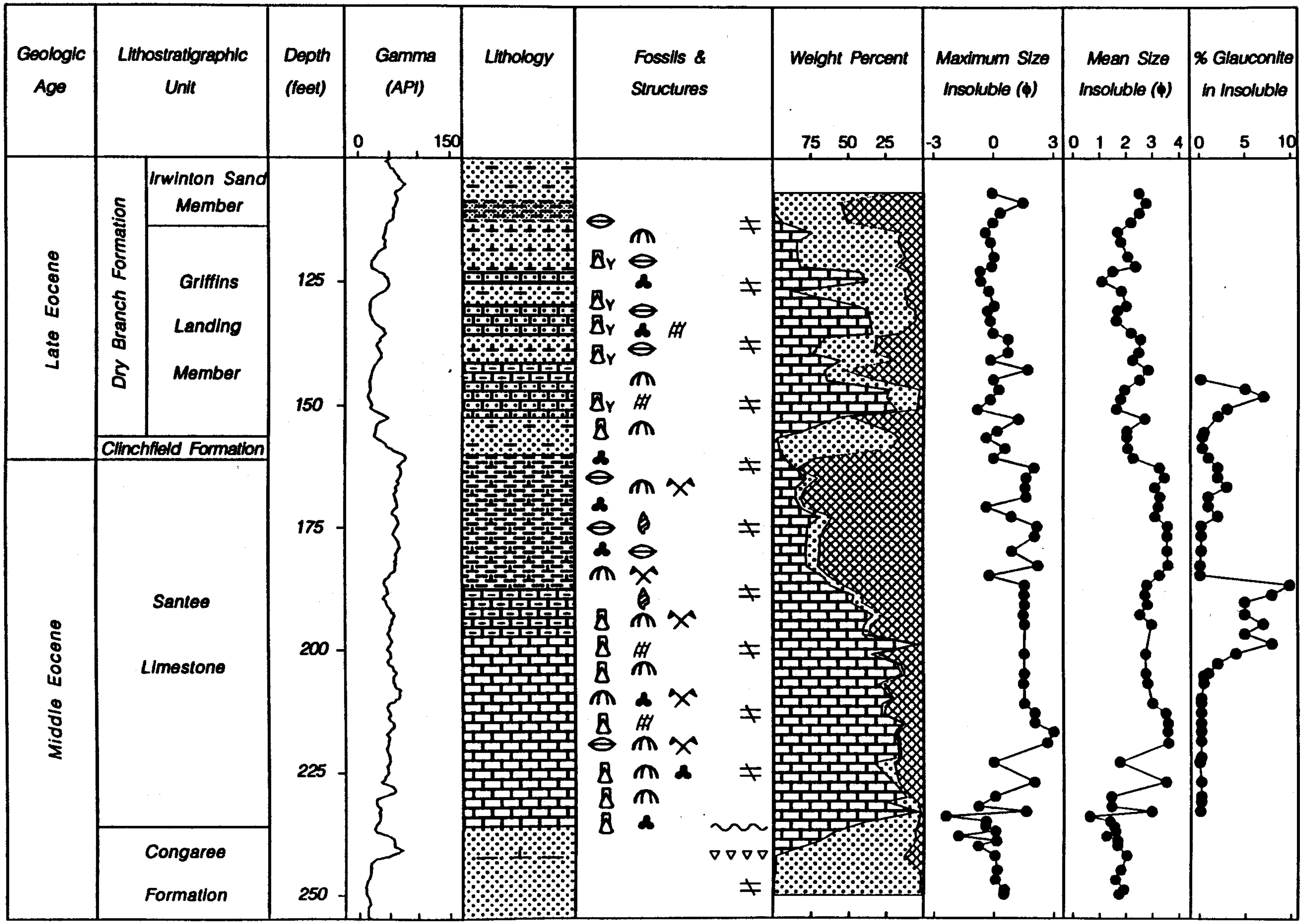

Figure 2. Stratigraphic sequence, lithologic characteristics, and gamma ray log for P-21TA well, Savannah River Site, South Carolina.

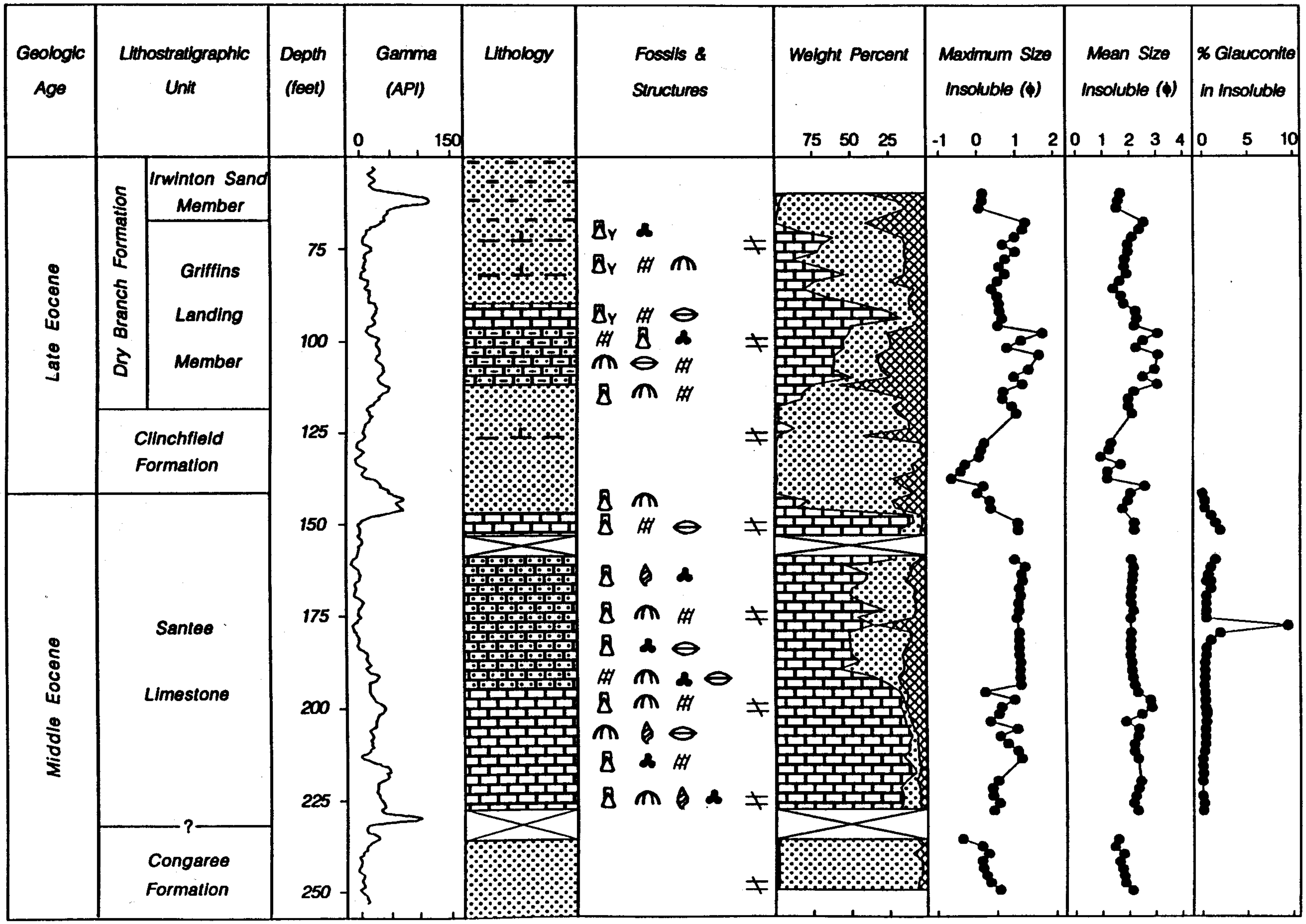

Figure 3. Stratigraphic sequence, lithologic characteristics, and gamma ray log for P-22TA well, Savannah River Site, South Carolina.

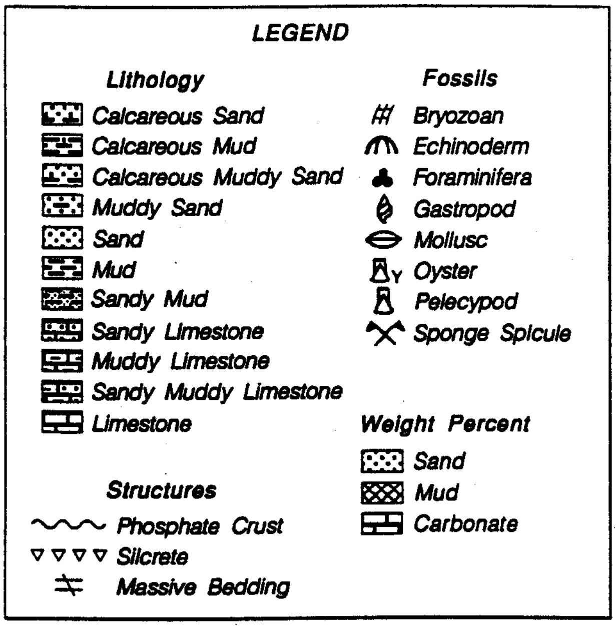

Figure 4. Symbols used in graphic logs.

maximum size averages lower coarse sand ($\bar{x}$ = 0.89ϕ, s = 0.22ϕ) in P-22 and upper medium sand ($\bar{x}$ = 1.26ϕ, s = 1.13ϕ) in P-21. Sorting of the terrigenous and fraction is moderate, and is slightly better in P-22 ($\bar{x}$ = 0.56ϕ, s = 0.19ϕ) than in P-21 ($\bar{x}$ = 0.64ϕ, s = 0.25ϕ).

Principal lithofacies of the Santee Limestone in downdip SRS wells include calcareous mud, calcareous quartz sand, skeletal wackestone-packstone, and quartz-rich skeletal grainstone. Non-carbonate grains common to all lithologies include quartz, feldspar, heavy minerals, muscovite, collophane, and glauconite (Fig, 2 and 3). Detrital heavy minerals are ubiquitous and include garnet, brown tourmaline, rutile, zircon, sillimanite, staurolite, kyanite, monazite, ilmenite, and magnetite.

Calcareous Mud

This lithofacies occurs only in P-21 where it is dominant above 187 ft (Fig. 2); it grades into muddy, skeletal wackestone below. The unit consists of terrigenous mud with subordinate skeletal allochems and minor, very fine, subangular quartz sand. Molluscs and foraminifers are the main allochems; most are sand size and abraded. Woody organic debris, diatom valves, sponge spicules, collophane, and muscovite are common, but form less than 1% of the total volume. Authigenic minerals include glauconite, pyrite, clinoptilolite, chalcedony, and opal-CT lepispheres. Porosity of this lithofacies is typically less than 5%. Pore types are chiefly moldic formed by dissolution of aragonitic molluscan shells and intraparticle in foraminifers. Permeability is very low because mesopores are isolated from each other by microporous mud.

Calcareous Quartz Sand

This lithfacies occurs at the base of the Santee in P-21 and at the top of the unit in P-22. It consists of friable, fine to medium quartz sand with subordinate echinoderm, molluscan, and foraminiferal allochems. Terrigenous mud matrix forms 5-15% of the total unit. Most of the echinoderm and molluscan fragments are broken and rounded, suggesting transport. Locally, aragonitic molluscan shells have been dissolved forming moldic pores. Rare sparry calcite cement forms syntaxial overgrowths on echinoderm fragments and partially fills moldic pores. Porosity in this lithofacies is 20-30% depending on the amount of mud matrix, and is mainly intergranular. Permeability is excellent because of the large pore throats connecting intergranular pores.

Skeletal Wackestone-Packstone

This is the dominant lithofacies in both wells and consists of molluscan-echinoderm wackestone interbedded with subordinate molluscan - echinoderm packstone. Micrite matrix forms 20-65% of whole-rock volume, and in places has aggraded to microspar. Terrigenous mud forms 5-49% and is most abundant in P-21. Fine and very fine quartz sand ranges from 1-35%, and is more common in P-22 than in P-21.

Skeletal allochems constitute 15-50 of whole-rock volume and consist of whole, broken, and abraded echinoderm and pelecypod fragments with subordinate bryozoans, foraminifers, gastropods, serpulid worm tubes, ostracodes, and comminuted skeletal debris. Most allochems are sand size, although gravel size pelecypods and bryozoans are dominant locally. Sponge spicules, diatom valves, collophane, woody organic debris, pyrite, clinoptilolite, and muscovite are common in P-21, but rare in P-22. Authigenic chalcedony is common in both wells and partly replaces calcitic molluscan allochems. Rare opal-CT lepispheres have grown within intraparticle and moldic pores. Glauconite, as discrete grains and fossil replacements, is common in both wells and is most abundant in the middle of the Santee, where there is a relatively high percentage mud (Figs. 2 and 3).

Porosity in this unit ranges from 3-25% and is chiefly mesomoldic and mesovug. Moldic pores formed by dissolution of aragonitic molluscan grains in the freshwater meteoric realm; hence, total porosity is controlled by the number and size of aragonitic allochems available for solution. In places, moldic pores have been reduced or closed by growth of sparry calcite cement. Enlargement of moldic pores by dissolution of surrounding allochems or micrite produced vugs. Other pore types include: intraparticle in foraminifers and bryozoans; channels formed by enlargement of molds and vugs; and intercrystal in spar-reduced molds. Permeability in this lithofacies is low because molds and vugs are isolated from each other by microporus micrite or microspar, which have small pore-throat diameters. Porosity and permeability values are significantly decreased where moldic and intraparticle pores have been reduced or closed by the growth of sparry calcite cement.

Quartz-Rich Molluscan Grainstone

This well-indurated lithofacies occurs principally in P-22 between 147-175 ft as thin beds intercalated with sandy, skeletal packstone. It consists of well-worn gravel and sand sized pelecypod and echinoderm fragments with subordinate foraminifers, bryozoans, and comminuted skeletal debris. Subangular quartz sand forms 5-40% of the unit and is lower medium to upper fine grained. Terrigenous mud comprises 2-10% of this lithofacies. Micrite, which forms less than 5% of the unit, occurs beneath pelecypod umbrellas and as geopetal infillings of pelecypod molds; most has aggraded to microspar. Accessory constituents include glauconite, collophane, carbonate intraclasts, feldspar, and heavy minerals. Sparry calcite cement occurs as syntaxial overgrowths on echinoderm fragments, and fills or partly fills intraparticle pores in foraminifers and bryozoans, as well as moldic pores formed by dissolution of aragonitic pelecypods.

Porosity averages 20.5% and is mesomoldic and mesovug formed by dissolution of aragonitic pelecypods. Minor secondary intergranular, intercrystalline, and channel pores also occur. Numerous molds have been reduced or filled by sparry calcite cement. Measured permeability (air) ranges from 1.4 to 6.1 Darcies and is high because many of the molds and vugs are connected as the result of close packing of original skeletal allochems.

Diagenesis

The major diagenetic events that have affected the Santee include: 1) marine phreatic – micritization of skeletal allochems, glauconitization, phosphatization, and rare fibrous calcite cementation within foraminifer tests: and 2) freshwater meteoric – neomorphism of micrite to microspar dissolution of aragonitic and opaline silica skeletal grains, precipitation of sparry calcite cement in primary and secondary pores, and syntaxial calcite overgrowths on echinoderm fragments. Opal-CT lepispheres and authigenic clinoptilolite crystals that line secondary moldic pores postdate the dissolution of aragonitic allochems. The primary source of silica was the dissolution of sponge spicules and diatoms valves.

Depositional Environment

The Santee contains a diverse fauna indicative of clear, open-marine shelf waters of normal salinity. The abundance of micrite and terrigenous mud suggests deposition below normal marine wave base. However, the presence of abraded molluscs, echinoderms, and bryozoans indicates that bottom transport by currents and storm-generated waves alternated with quiet-water conditions in which muds could accumulate. The abundance of terrigenous mud, woody organic debris, and muscovite in P-21 suggest a proximal riverine input. The increase in size and percentage of quartz sand in P-22 implies higher energy conditions, possibly a shoal environment.

GRIFFINS LANDING MEMBER

The Griffins Landing Member of the Dry Branch Formation unconformably overlies the Clinchfield Formation (Figs. 2 and 3) and has been correlated to the upper Eocene TA4.2 cycle (Harris and Zullo, 1992). The Griffins Landing sequence probably represents transgressive and highstand deposits (Harris and Zullo, 1992).

The Griffins Landing is friable to moderately indurated, although thin beds of well indurated carbonate occur in the basal 15 ft of P-21. Colors are variable, including tan, greenish-gray, grayish-green, and light gray. Weight percent carbonate averages 39.1% (s-21.2%; range = 2 to 83%) and is slightly higher in P-21 ($\bar{x}$ = 44.1%, s- 23.0%) than in P-22 ($\bar{x}$ = 35.3%, s = 19.2%). The unit is characterized by alternations of carbonate-rich beds with calcareous muds and muddy, calcareous sands (Figs. 2 and 3). The terrigenous fractions consists of fine, subangular quartz sand (x = 41.4%, s = 20.3%) with subordinate mud ($\bar{x}$ = 19.4%, s = 12.4%).

Mean size of the quartz fraction is upper fine sand ($\bar{x}$ = 2.09ϕ, s = 0.4ϕ), and ranges from upper very fine (3.05ϕ) to upper medium (1.08ϕ) grained. Generally, mean size is largest near the base and top of the unit. Maximum grain size ranges from upper very coarse (-0.82%ϕ to lower medium (1.70ϕ) sand, and closely follows the trend of mean size (Figs. 2 and 3). Sorting of the terrigenous sand fraction is moderate ($\bar{x}$ = 0.67ϕ, s = 0.12ϕ) in both wells.

The Griffins Landing includes four lithofacies: sandy, calcareous mud; muddy, calcareous quartz sand; muddy, quartz-rich packstone; and muddy, quartz-rich grainstone. Muscovite is common and is most abundant in fine grained, mud-rich units. Rare glauconite, pyrite, sponge spicules, and bluish-gray and pink quartz occur in all lithologies. The heavy mineral suite includes tourmaline, garnet, zircon, rutile, sphene, staurolite, kyanite, sillimanite, ilmenite, and magnetite. Opal-CT lepispheres line primary and secondary pores in all units, and fibrous chalcedony commonly replaces or partly replaces low-Mg calcite molluscs. Authigenic clinoptilolite occurs as 2-5um crystals that line primary and secondary pores.

Sandy Calcareous Mud

This minor lithofacies occurs near the base of the Griffins Landing in both wells. It consists of terrigenous sandy mud containing subordinate sand and gravel size fragments of oysters, other pelecypods, echinoderms, foraminifers, and comminuted skeletal grains. Abraded bioclastic grains fro 10-30% of whole rock volume. Porosity is usually less than 5% and is primarily intraparticle in foraminifers and mesomoldic formed by the dissolution of aragonitic pelecypods. Permeability is very low owing to high percentage of mud in this lithofacies.

Muddy, Calcareous Quartz Sand

This lithofacies is abundant in both wells and consists of subangular, fine quartz sand containing 10 to 40% skeletal allochems set in a terrigenous mud and micrite matrix that ranges from 10-30% of whole rock volume. The unit grades into muddy, quartz-rich packstone and grainstone. Allochems are gravel and sand sized fragments of oysters, other pelecypods, echinoderms, foraminifers, bryozoans, barnacles, sponge spicules, diatoms, ostracodes, and gastropods. Most of the mollusc and echinoderm fragments are abraded. Sparry calcite cement forms 2-5% and occurs mainly as syntaxial overgrowths on echinoderm fragments; it also partly fills interparticle and moldic pores. Porosity ranges from 3-10% and is mostly interparticle and moldic. Permeability is low because terrigenous mud and micrite occlude pores and pore throats.

Muddy, Quartz Rich Packston

This lithofacies, which occurs in both wells, consists of skeletal packstone containing 10-30% fine quartz sand and 5-15% terrigenous mud matrix. Gravel and sand sized oysters, echinoderms, other pelecypods, and bryozoans are the main allochems; most are abraded. Also present are foraminifers, gastropods, serpulid worm tubes, sponge spicules, barnacles, ostracodes, and finely comminuted shell debris. Micrite forms 10-30% of whole rock volume and is locally pelleted. Other constituents include glauconite, collophane, muscovite, carbonate intraclasts, heavy minerals, and woody organic debris. Sparry calcite forms overgrowths on echinoderm fragments and partly lines moldic and intraforam pores. Porosity ranges form 5-22% and is moldic and intergranular with minor vug and intraparticle in foraminifers and bryozoans. Permeability is low because pores are isolated from each other bymicrite or terrigenous mud.

Muddy, Quartz Rich Grainstone

This minor lithofacies occurs as thin beds intercalated with quartz rich packstone and calcareous quartz sand. It consists of abraded gravel and sand size skeletal fragments mixed with subordinate fine quartz sand and minor terrigenous mud. Skeletal fragments include oysters, other pelecypods, echinoderms, bryozoans, barnacles, and foraminifers. Minor sparry calcite occurs as overgrowths on echinoderm fragments and partly fills intraparticle pores in foraminifers and bryozoans. Porosity of this lithofacies averages 21% and is mainly intergranular. Permeability is high because of the large number of well connected interparticle pores.

Diagenesis

Diagenetic events in the Griffins Landing Member include: 1) marine phreatic – micritization of skeletal allochems and minor glauconitization; and 2) freshwater meteoric dissolution of opaline silica and aragonitic skeletal grains, along with sparry calcite cementation in primary and secondary pores and as overgrowths on echinoderm fragments. Opal-CT lepispheres and authigenic clinoptilolite crystals that line the margins of secondary moldic pores indicate that they formed after dissolution of aragonitic allochems. The dissolution of sponge spicules and diatoms is the likely source of silica for formation of opal-CT lepispheres and chalcedony replacements of molluscan shells.

Depositional Environment

Huddlestun and Hetrick (1986) proposed a marginal marine, coastal environment for the Griffins Landing Member. The abundance of terrigenous quartz and mud suggests a nearby source terrane, as does the presence of woody organic debris. Faunal elements in this unit indicate relatively clear marine waters of normal salinity. The presence of abraded gravel and sand sized skeletal allochems suggest that high energy conditions alternated with quiet water deposition in which muds accumulated.

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THE MCBEAN FORMATION AND ORANGEBURG DISTRICT BED — COOK MOUNTAIN AND GOSPORT EQUIVALENTS (MIDDLE EOCENE) IN THE COASTAL PLAIN OF SOUTH CAROLINA

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INTRODUCTION

The Orangebury District bed is an informal stratigraphic unit introduced by Dockery and Nystrom (1990, 1992) for fossiliferous sands at Orangeburg, South Carolina, that have a diverse silicified fauna. This bed disconformably overlies carbonates of the McBean Formation and underlies nonfossiliferous sands of the Jackson Group. Silicified fossil invertebrates of the Orangebury District bed are diverse and occur in thin concentrations at diastems and lenses. The molluscan fauna includes 169 species and subspecies. A little more than a third of these species are known only from Orangeburg; a little less than a third occur in both the Cook Mountain Formation and Gosport Sand of the Gulf Coastal Plain; and the remainder occur in either Cook Mountain or older units or the Gosport or younger units. Notably absent from this fauna are two Cook Mountain guide fossils, the bivalve *Cubitostrea sellaeformis* and *Pteropsella lapidosa*. The later species occurs as internal molds in McBean carbonates underlying the Orangeburg District bed at Orangeburg, and the former occurs in the McBean at nearby localities. Notably present in this fauna is the common occurrence of a Gosport guide fossil, the bivalve *Glyptoactis* (*Claibornicardia*) *alticostata*. Based on the absence and presence of these species, the mollusks indicate the Orangeburg District bed to be of Gosport age.

RECOGNITION OF GOSPORT EQUIVALENT UNITS IN THE ATLANTIC COASTAL PLAIN

Gosport age units have been recognized in the Santee Limestone of South Carolina's lower coastal plain by Ward et al. (1979) and in the Castle Hayne Limestone of North Carolina's coastal plain by Zullo and Harris (1987). Ward et al. (1979) proposed the Martin Marietta Company Berkeley Quarry as the neostratotype of the Santee Limestone. Here they named two members, the Moultrie and Cross. The Moultrie is a moldic biosparite with abundant shells of Cubitostrea sellaeformis. This unit was correlated with the middle Claiborne Lisbon Formation of Alabama. Disconformably overlying it are the bryozoan-brachiopod-bivalve biomicrites of the Cross Member. This member contains molds of a Gosport guide fossil, the bivalve *Crassatella alta*, and was assigned a Gosport age. Ward et al. (1979) gave measured sections of the Cross Member at its type locality and at the Martin Marietta Company Georgetown Quarry and the Giant Portland Cement Company Quarry. Ward (personal communication)later found that the Cross type section contained *Cubitostrea sellaeformis* and decided that Giant Quarry would have been the better stratotype for the unit the authors originally had in mind. At the Giant Quarry, Gosport-age mollusks are present in an interval that lacks *Cubitostrea sellaeformis*. Thus, the Giant Quarry has an unnamed carbonate sequence of Geosport age, while the type Cross is in the *Cubitostrea sellaeformis* zone of Cook Mountain age (Ward, personal communication).

Zullo and Harris (1987) recognized four depositional sequences within the Castle Hayne Limestone. Sequence 3 is equivalent to the Comfort Member of Ward et at. (1978) and was correlated with the Cross Member of South Carolina and the Gosport Sand and lower Moodys Branch Formation of Alabama. The correlation with the lower Moodys Branch Formation was based on the occurrence of *Periarchus lyelli*. Another name for the "lower Moodys Branch Formation" is the *Scutella* (=*Periarchus*) bed, a unit that separates the Gosport Sand and calcareous "upper Moodys Branch Formation" in southern Alabama. This unit is characterized by an abundance of the flat echinoid *Periarchus lyelli*, a fossil incorrectly considered by some as a guide to the Moodys Branch Formation. Complete specimens of *P. lyelli* occur in the Gosport Sand at the classic Little Stave Creek locality in Alabama. Zullo and Harris (1987) dismissed earlier published accounts of this echinoid in the Gosport Sand and considered the *Scutella* bed to be of Moodys Branch age. One occurrence they dismissed was a citation by Cooke (1959, p. 42 pl. 14, fig. 1-3) of *P. lyelli* from the Gosport Sand at Gopher Hill on the Tombigbee River in Washington County, Alabama. At this locality (as observed by L.W. Ward and Dockery), the *Scutella* bed contains a typical Gosport molluscan fauna and is considered here to be a facies of the Gosport Formation. Therefore, Sequence 3 of Zullo and Harris (1987) is of Gosport age only.

Dockery and Nystrom (1990, 1992) first recognized a Gosport age fauna in the upper coastal plain of South Carolina in what had classically been called the McBean Formation. A construction site at Orangeburg showed a two-part division of the McBean consisting of an upper clastic sequence with a diverse silicified fauna containing *Glyptoactis* (*Claibornicardia*) *alticostata* and a lower carbonate sequence containing *Pteropsella lapidosa*. The upper unit was informally named the Orangeburg District bed and assigned a Gosport age, and the lower unit was considered to be the typical McBean Formation and assigned a Cook Mountain age. A similar division of the "McBean Formation" was noted by J. Hazel (personal communication), who examined ostracods from test hole samples at the Savannah River Site. Also, D. Campbell (1992) made an independent collection and study of the Orangeburg District bed's molluscan fauna and assigned it a Gosport age.

CORRELATION PROBLEMS ACROSS FAU NAL PROVINCES

Cubitostrea sellaeformis serves as a guide fossil to sediments of Cook Mountain age across the Gulf and Atlantic coastal plains from Texas to Virginia. Overlying this zone and underlying sediments of Jacksonian age in Alabama is the Gosport Sand and its characteristic molluscan fauna including *Glyptoactis* (*Claibornicardia*) *alticostata* and *Crassatella alta*. These faunal divisions hold true in the McBean Formation and Orangeburg District bed of South Carolina's upper coastal plain and are considered to be good middle Eocene zonations for the mixed clastic and carbonate, nearshore, shelf sediments of the northern Gulf and southern Atlantic coastal plains. Dockery (1985, 1988) included these faunas in his "Northern Gulf Province" as he found many Eocene molluscan species in common between coastal states from Texas to South Carolina.

A distinct Eocene molluscan fauna with Tethyan elements such as the gastropods *Velates* and *Gisortia* occurs in peninsular Florida. This fauna, the Florida Province (Dockery 1985, 1988), lived in a tropical carbonate environment similar to that of the Santee Limestone and was separated from the Northern Gulf Province by the Gulf Trough and ancient Gulf Stream. Though the molluscan faunas of the Santee and Castle Hayne limestones of South and North Carolina are poorly known, it is probable that they are a northerly extension of the Florida Province and were within the Gulf Stream's course.

Correlation problems exist between the faunal zones of the Northern Gulf and extended Florida provinces. In the Santee Limestone of the Martin Marietta Company Berkeley Quarry, *Cubitostrea sellaeformis*, *Glyptoactis* (*Claibornicardia*) *alticostata*, and *Crassatella alta* occur together in the same rock. Here either the Cook Mountain guide fossil *C. sellaeformis* has a higher last appearance datum (LAD) or the Gosport guide fossils *G.* (*C.*) *alticostata* and *C. alta* have a lower first appearance datum (FAD). Dockery and Nystrom (1992) argued that the latter was true and that the two Gosport guide fossils have a stepwise diachronous FAD from the Santee to the Orangeburg District bed. *G.* (*C.*) *alticostata* and *C. alta* occur above the *C. sellaeformis* LAD in the nearby Giant Portland Cement Company Quarry (L. W. Ward, personal communication) as is the case in the northern Gulf.

It is likely that many Gosport taxa originated in tropical environments associated with the Florida Province and did not migrate across the Gulf Trough into the Northern Gulf until after the extinction or at least the decline of *C. sellaeformis*. Larvae of these species readily colonized the tropical carbonate environments beneath the Gulf Stream along what is now the South and North Carolina coastline. Migration into the Northern Gulf Province probably corresponded with a sea level rise during the late Claibornian sequence event TE3.1 of Mancini and Tew (1991) and came during a war climatic period in the Gulf.

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NANNOFOSSIL BIOSTRATIGRAPHY AND SEQUENCE STRATIGRAPHY OF MIDDLE TO UPPER EOCENE STRATA IN THE SOUTHWESTERN SAVANNAH RIVER SITE AND ADJACENT AREAS OF GEORGIA

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INTRODUCTION

Core VSC-4 (Figure 1, 2) contains a relatively complete middle to upper Eocene stratigraphic section typical of the southwestern Savannah River Site and adjacent areas of Georgia. The core is at an elevation of 156.7 feet; and penetrates a Cenozoic section of almost 500 feet; the Cretaceous Tertiary boundary is placed at a depth of 494.6 feet. Paleogene stratigraphic units recognized in the core include the Paleocene Ellenton Formation, an upper Paleocene/lower Eocene? Un-named unit, the middle Eocene Congaree Formation, Warley Hill (?) Formation and Blue Bluff Marl, and the upper Eocene Utley Limestone Member of the Clinchfield Formation, the Griffins Landing Member of the Dry Branch Formation and undifferentiated Barnwell Group sands. We will focus our attention on the middle to upper Eocene section which extends from the surface to a depth of 325 feet at the base of the Congaree Formation (see Figure 2).

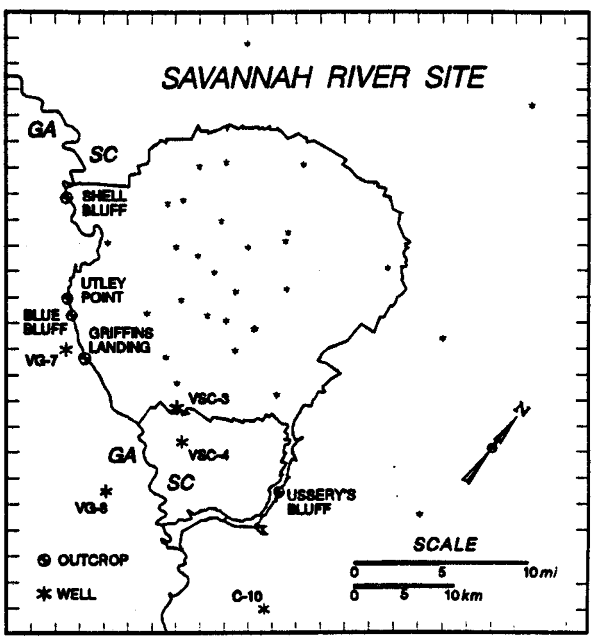

Figure 1. Location of cores and outcrops.

Lithostratigraphy

The Congaree Formation extends from 325 to 236 feet depth and comprises clean, coarse, pebbly, Fe-stained quartz sand with occasional kaolin lithoclasts at the base grading upward into fine to medium clean quartz sand with occasional thin gray to green clay beds. The contact with the underlying intensely weathered kaolinite of the un-named unit is sharp, is characterized by local concentrations of reworked coarse sediments, and represents a regional unconformity. From 236 to 218.6 feet depth interbedded calcareous sand and sandy molluscan-mold grainstone may correlate to the Warley Hill Formation. The contact with the underlying Congaree is subtle and is marked by a change in sand size and the addition of calcareous material. The Blue Bluff Marl extends from 218.6 to 136 feet depth and consists of impure micrite or argillaceous, silty to sandy micrite becoming clayey at the top. The contact with the underlying Warley Hill Formation is picked where sand suddenly decreases in quantity and size; it represents a regional unconformity. The Utley Limestone in 21 feet thick in the core and comprises a sandy, molluscan-mold biosparudite. Thin interbeds of calcareous quartz sand are present in the Utley. The contact with the underlying Blue Bluff Marl is quite distinct and represent a major regional unconformity that is mapped over the area. The Griffins Landing Member extends from 45 to 115 feet depth and consists of sandy calcareous and kaolinitic clays containing large *Crassostrea*. The contact with the underlying Utley Limestone is sharp and represents a regional unconformity. We assign the remainder of the core from the top of the Griffins Landing at 45 feet to the surface to undifferentiated Barnwell Group sands and clays (see Figure 2).

Biostratigraphy

Poorly to well preserved calcareous nannofossils occur in the interval from 76 to 256 feet depth, (i.e. mid Congaree Formation through mid Griffins Landing Member). Preservation is best in the Blue Marl and Griffins Landing Member which includes the Middle-Upper Eocene boundary. Table 1 presents a list of calcareous nannofossil species recorded from the lithic units included in this study. That list was compiled from examination of samples from cores VSC-3, VSC4, VG-7, and VG-8. Figure 2 shows the occurrence of selected age-diagnostic nannofossils in VSC-4. Range of calcareous nannofossils for the purpose of correlation are taken from Perch-Nielsen (1985). “NP” zones refer to the zonation of Martini (1971) as described in Perch-Nielsen

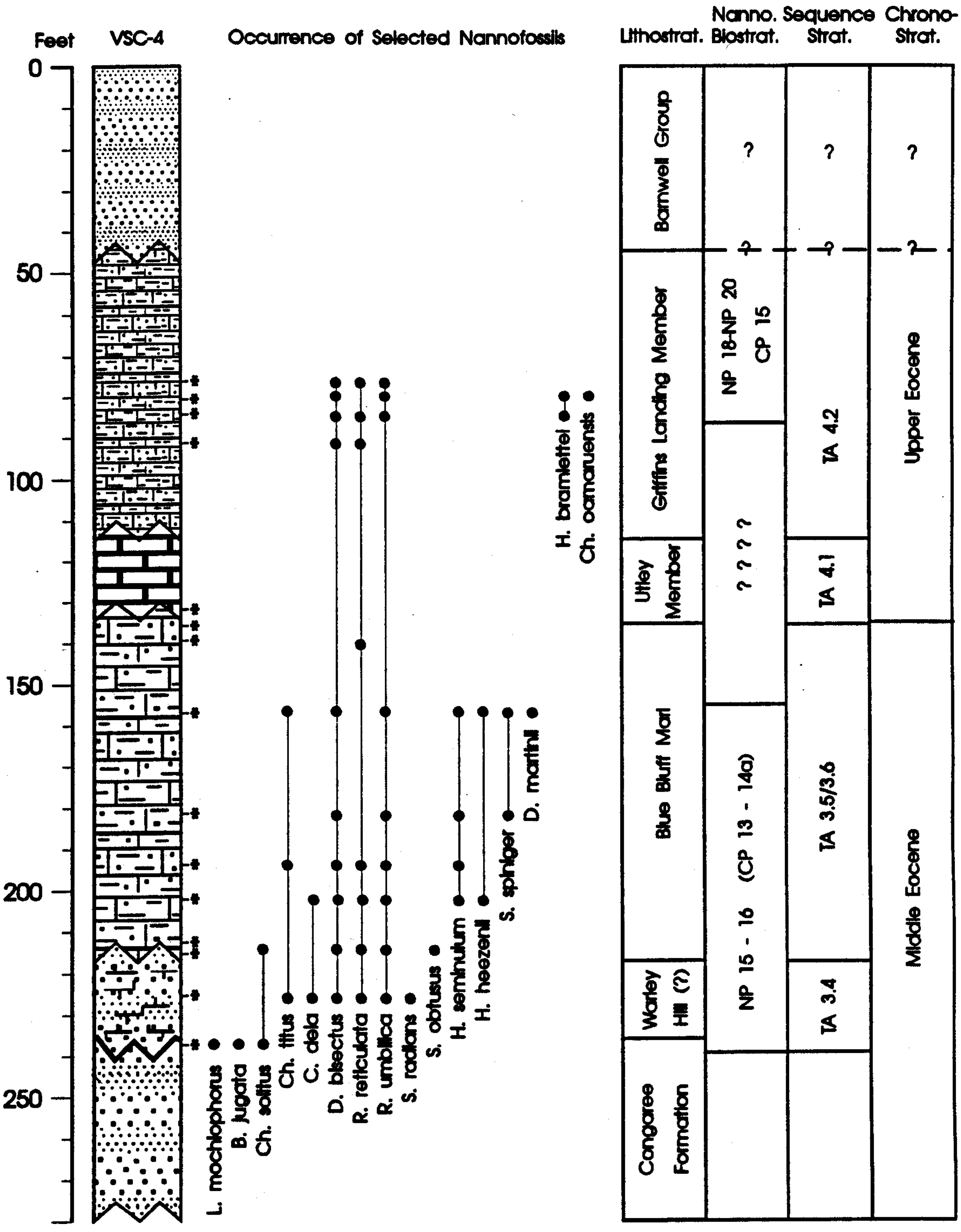

Figure 2. Middle to upper Eocene lithostratigraphy, biostratigraphy, and sequence stratigraphy of core VSC-4. Asterisks represent location of calcareous nannofossil samples. Solid dots indicate the occurrences of each species.

(1985). "CP" zones refer to the zonation of Okada and Burkry (1980) as described by Perch-Nielsen (1985).

One sample from calcareous beds in the upper Congaree Formation contains moderately well preserved nannofossils. The sample at 237 feet contain *Lophodolithus mochlophorus* which has a last occurrence (LO) in NP 15. Several nannofossils including *Reticulofenestra umbilica* and *R. reticulata* which first appear in the sample from 225 feet (Warley Hill?) may have first occurrences in NP 16. However, the definitive taxa *Chiasmolithus gigas* and *Rhabdosphaera gladiu* do not occur in these samples, and therefore, we cannot separate NP 15 and NP 16. Samples

Table 1. Calcareous nannofossil species recorded from middle to upper Eocene strata in the vicinity of southwestern Savannah River Site and Vogtle Power Plant.

Congaree Formation

VSC-4-237'

Birkelundia jugata
Chiasmolithus solitus
Coccolithus pelagicus
Cyclococcolithus formosus
Cepekiella lumina
Lophodolithus mochlophorus
Pontosphaera multipora
Transversopontis obliquipons
T. pulchra
Toweis sp.

Warley Hill Formation

VSC-4-225'

Campylosphaera dela
Cepekiella lumina
Chiasmolithus titus
Coccolithus pelagicus
Cyclococcolithus formosus
Dictyococcites bisectus
Erisonia fenestra
Helicosphaera salebrosa
Markalius inversus
Neochiastozygus dubius
Pemma basquense
P. papillatum
Reticulofenestra reticulata
R. umbilica
R. dictyoda
Rhabdosphaera tenuis
R. spinosa
Sphenolithus radians
Transversopontis obliquipons
Zygrhablithus bijugatus

Blue Bluff Marl

VSC-4-218',216',203', 194',182', 156.6',137.5',135.5'

Campylosphaera dela
Cepekiella lumina
Chiasmolithus titus
Ch.grandis
Ch. Solitus
Coccolithus pelagicus
Cyclococcolithus formosus
Dakylethra punctulata
Dictyococcites bisectus
D. Martinii
D. tani
Ericsonia fenestra
Helicosphaera seminulum
H. heezenii
Markalius inversus
Micrantholithus proceras
Neochiastozygus dubius
Pemma basquense
P.Papillatum
Pontosphaera multipora
Reticulofenestra reticulata
R. umbilica
R. dictyoda
Rhabdosphaera tenuis
R. spinosa
Sphenolithus radians
S. spiniger
S. moriformis
Transversopontis obliquipons
Zygrhablithus bijugatus

Additional Taxa from VSC-3, VG-7, & VG-8

Braarudosphaera bigelowii
Coronoanulus germanicus
Discoaster tani nodifer
D. binodosus
D. elegans
D. bifax
Helicosphaera compacta
Laternithus minutus
Lithostromation perdurum
Reticulofenestra dictyoda

Griffins Landing Member

VSC-4-91.', 84', 82', 76'

Braarudosphaera bigelowii
Cepekiella lumina
Chiasmolithus oamaruensis
Coccolithus pelagicus
Cyclococcolithus formosus
Dictyococcites bisectus
Discoaster barbadiensis
Helicosphaera bramlettei
Micrantholithus sp.
Pontosphaera multipora
Reticulofenestra reticulata
R. umbilica
Rhabdosphaera tenuis
Transversopontis obliquipons

Taxa from VG-7, VG-8, C-10

Discoaster saipanensis
Helicosphaera euphratis
Isthomolithus recurvus
Lithostromation reginum
Markalius inversus
Pemma papillatum
Reticulofenestra dictyoda
Sphenolithus moriformis
Zygrhablithus bijugatus

from the base of the Blue Bluff Marl up to the sample at 156.6 feet contain a nannofossil assemblage typical of NP 16. *Sphenolithus spiniger* and *Discoaster martinii* which occur in sample 156.6 have LO in NP 16. The interval from 150 feet to 83 feet in VSC-4 contains rare, poorly preserved, long-ranging species. This interval includes the upper Blue Bluff Marl, the Utley member and the lower half of the Griffins Landing Member (see Figure 2). The sample at 82 feet contain *Chiasmolithus oamaruensis*, the indicator for NP 18 to NP 20 in Martini's zonation (Upper Eocene). Samples of the Griffins Landing Member from other cores in the area contain *Isthmolithus recurvus* the indicator for NP 19/20. The Utley Member was barren of nannofossils and correlation of it is based on other evidence.

Sequence Stratigraphy

Four middle Eocene depositional sequences are recognized in the Savannah River area. The Congaree Formation is represented by two of the sequences, the Warley Hill Formation by one sequence, and the Blue Bluff Marl (McBean) by one sequence. The Congaree Formation is these cores does not contain an abundant calcareous nannofossil suite; however, the occurrence of Lophodolithus mochlophorus, which has a last occurrence (LO) in NP 15, at 237 feet suggests assignment of the Congaree Formation to the TA3.3 cycle of Haq et al. (1987). Harris et al. (in press) indicate that the Congaree Formation is represented by two depositional sequences (TA3.3 and TA3.2) in Savannah River area. Although a depositional sequence is recognized between the Congaree Formation and the Blue Bluff Marl which may correlate to the Warley Hill Formation, calcareous nannofossils do provide definitive age control. This sequence is assigned to the TA3.4 cycle on the basis of superposition and correlation. The Blue Bluff Marl contains an abundant calcareous nannofossil suite including Sphenolithus spiniger and Discoaster martinii which have LO in NP 16. Based on their occurrence this sequence is assigned to the TA3.6/3.5 cycle of Haq et at. (1987). The depositional sequence represented by the Utley Formation, although barren, is assigned to the TA4.1 cycle of Haq et al. (1987) on the basis of superposition and correlation to the “scutella bed” of the lower Moodys Branch Formation of the eastern Gulf Coastal Plain and exposures along the Savannah River. The Griffins Landing Member of the Dry Branch Formation is placed in the TA4.2 cycle of Haq et al. (1987) on the basis of occurrence of Chiasmolithus oamaruensis which is the indicator for NP 18 to NP 20 in Martini's zonation and the occurrence of Isthmolithus recurvus, an indicator for NP 19/20 in samples from other cores in the area that are correlative.

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SOME CHARACTERISTIC FOSSIL DINOFLAGELLATE CYSTS OF EOCENE STRATA, SAVANNAH RIVER SITE, SOUTH CAROLINA

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INTRODUCTION

Dinoflagellates, among other things the plankton that account for red tides and marine bioluminescence, are unicellular organisms of a primitive, eukaryotic nature (Phrrhophyta) that have been on earth demonstrably since the Silurian, and probably since the Precambrian. Their small size (20-200 microns), widespread geographic and stratigraphic distribution, rapid evolution, and persistent preservation in rocks have made them useful in stratigraphic study. Over the last 20 to 30 years, dinoflagellate fossils have played an important role in stratigraphy related to petroleum exploration. At Savannah River Site, they have been key stratigraphic indicators applied to hydrogeological problems.

Most dinoflagellates are preserved as organic-walled resting cysts. The preserved material is neither calcium carbonate nor silica, but rather a complex organic polymer similar to the material that comprises pollen and spores, "sporopollenin" or nature's plastic. Sporopollenin is highly resistant to acid attack and not readily broken down by other chemical and physical deterioration, making dinoflagellate cysts survivors as fossils under conditions which destroy calcareous and siliceous microfossils. Hence, frequently, as in some strata from Savannah River Site, dinoflagellates and pollen are the only fossils found.

PERSISTENT PROBLEMS IN DINOFLAGELLATE STRATIGRAPHY

Taxonomy

Fundamental to any stratigraphic paleontology is identification of species. Species have geologic ranges. Species ranges identify zones, stages, and larger time rock units. Although great strides have been made in dinoflagellate taxonomy in the last 20 years, a great many species remain without formal description and publication, and many that are described are taxonomically troubled, i.e., their variability and/or our inability to understand the significance of details of their morphology cause us difficulty in distinguishing species, genera, and higher levels of classification. Sometimes the question even comes down to "is it a dinoflagellate?"

At Savannah River Site, I have encountered over 150 species of dinoflagellate cysts in Cretaceous and Tertiary strata. At least 25% of these are either undescribed or taxonomically troubled. These problems mean that I cannot always compare my findings with those of other workers and so have difficulty making refined and accurate age calls. On the plus side, however, is that with continuing work, this abundance of species can be used to develop a zonation at Savannah River Site, and this zonation will be useful in the Gulf and Atlantic Coastal Plains for refined biostratigraphy

Provinciality

Although dinoflagellates are planktonic and some species have worldwide distribution, no universally accepted or applicable worldwide zonation exists based on dinoflagellates. Ranges of some species included in European and North America, North Atlantic zonations are applicable to the Savannah River Site material, but other species clearly exhibit longer or shorter ranges in the Savannah River site material than they do even in sections as close as the Atlantic Coastal Plain of North America, i.e., Maryland and New Jersey. The Savannah River Site lies close to the provincial boundary of the Atlantic Coastal Plain and the Gulf Coastal Plain, but in terms of dinoflagellate assemblages, especially in the Eocene, it is more similar to sections in Alabama of similar age rock, than it is to Maryland.

This provinciality of the dinoflagellates presents difficulties because there exists no published zonation for the Gulf Coastal Plain province. Unpublished material is available, and hence age calls are possible. On the plus side, again, is the potential for the Savannah River Site to be a type section for Gulf Coastal Plain dinoflagellate stratigraphy.

Environmental Facies

Especially within complex, nearshore marine paleoenvironments, such as we find in the Eocene of Savannah River Site, environmental facies present problems for biostratigraphy. The apparent first or last occurrence of a species may have more to do with changes in the local environment than with evolution and extinction. Furthermore, it is often the case that long ranging species are abundant, while short ranging, more stratigraphically useful species are rare in the assemblages, their numbers diluted by floods of dominant, presumably well-adapted species.

Relatively little is known about the environmental significance of dinoflagellate cyst assemblages. At Savannah River Site dinoflagellates occur frequently as floods of one or a few species, apparently as a response to paleoenvironmental factors. Again, the potential for new understanding of the significance of these assemblages is considerable because cores at Savannah River Site have been extensively studied sedimentalogically and for other types of fossils. Once this evidence is compared to this distribution of dinoflagellate assemblages, we may be able to infer paleoenvironmental relationships with the dominance of dinoflagellate cysts.

EOCENE DINOFLAGELLATE STRATIGRAPHY OF THE SAVANNAH RIVER SITE

Several lithostratigraphic schemes have been proposed for the strata beneath the Savannah River Site (Siple 1967; Prowell et al. 1985; Fallaw et al. 1990; Harris and Zullo, 1990, to name a few). This presentation follows, for convenience, the major units named by Fallaw et al. (1990) and Harris and Zullo (1990).

I am making no assertion about the lithostratigraphy, correlations to other stratigraphic units, nor the dating of these units. The dinoflagellates that I have illustrated are characteristic of the Eocene strata of the Savannah River Site and have their first and last occurrences in the lithostratigraphic units as indicated on the range chart. They do not necessarily occur in all of the intervening units; in fact I do not think that I have found any of them in the Warley Hill Formation. The range chart simply connects the first and last occurrences that I have encountered. In all cases except that of *Pentadinium goniferun and P. favatum,* the whole formation is included in the range of the species if the species is found in it at all. In future I hope to present more precise data regarding the occurrence of these and other species at Savannah River Site.

The oldest Eocene unit at Savannah River Site is disputed and controversial. Two possible lithostratigraphic units have been considered to be Paleocene or lower Eocene and correlated variously to the Williamsburg Formation, the Fishburne Formation, and been called the “Snapp beds,” and E1 of Prowell et al. (1985). Characteristic dinoflagellate species illustrated herein include *Wilsonidium tabulatum (?), Wetzeliella meckelfeldensis, W. articulata, and Glaphyrocysta exuberans.*

Unconformably overlying the Fishburne or “Snapp” is the Congaree, mainly lower middle Eocene. This unit is also characterized by abundant *W. articulata and Glaphyrocysta exuberans.* Making first appearances are *Pentadinium favatum, Glaphyrocysta vicina, Charlesdowniae coleothrypta,* and higher in the formation, *Pentadinium goniferum.*

The Warley Hill Formation has yielded few datable assemblages of dinoflagellates. The overlying Santee is characterized by *Glaphyrocysta exuberans, G. vicina, G. semitecta, Charlesdowniae coleothrypta, and Pentadinium goniferum.* Nearly all assemblages form the Clinchfield and

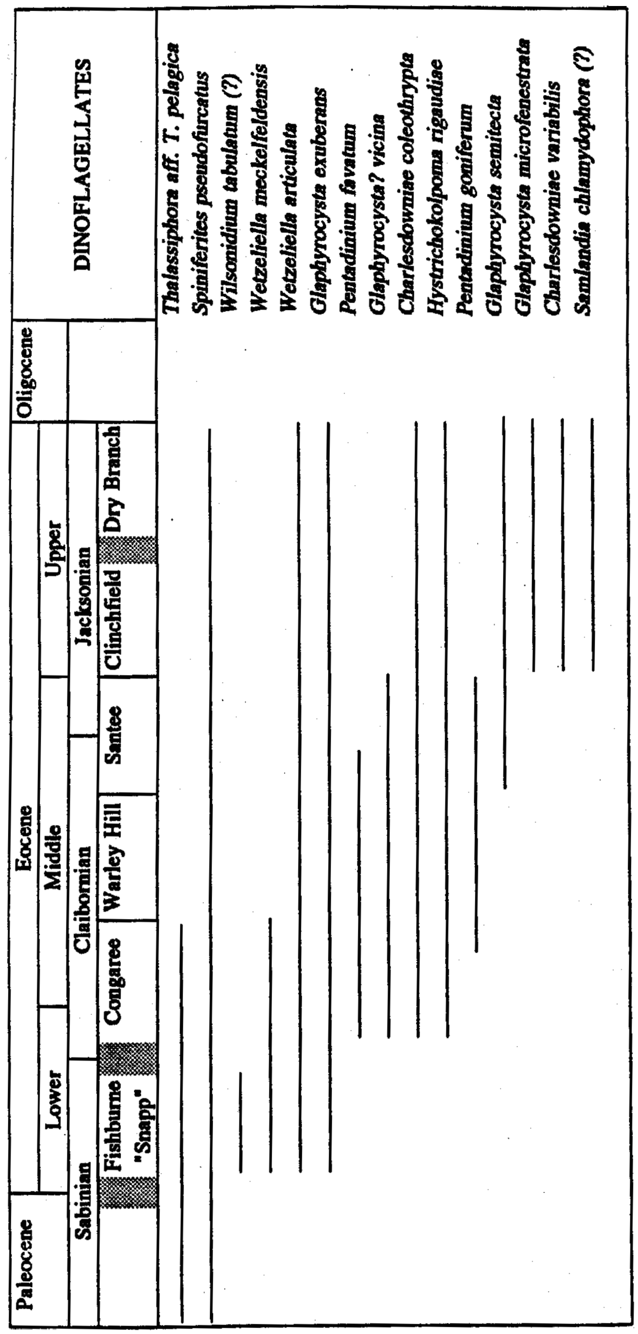

FIGURE 1. Dinoflagellate Ranges at Savannah River Site. Lithostratigraphic units based on Fallaw et al. (1990).
Bars represent total range from first to last occurrence at SRS, not actual recorded occurrences in the stratigraphic units.

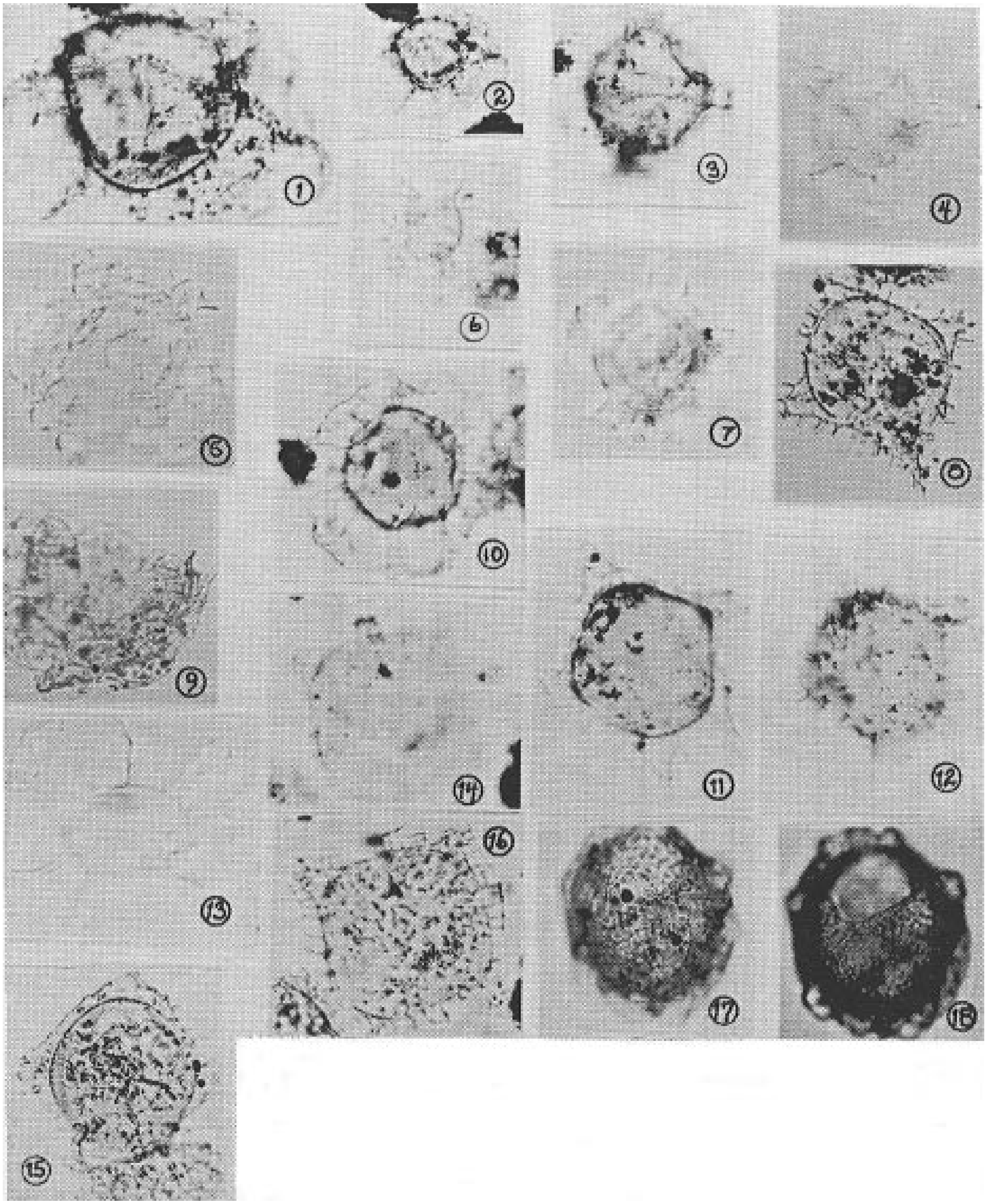

Plate 1. 1,2 ***Thalassiphora aff. T. pelagica; 3 Pentadinium favatum; 4 Pentadinium goniferum; 5 Glaphyrocysta semitecta; 6 Hystrichokolpoma rigaudiae; 7 Spiniferites pseudofurcatus; 8 Wetzeliella meckelfeldensis; 9 Glaphyrocysta? Vicina; 10 Glaphyrocysta exuberans; 11, 12 Wetzeliella articulata; 13 Glaphyrocysta microfenestrata; 14, 16 Charlesdowniae variabilis; 15 Wilsonidium tabulatum ?; 17, 18 Samlandia chlamydophora.***

Dry Branch units are from the Griffins Landing member of the Dry Branch. These assemblages are characterized by *coleothrighypta, C. variabliis, Glaphyrocysta microfenestrata, and Samlandia chlamydophora.*

Edwards (1990) reported the occurrence of some of the species herein illustrated, and her reports are consistent with my findings. In general, the ranges of these dinoflagellate species at Savannah River Site are consistent with those reported in the literature. Some exceptions are that *Spiniferites pseudofurcatus* is sometimes considered to have its first occurrence in the Eocene (e.g. Williams and Bujak, 1985), but it has been reported in unpublished literature from the Gulf and Atlantic Coastal Plains from the late Paleocene (e.g. McLean, 1971). *Hystrichokolpoma rigaudiae* has its base, worldwide, in older, lower Eocene rocks, but I have not found it in the Fishburne. As far as I know, the only other recorded occurrence of *C. variabilis* is in the late middle Eocene Barton beds of England, whereas I have found it in the upper Eocene Dry Branch.

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MIDDLE AND LATE WISCONSINAN RADIOCARBON DATES OF PEAT IN UPPER THREE RUNS AND TINKER CREEK ALLUVIAL SEDIMENTS: CONSTRAINTS ON RATES OF INCISION AND SEDIMENTATION

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INTRODUCTION

The Savannah River Site is located between the Cape Fear Arch and the southeast Georgia Embayment, two features which have affected sedimentary patterns in the Carolinas and Georgia since the Cretaceous. Evidence for continuing tectonic adjustment in the region from the Late Cretaceous through the Holocene includes the warping of units, faulting, and earthquake-induced structures (Prowell and Obermeier, 1991). The incised topography of the SRS and surrounding area certainly suggests epierogenic uplift played a role in sculpturing the landscape.

In the late middle to early late Miocene uplift in the Blue Ridge and western Piedmont caused the fluvial deposition of the upland unit/Altamaha Formation which covered the Upper Coastal Plain from northeast of the Wateree River in South Carolina to south of the Occmulgee River in Georgia (Nystrom and others, 1986, Nystrom and Willoughby, 1992). As the cobble facies of the upland unit delineates the ancestral Savannah River (Nystrom, 1990), the evolution of the Savannah River valley began during deposition of the upland unit and has continued until today. The detailed investigation of surficial deposits in the Augusta area by Newell and others (1980) showed the development of the landscape began in the Miocene and that uplift has been the major influence in shaping the topography. The higher elevations, greater relief and greater drainage density which characterize the erosional topography of the Upper Coastal Plain, compared with the more subdued, predominantly depositional topography on the middle Pliocene Duplin Formation below the Orangeburg Scarp (Dowsett and Cronin, 1990), indicates that most of the uplift and incision occurred before the middle Pliocene (Coloquhoun, 1981).

Yet, the geomorphology of the Upper Coastal Plain cannot be properly interpreted without a full appreciation of the diverse effects of the geologic and climatic changes during the Plio-Pleistocene. The rise and fall of sea level and thus river base level, and the severe climatic fluctuations were important controls on landscape development.

In the Upper Coastal Plain the Savannah River has incised the uplands and migrated to the southwest leaving unpaired fluvial terraces to the northeast of the river. Today the broad, flat floodplains of the Savannah, Upper Three Runs and Tinker Creek suggest the more recent history of the river and its major tributaries has been characterized by sedimentation more than erosion. The floodplain and alluvial terrace deposits can tell us much about the Quaternary history of the area.

It is the purpose of this short paper to present preliminary information on the stratigraphic setting and radiocarbon ages of peat deposits in alluvial sediments of Upper Three Runs and Tinker Creek in the northern part of the SRS. The dates should place some constraints on rates of incision and sedimentation in those streams. In addition, as more peat deposits are dated those dates will allow comparison between the alluvial record and independent base level, climatic, and tectonic records to better determine the relative influence of those controls

METHODS

During the summer of 1990, using a truck-mounted drill rig, a series of holes was drilled across Upper Three Runs valley, then another series was drilled across part of Tinker Creek Valley (figures 1,2,and 3). Cross-section A-A' and B-B" were constructed from 1:24,000 scale topographic maps and the drill hole logs. Each hole was drilled using the power auger technique of penetrating 10 feet, then pulling the auger out and making a detailed lithologic log of the sediments on the auger flanges. That procedure was repeated in 10 foot intervals until the target depth was reached. The average depth of the holes was approximately 60 feet. A sharp lithologic change marked the base of the alluvial section in each hole. All of the peat deposits intersected were described and sampled. The peat samples were split, and Kathryn Hanson and Tom Bullard of Geomatrix Consultants had radiocarbon dating done by Beta Analytic Inc. (Table 1)

Table 1. Radiocarbon assays for samples from Upper Three Runs and Tinker Creek.

Sample No.	C-14 Age Years B.P	Material	Location
GMP-3	33,900±370	Peat/organic Sediment	Upper Three Runs
GMP-12-1	Greater than 45,000	Peat/organic Sediment	Tinker Creek terrace
GMP-12-2	37,950±620	Peat/organic Sediment	Tinker Creek terrace
GMP-12-3	Greater than 46,800	Peat/organic Sediment	Tinker Creek terrace
GMP-13	11,110±50	Peat/organic Sediment	Tinker Creek floodplain

*all old samples given quadruple-normal counting time

DRILL HOLE DESCRIPTIONS AND INTERPRETATIONS

Hole GMP-3

Description

This hole (figure 2) was drilled on the south-side of Tyler Bridge Road 3400 ft west of the bridge over Upper Three Runs. The collar elevation was 198 ft (estimated from 1:24,000 topographic map) and the hole was drilled to a depth of 60 ft. The Qal at the site is 40 ft thick. The interval from 0 to 25 ft is mainly poorly, sorted medium to very coarse grained sand with some granules. Sample GMP-3 was collected from a layer of wet, black, organic, gooey sand in the 25 to 30 ft interval of the hole. The base of the organic rich bed is about 10 ft above the base of the Qal, which is mainly a section of coarse to very coarse grained sand with minor granules dispersed throughout. The lower four ft is a prominent pebbly grit. The organic rich bed was not intersected in hole GMP-4 located 1600 ft to the east. In that hole the sediment in the elevation range corresponding to the organic rich bed is poorly sorted, medium to very coarse grained sand with granules like that in the 0 to 25 ft interval of hole GMP-3.

Interpretation

Where Tyler Bridge Road crosses Upper Three Runs valley the 1:24,000 scale topographic map of New Ellenton SW Quadrangle shows an alluvial fan extending onto the Upper Three Runs floodplain. The alluvial fan is located at the mouth of a tributary entering the floodplain from the west. The 0 to 25 ft interval in hole GMP-3 is entirely or mainly alluvial fan sediment. The organic rich layer in the 25 to 30 ft interval was deposited as floodplain sediment at the top of a fining upward sequence now buried by the alluvial fan. As the top of the organic rich bed is slightly higher than the active floodplain the fining upward sequence is an old terrace rather than part of the active floodplain.

The radiocarbon date of 33,900±370 yr. B.P. (see Table 1) should be the age of the fining upward sequence at the base of the alluvial section, and may approximate the age of the youngest terrace sediments adjacent to the active floodplain of Upper three Runs. The active floodplain, then, is younger than that date. Furthermore, before deposition of the dated peat deposit, incision along this part of Upper Three Runs had reached a level approximately 240 ft below the present inter-fluves. Therefore, in this area Upper Three Runs valley was cut almost to the present base of floodplain alluvium prior to 33,900 yr. B.P.

GMP-12

Description

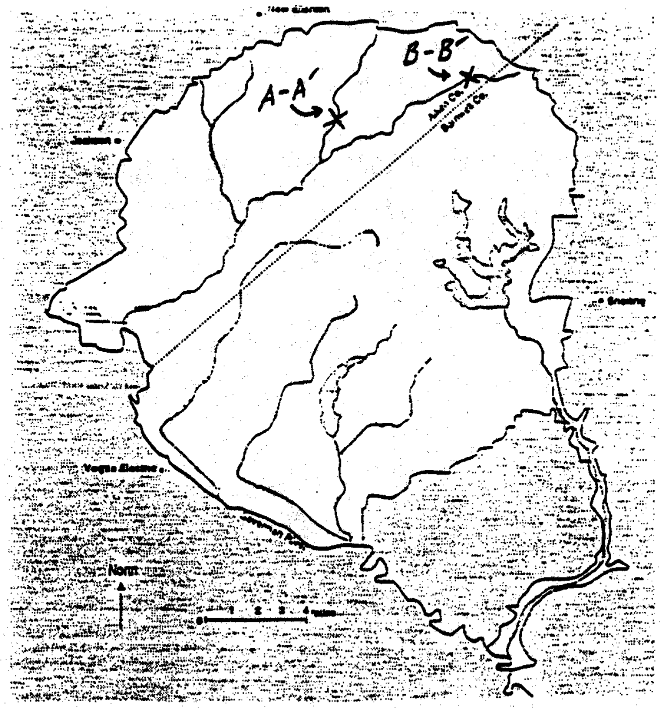
This hole (figure 3) was drilled on the northeast side of Hickson Mill Road on the lower north bank of Tinker Creek approximately 1.6 miles west of Kennedy's Pond. The collar elevation was 220 ft (estimated from 1:24,000 topo map). Twenty-three ft of alluvial sediments including three separate peat beds were intersected. From 0 to 9 ft the sediment is poorly sorted, fine to very coarse grained sand with a noticeable amount of heavy minerals. From 9 to 11 feet there is a bed of brown peat which is somewhat sandy from 10 to 11 ft. Sample GMP-12-1 ft. was taken from the 9 to 10 ft. interval. The 11 to 15 interval is very poorly sorted, medium to very coarse grained sand with granules, and noticeable medium to coarse grained heavy minerals. From 15 to 18 ft there is black sand with much organic material including some brown wood fragments. Sample GMP-12-2 was collected from this interval. The 18 to 20 ft intervals is fine to coarse grained sand. Another layer of brown peat occurs in the 20 to 22 ft interval, and sample GMP-12-3 was collected from this bed. Poorly sorted pebbly sand with noticeable dark heavy minerals comprises the basal ft (22 to 23) of the alluvial section.

Interpretation

The site for this drill hole is not in the active floodplain of Tinker Creek, but is located on the north bank of a fluvial terrace. The lithologic log for the hole indicates four fluvial sequences were intersected in the 23 ft alluvial section. The uppermost part of the section is a sequence from 0 to 9 ft with no recognizable surficial floodplain sediments. Below the upper 9 ft of section are three fluvial sequences, each capped by peat deposits. Thus the alluvial terrace section in this drill hole indicates repeated events of channel deposition followed by floodplain stabilization.

The youngest radiocarbon date of 37,950±620 yr. B.P. for the middle peat bed bracketed by older dates of greater than 45,000 yr. B.P. for the peat bed above, and greater than 46,800 yr. B.P. for the peat bed below, causes some concern about how to interpret these dates. Stone and Brown (1981) discussed the need for critical interpretation of radiocarbon dates in the range of 30,000 to 40,000 y. B.P. which is near the limit for the technique. They pointed out that due to contamination by small amounts of more recent carbon, it can be difficult to discriminate between sediments actually deposited 35,000 yr. B.P. and those deposited during a much earlier time. The date of 37,950±620 yr. B.P. should be a minimum age for the beds from which samples GMP-12-2 was collected must be somewhat younger than the middle peat bed, and could be much younger. The radiocarbon date of greater than 45,000 yr. B.P., however, suggests that it may not be much younger than the 37,950±620 yr. B.P. date for the middle peat bed. The date for the middle peat bed is close to the 33,900±370 yr. B.P. date for the buried terrace intersected in hole GMP-3.

Figure 1



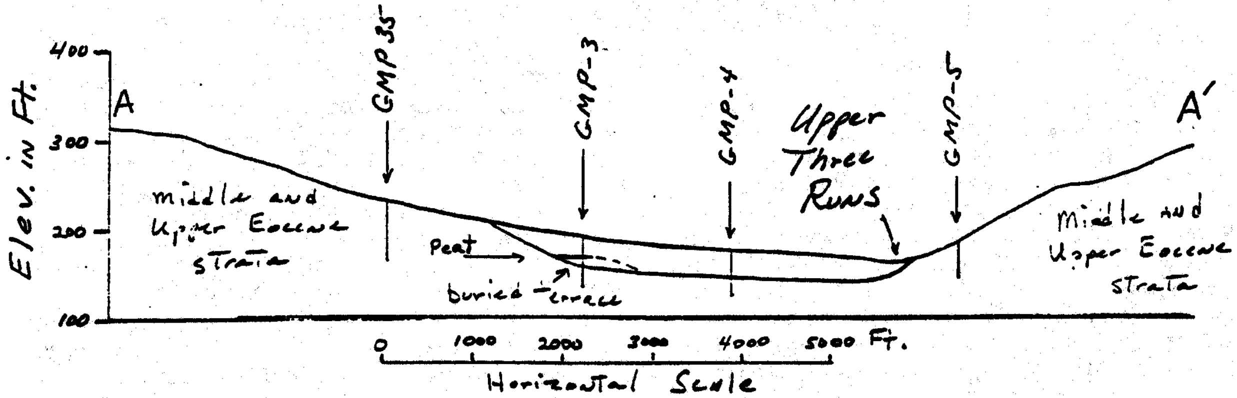


Figure 2

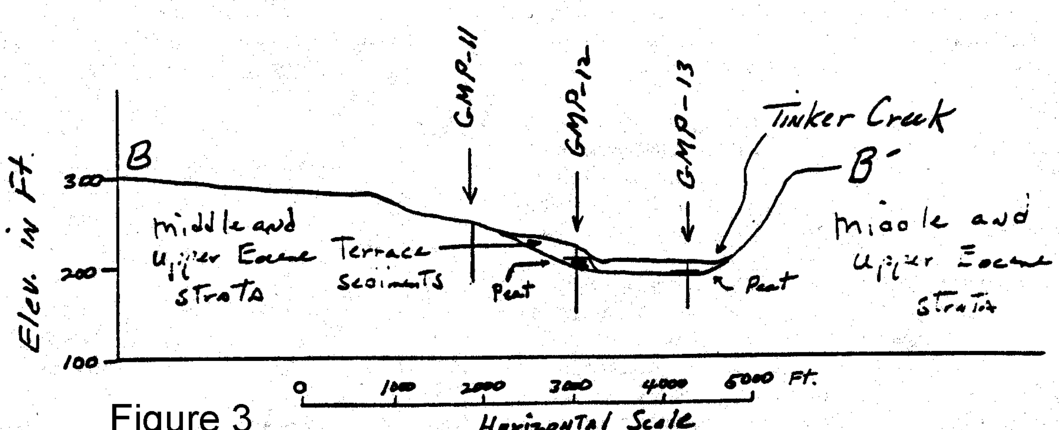


Figure 3

GMP-13

Description

This hole (figure 3) was drilled on Hickson Mill Road in the floodplain of Tinker Creek approximately 1.5 miles west of Kennedy's Pond. The collar elevation was 205 ft. The Qal was is only 12 ft thick at this site. The interval from 0 to 7 ft is black, wet, gooey ooze with bits of wood and other plant matter. From 7 to 11.5 ft there is brown peat. Sample GMP-13 was collected from the 7 to 10 ft interval. From 11.5 to 12 ft there is a pebbly grit which marks the base of the Qal.

Interpretation

There is only one fining upward sequence in this alluvial section. The radiocarbon date of 11,110±50 yr. B.P. is the age for deposition of the basal part of the floodplain sequence intersected in this hole. Sediments in the upper few feet of the floodplain are, of course, younger since some plant matter is added to the surface each year. The radiocarbon date indicates that this part of the Tinker Creek valle has been relatively stable with virtually no floodplain incision and very little deposition in the last 11,110 years.

SUMMARY AND CONCLUSIONS

The middle Wisconsinan radiocarbon dates for terrace sediments adjacent to Upper Three Runs (GMP-3; table 1) and Tinker Creek (GMP-12-1, GMP-12-2 and GMP-12-3; table 1) pre-date by 16,000 to 20,000 years the glacial maximum and corresponding low sea level stand approximately 18,000 years ago. The late Wisconsinan date of 11,110±50 yr. B.P. for sediments in the floodplain of Tinker Creek is considerable older than Stevenson's (1982) oldest date of 4,010±130 yr. B.P. from the Savannah River floodplain. This suggests active deposition in the Savannah River floodplain has occurred more recently than in the headwater area of Tinker Creek. Therefore, aggradation of the valley floor similar to that suggested for the Savannah during the Holocene sea level rise (Stevenson, 1982) did not extend to upper Tinker Creek.

Brooks and Colquhoun (1991) concluded the age of the youngest terrace adjacent to the active Savannah River floodplain is approximately 10,000 years based on artifacts. Whereas Hanson and Bullard (1992) proposed an age of 200,000 to 350,000 years for the same terrace based on characteristics of the soil profile. Neither of these views correlate well with the middle Wisconsinan radiocarbon dates for terrace sediments along Upper Three Runs and Tinker Creek. This points to the need for more work on the geomorphology of the SRS. Additional dating of terrace and floodplain sediments will lead to a more complete understanding of the evolution of the landscape. Also, pollen analyses of peat will contribute to a sharper assessment of the climatic variations which occurred during the late Cenozoic.

ACKNOWLEDGEMENTS

I thank Kathryn Hanson and Tom Bullard of Geomatrix, Inc., for sharing the radiocarbon dates of the peat. Also, Tom Bullard and S.A. Schumm generously provided literature unfamiliar to me for which I express my appreciation.

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HYDROSTRATIGRAPHY OF THE SAVANNAH RIVER SITE REGION, SOUTH CAROLINA AND GEORGIA

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INTRODUCTION

Numerous studies have described and modeled the hydrostratigraphy in and around the Savannah River Site (SRS) area (Siple, 1967; Colquhoun and others, 1983; Brooks and others, 1985; Clarke and others, 1985; Miller, 1986; Aucott and others 1987; Aucott, 1988; Krause and Randolph, 1989). Central to all previous studies is the one to one correspondence between hydrostratigraphic units and lithostratigraphic units. This method is difficult to apply regionally owing to the abrupt facies changes in stratigraphic units of the updip Coastal Plain sequence. For example, lithostratigraphic units included in aquifer and confining units at one location are often not present or are of different hydraulic character elsewhere.

Detailed analysis of drill core, geophysical, and hydrologic data from 144 wells provides the basis for a hydrostratigraphic classification system of the SRS region (Figs. 1 and 2) (Aadland and others, 1992a,b), which makes use of hydrologic properties, most significantly hydraulic conductivity, porosity, and specific storage. These criteria eliminate any "formal" reliance of the classification scheme on lithology, age, geologic history, stratigraphic position or other feature. The resultant classification scheme ranks hydrostratigraphic units at four levels, which from highest to lowest are (Aadland and others, 1992a,b): 1). Hydrogeologic province, 2). Hydrogeologic system, 3). Hydrogeologic unit, and 4). Hydrogeologic zone (informal).

A hydrogeologic province is a major body of rock and/or sediment that behaves as a single hydrologic unit on a regional scale. Aquifer and confining systems may be composed of two or more aquifer and confining units that transmit (or impede) ground water on a regional basis. Where aquifer systems coalesce, the unified aquifer system is named by hyphenating the names of the uppermost and lowermost constituent systems.

An aquifer unit is mappable (>400mi^2) body of rock or sediment that is sufficiently permeable to conduct ground water and yield significant quantities of water to wells and springs (Burt, 1987a, b). A confining unit is a mappable body of rock or sediment of significantly lower hydraulic

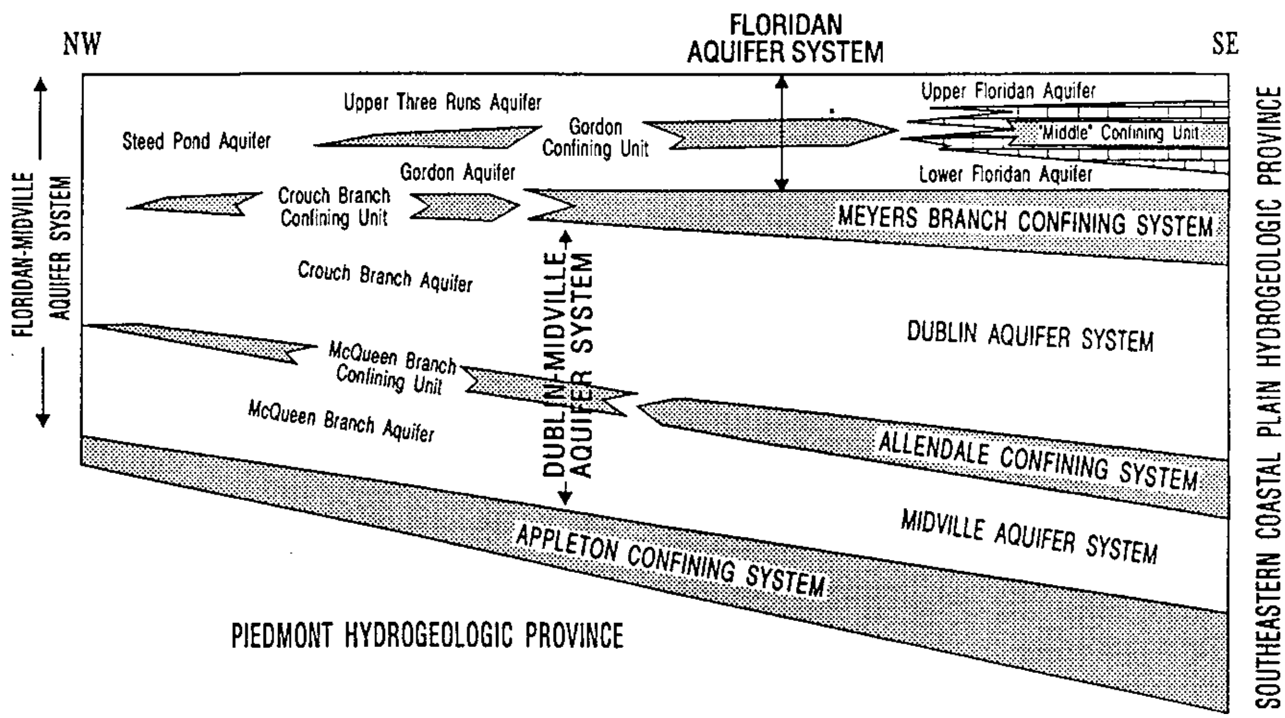

Figure 1. Generalized hydrostratigraphic cross-section of the SRS region.

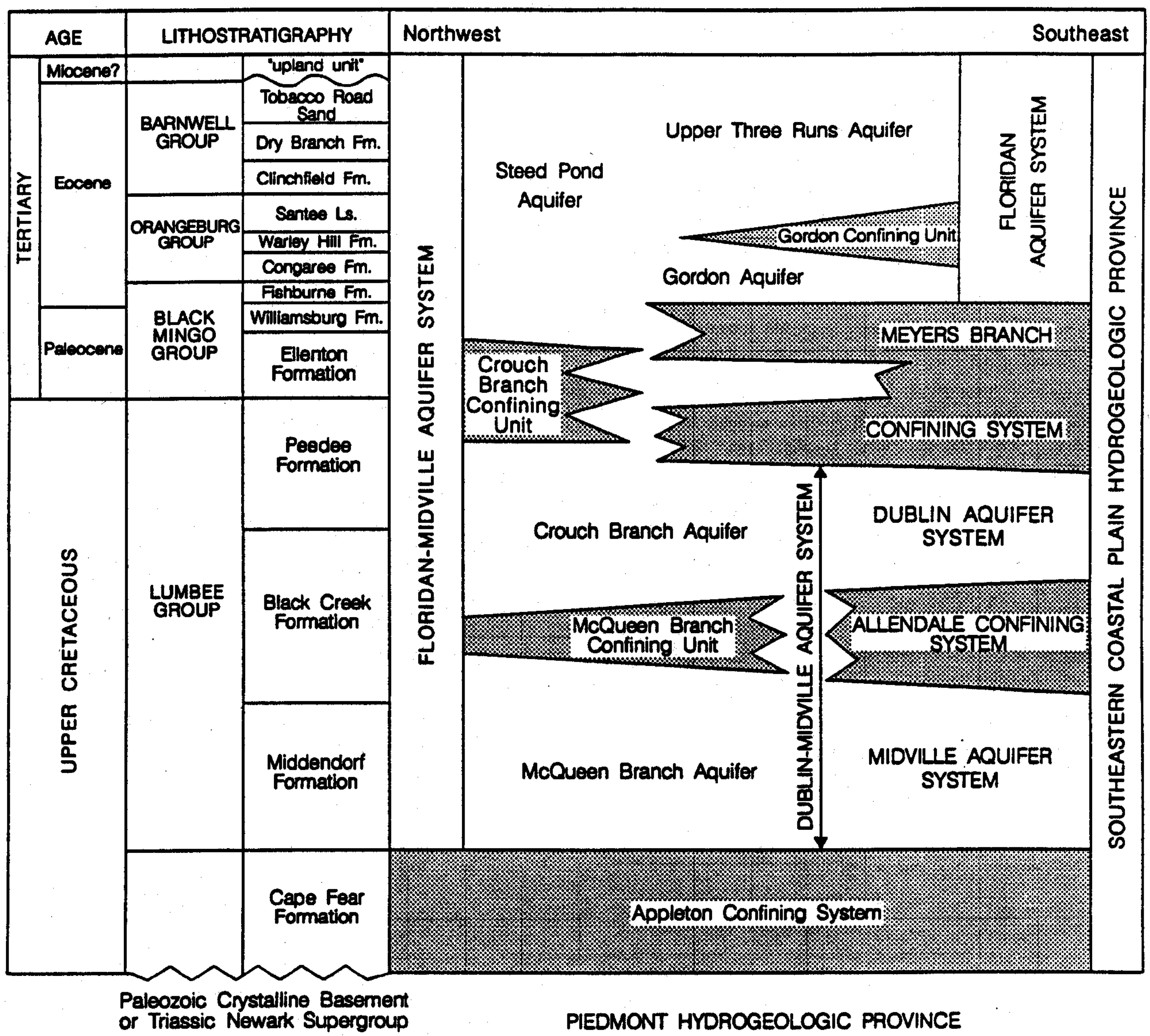

Figure 2. Comparison of lithostratigraphy and hydrostratigraphy for the SRS region.

conductivity than an adjacent aquifer (Burt, 1987a, b; Lohman, 1972).

Hydrogeologic units may be informally subdivided into aquifer or confining zones, which are characterized by properties significantly different from the rest of the unit, such as hydraulic conductivity, water chemistry, or lithology. The assignment of level and name to a hydrostratigraphic unit does not imply a quantitative ranking of hydraulic continuity, but is intended to distinguish relative differences in hydraulic properties between adjacent units.

HYDROSTRATIGRAPHIC FRAMEWORK

Hydrogeologic Provinces

Two hydrogeologic provinces are recognized in the subsurface beneath the SRS region. The Piedmont hydrogeologic province includes un-weathered Paleozoic igneous and metamorphic basement, and lithified mudstone, sandstone, and conglomerate of the Triassic Dunbarton basin (Figs. 1 and 2). The Southeastern Coastal Plain hydrogeologic province comprises all sedimentary units from the ground surface to the top of the un-weathered basement, and in the SRS region is divided into three aquifer and three confining systems (Figs. 1 and 2). Figure 3 shows the updip limits of confining systems and the areal extent of aquifer systems in the

SRS region.

The strata that form the three aquifer systems consist of fine to coarse grained sand, with local gravelly zones, deposited under relatively high energy conditions in fluvial to shallow marine environments. Marine limestone is locally intercalated with the sands. Generally, the fine grained sediments that comprise the regional confining systems were deposited in low energy marine and fluvial environments. Locally the confining system contain beds of sand or other high permeability materials, but overall, the units retard vertical flow between the overlying and underlying aquifer systems.

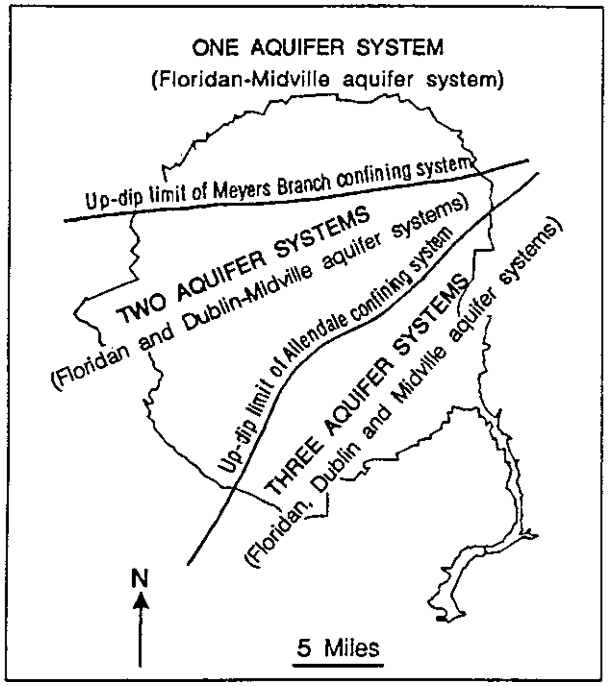

Figure 3. Map showing the updip limits of the confining systems and extent of aquifer systems in the SRS region.

Appleton Confining System

Throughout the region, the Southeastern Coastal Plain hydrogeologic province is separated from the Piedmont hydrogeologic province by the Appleton confining system. The Appleton rests directly on un-weathered crystalline and sedimentary rocks of the Piedmont hydrogeologic province (Fig. 1); it includes saprolite derived from weathering of basement rocks, and muddy sand and sandy mud of the Cape Fear Formation (Fig. 2). The Appleton confining system varies from less than 50 to over 250 feet thick in the SRS region (Fig. 4).

Midville Aquifer System

The Midville Aquifer system was defined by Clarke and others (1985) in a well located near the town of Midville in Burke County, Georgia. In the SRS region, the Midville attains a thickness greater than 300 feet (Fig. 5), and consists of sand and muddy sand of the Middendorf and lower part of the Black Creek Formation (Fig. 2). The extent of the Midville aquifer system is defined by the updip limit of the overlying Allendale confining system (Fig. 3); northwest of the updip terminus, the Midville aquifer is termed the McQueen Branch aquifer of the Dublin-Midville and Floridan-Midville aquifer systems (Figs. 1 and 2).

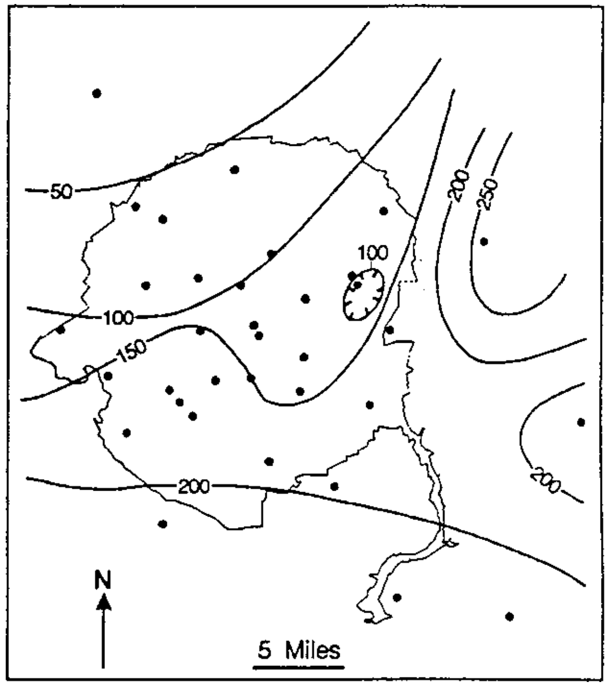

Figure 4. Isopach map of the Appleton confining system.

Allendale Confining System

The Allendale confining system consists of sandy mud and clay of the Black Creek Formation and is defined in a well drilled near the town of Allendale, Allendale County, South Carolina. The Allendale is present in the southeastern half of the SRS region and defines the regional extent of the Midville and Dublin aquifer systems (Figs. 1 and 3). The Allendale thins updip to become the McQueen Branch confining unit of the Dublin Midville and Floridan Midville aquifer systems (Fig.1).

Dublin Aquifer System

The Dublin aquifer system is present in the southeastern half of the SRS region (Fig. 3), where it attains a thickness of more than 300 feet (Fig. 6). North of the updip limit of the Allendale confining system, the Dublin aquifer syste becomes the Crouch Branch aquifer of the Dublin Midville and Floridan Midville aquifer systems. The Dublin aquifer system was defined by Clarke and others (1985) in a well drilled near the town of Dublin in Laurens County, Georgia. In the SRS region, the Dublin consists of sand and muddy

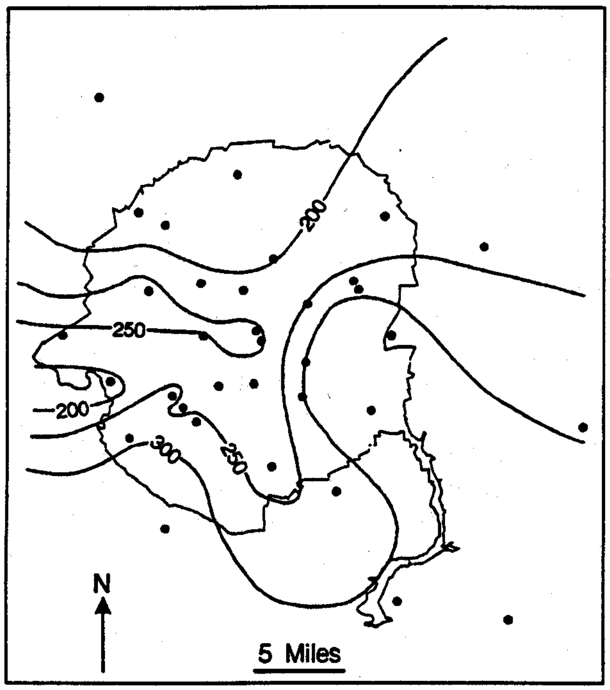

Figure 5. Isopach map of the Midville aquifer system/McQueen Branch aquifer unit.

sand of the Upper Cretaceous Peedee and upper Black Creek Formations (Fig. 2).

Meyers Branch Confining System

The Meyers Branch confining system consists of clay and sandy clay of the Paleocene Ellenton and Williamsburg Formation (Fig. 2). The Meyers Branch extends across the southern two-thirds of the SRS region and constrains the areal extent of the overlying Floridan aquifer system. Where the Meyers Branch ceases to act as a regional confining system it becomes the Crouch Branch confining unit of the Floridan Midville aquifer system (Figs. 1 and 2).

Dublin Midville Aquifer System

The Dublin Midville aquifer system underlies the central part of the SRS (Fig. 3). Its areal extent is established by the updip limit of the overlying Meyers Branch confining system and the updip limit of the underlying Allendale confining system (Figs. 1 and 3). The Dublin Midville aquifer system is equivalent to the Dublin Midville aquifer system as defined by Clarke and others (1985) in Georgia. The Dublin Midville consists of all strata within the Lumbee Group from the Middendorf Formation up to the sand in the lower part of the Peedee Formation (Fig. 2).

The Dublin Midville aquifer system includes two aquifer units, the McQueen Branch aquifer and the Crouch Branch aquifer, which are separated by the McQueen Branch confining unit (Figs. 1 and 2). The two aquifers can be traced northward, where they constitute an integral part of the Floridan Midville aquifer system.

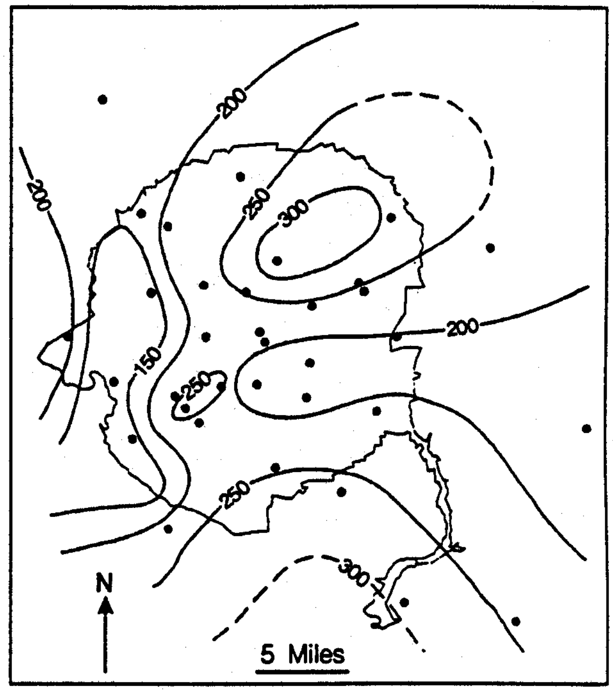

Figure 6. Isopach map of the Dublin aquifer system/Crouch Branch aquifer unit.

Floridan Aquifer System

Miller (1986) defined the Floridan aquifer system as a "vertically continuous sequence of carbonate rocks of generally high permeability that are mostly of middle and late Tertiary age." Terrigenous sediments in the SRS region are connected hydraulically to the carbonate rocks of the Floridan (Aucott and others, 1987). The Floridan is extended updip across the SRS region to include all strata from the water table to the top of confining beds in the Paleocene Black Mingo Group (Fig. 2). Downdip, the Floridan includes the upper and the lower Floridan aquifers (Miller, 1985; Krause, and Randolph, 1989), separated by the "middle confining unit" (Fig. 1). The updip part of the Floridan is divided into the Gordon aquifer, Gordon confining unit, and Upper Three Runs aquifer. The Upper Three Runs aquifer is subdivided into two aquifer zones over much of the SRS area.

Gordon Aquifer Unit

The Gordon aquifer consists of the sandy parts of the Williamsburg Formation and the sands of the overlying Fishburne and Congaree Formations (Fig. 2). The Gordon varies from 50 to over 150 feet thick, and is not present north of the updip limit of the Gordon confining unit (Fig. 7).

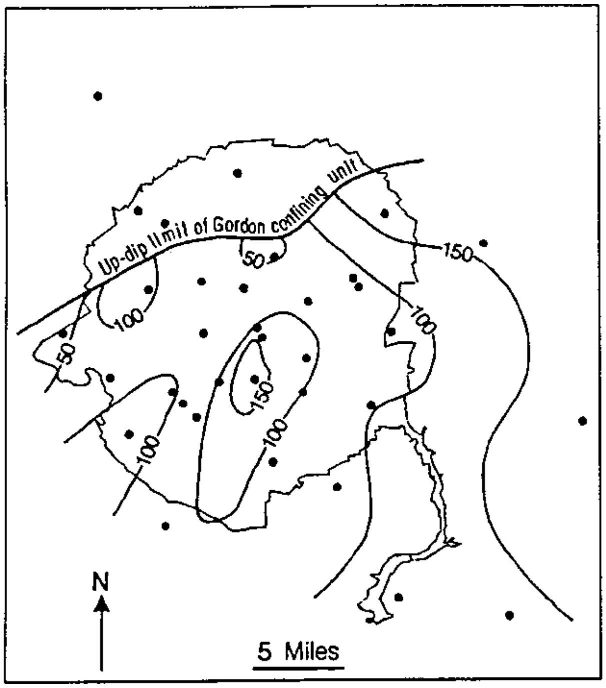

Figure 7. Isopach map of the Gordon aquifer unit.

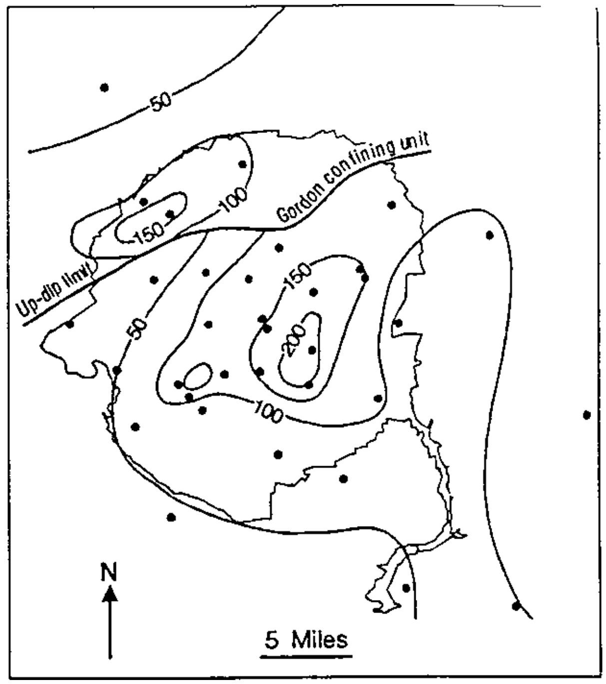

Figure 8. Isopach map of the Upper Three Runs and Steed Pond aquifer units.

Gordon Confining Unit

The Gordon confining unit consists of fine grained, glauconitic, muddy sand and clay of the Warley Hill Formation (Fig. 2). In the study area, Warley Hill strata are generally less than 50 feet thick. The Gordon confining unit has been informally termed the "green clay" in updip areas of the SRS. The Gordon confining unit is not defined in the northwestern part of the SRS (Figs. 7 and 8); instead, discontinuous lenses of Warley Hill Formation from the "green clay" confining zone within the Steed Pond aquifer.

Upper Three Runs Aquifer Unit

The Upper Three Runs aquifer consists of all strata above the Warley Hill Formation, and includes the sandy and sometimes calcareous sediments of the Santee Limestone and all of the overlying Barnwell Group from the water table down to the top of the Gordon confining unit (Fig. 2). The Upper Three Runs aquifer is the updip terrigenous equivalent of the upper Floridan aquifer (Fig. 1). The Upper Three Runs aquifer varies from less than 50 to more than 200 feet thick in the SRS region (Fig. 8).

Floridan Midville Aquifer System

In the northwestern part of the SRS region, the Floridan and Dublin Midville aquifer system coalesce to form the Floridan Midville aquifer system (Figs. 1, 2, and 3). The Floridan Midville is divided into three aquifers separated by two confining units (Fig. 2).

Steed Pond Aquifer Unit

Where the Gordon confining unit becomes too thin to be an effective confining unit, the Gordon and Upper Three Runs aquifers merge to form the Steel Pond aquifer (Figs. 1 and 2). The Steed Pond includes strata from the water table down to the clays and muddy sands of the Ellenton Formation and upper Peedee Formation (Fig. 2). The Steed Pond varies from less than 30 to more than 150 feet thick in the SRS region (Fig. 8).

CONCLUSION

The hydrostratigraphic classification described herein utilizes a four-level hierarchy to delineate the hydrostratigraphy of the SRS region. The Piedmont hydrogeologic province is overlain by Cretaceous and Tertiary strata of Southeastern Coastal Plain hydrogeologic province. Downdip, the Coastal Plain sequence is divided into three aquifer systems and three confining systems. Updip thinning of the sedimentary sequence results in the coalescence of the three-aquifer systems into one at the Fall Line.

The classification system allows subdivision of the hydrostratigraphic units into as much detail as the local geology demands while keeping within a regional framework. This feature makes the system especially attractive for use in site specific hydrostratigraphic studies where a complete description of the hydrologic regime is required.

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PETROLOGY AND POROSITY PERMEABILITY CHARACTERISTICS OF TERTIARY AQUIFER SANDS, SAVANNAH RIVER SITE REGION, SOUTH CAROLINA

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INTRODUCTION

The purpose of this paper is to describe the textural, petrographic, and porosity permeability characteristics of Tertiary sands that comprise the terrigenous portions of the Floridan and Floridan Midville aquifer systems in the Savannah River Site (SRS) region (Fig. 1). The Gordon and Upper Three Runs aquifer units represent the updip clastic phase of the Floridan aquifer system and are separated by the Gordon confining unit (Aadland and others, 1992; this volume). In the northwestern part of the SRS region, where the Gordon confining unit becomes too thin to be an effective barrier to flow, the Gordon and Upper Three Runs aquifer units coalesce to form the Steed Pond aquifer of the Floridan Midville aquifer system (Aadland and others, 1992) (Fig. 1).

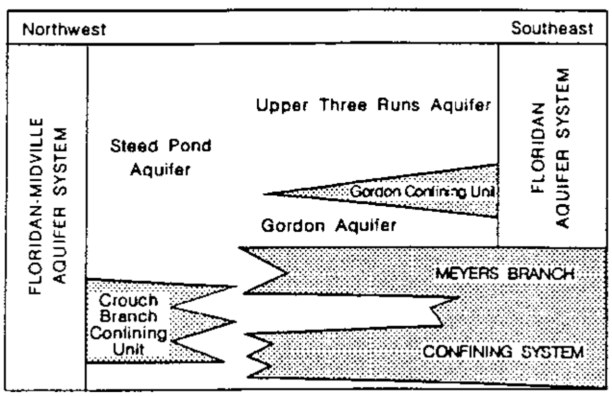

Figure 1. Tertiary hydrostratigraphic units in the Savannah River Site region (from Aadland and others, 1992).

GORDON AQUIFER

The Gordon aquifer consists of the sandy portions of the Paleocene Williamsburg Formation and sands of the overlying lower and middle Eocene Fishburne and Congaree Formations. (Aadland and others, 1992). The Gordon is an unconsolidated quartz sand that contains thin, discontinuous layers of mud and minor zones of opal and chalcedony cemented quartzarenite (Robertson, 1990). Figure 2 shows the percent gravel, sand, and mud for 443 Gordon samples. Figure 3 shows the percent sand, silt, and clay for 10 representative Gordon sands. The average grain size of 410 Gordon sands is 1.66 $\pm$ 0.04ϕ (lower medium). Sands range from upper very coarse (-0.74ϕ) to very fine (3.97ϕ); about 80% of the sampled population is coarse and medium grained. The mean sorting of 410 Gordon sands is 1.32 $\pm$ 0.04ϕ, which is poorly sorted on the Folk and Ward (1957) scale; sorting ranges from 0.44ϕ (well sorted) to 4.77ϕ (extremely poorly sorted). About 70% of the sampled population is moderately and poorly sorted. Robertson (1990) showed that sorting of Gordon sands is controlled chiefly by the percentage of mud matrix. That is, the greater the amount of mud the poorer the sorting. Mean skewness of 410 Gordon sand is 0.19 $\pm$ 0.01 (fine-skewed). Skewness ranges from –0.53 (strongly coarse-skewed) to 0.84 (strongly fine-skewed), and is controlled by the amount of mud and gravel in the sands. Sands with high mud contents are usually fine and very fine-skewed, whereas those with high percentages of gravel are coarse and strongly coarse-skewed. Mean kurtosis of 410 Gordon sands is 1.52 $\pm$ 0.04, which is very leptokurtic according to Folk and Ward's (1957) verbal scale. Kurtosis varies from 0.69 (platykurtic) to 5.61 (extremely leptokurtic); most sands are leptokurtic and very leptokurtic, indicating that the sorting in the central two-thirds of the distribution is better than that in the "tails".

Porosity and permeability of 382 Gordon sands were determined from sieve analyses using the Beard and Weyl (1973) empirical method, based on Trask (1930) median size and sorting. Mean porosity of Gordon sands is 35.1 $\pm$ 2.5% and ranges from 27.3 to 40.2%. The distribution of porosity is skewed toward lower values, although it appears to follow a near normal distribution (Fig. 4). Calculated permeabilities range from 2 to 220 Darcies (D) (5 to 537 ft/day); 75% of the permeability values fall between 16 and 128 D (39 to 312 ft/day) (Fig. 5). The geometric mean permeability of the 382 sand samples is 39.6 D (97 ft/day). Calculated permeabilities of Gordon aquifer sands are skewed toward high values and appear to follow a log normal distribution (Fig. 5).

Robertson (1990) and Robertson and Thayer (1992) constructed facies maps showing the distribution of textural parameters and permeability for the Gordon aquifer. The facies maps showed the following downdip (i.e., toward the southeast) changes: mean grain size and coarsest percentile (1st) decreased; sorting became poorer; kurtosis became more leptokurtic; and percent mud increased. Geometric mean permeability also decreased in a downdip direction, and varied from 90 D (220 ft/day) in the north to 20 D (49 ft/day) in the south. The decrease in permeability toward the south results from a decrease in mean grain size coupled

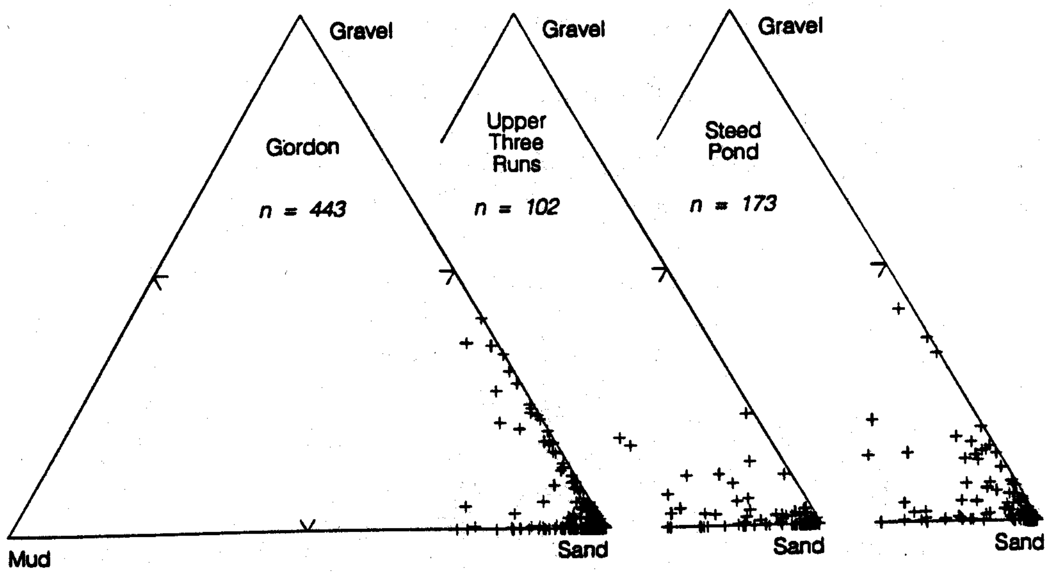

Figure 2. Ternary diagrams showing the percent gravel, sand, and mud in the Gordon, Upper Three Runs, and Steed Pond aquifer units.

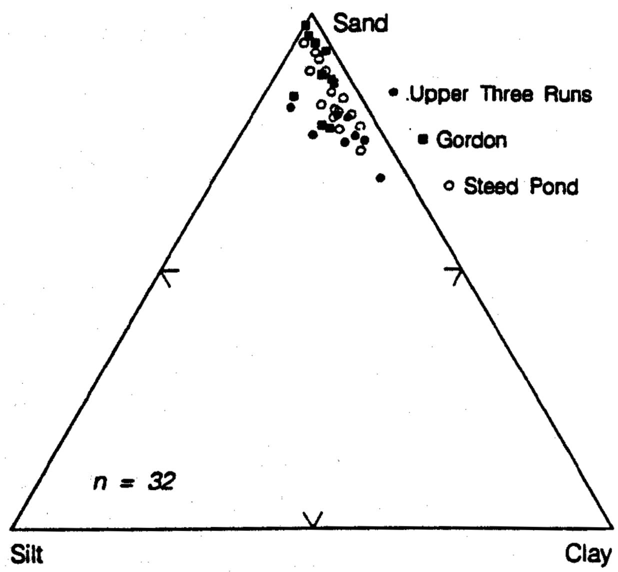

Figure 3. Ternary diagram showing the percent sand, silt, and clay in the Gordon, Upper Three Runs, and Steed Pond aquifer units.

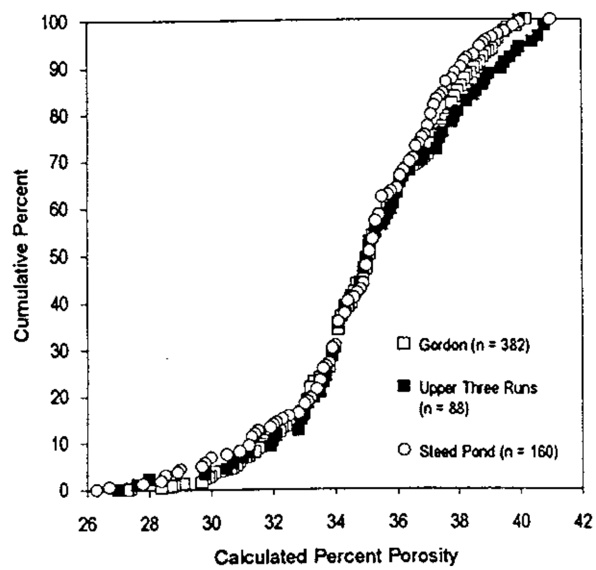

Figure 4. Cumulative frequency curves showing the distribution of mean porosity values for the Gordon, Upper Three Runs, and Steed Pond aquifer units.

with an increase in percent mud matrix and a deterioration of sorting (i.e., sorting becomes poorer).

Bledsoe and others (1990) measured the porosity and permeability of 13 Gordon aquifer samples collected from SRS P-wells. Permeability was measured by the falling head method. Mean porosity of six muddy sand samples is 41.3 $\pm$ 3.0%, and geometric mean permeability (vertical) is 3.08 x 10^{-7} D (7.51 x 10^{-7} ft/day). The geometric mean of five horizontal permeability measurements on the muddy sand samples is 8.89 x 10^{-2} D (2.17 x 10^{-1} ft/day). The average porosity of seven mud samples from intra-aquifer confining layers is 45.0 $\pm$ 3.2%, and geometric mean permeability (vertical) is 7.90 x 10^{-9} D (1.93 x 10^{-8} ft/day). The geometric mean of five horizontal permeability measurements on the same mud samples is 9.93 x 10^{-4} D (2.42 x 10^{-3} ft/day).

Robertson and Thayer (1992) have shown that Gordon sands plot as quartzarenites on Folk's (1980) sandstone composition diagram. Petrographic analyses of 42 thin sections shows that the unit consists of 98.4% framework quartz, 0.3% feldspar, 0.5% heavy minerals, 0.4% opaque minerals, 0.3% muscovite, and 0.1% glauconite. Staurolite, zircon, garnet, tourmaline, and rutile are the major detrital heavy minerals.

Monocrystalline quartz from 99% of the total quartz population; of this 65.5% is non undulatory and 33.5% is undulatory. Robertson and Thayer (1992) also indicated that there is little or no variation in mineral composition between updip and downdip wells in the SRS area. Plots of quartz types on the Basu and others (1975) quartz provenance diagram, along with the presence of garnet, kyanite, staurolite, and sillimanite indicate a medium to high rank metamorphic provenance for most Gordon sands.

Strom and Kaback (1992) did semi quantitative X-ray diffraction analyses on 18 Gordon sands from the SRS p-wells. Their results show that the sands consist mostly of quartz with 5 – 18% clay. Smectite and kaolinite are the dominant clay minerals with minor to trace quantities of illite. Authigenic minerals include clinoptilolite, 2 – 5 um diameter cristobalite lepispheres, and fibrous chalcedony (Strom and Kaback, 1992; Thayer, 1989, 1992). X-ray diffraction analyses of four sandy mud samples from intra aquifer confining layers show that they consist of quartz and 51 – 64% clay minerals. Kaolinite is the dominant clay mineral in the muds with minor illite and smectite.

UPPER THREE RUNS AQUIFER

The Upper Three Runs aquifer consists of all strata from the water table to the top of the Gordon confining unit (Fig. 1), and includes the sandy and sometimes calcareous sediments of the Santee Limestone, and all of the Barnwell Group (Aadland and others, 1992). The Upper Three Runs aquifer consists mainly of unconsolidated quartz sand intercalated with thin, discontinuous layers of sandy mud and carbonate. Figure 2 shows the percent gravel, sand, and mud for 102 samples from the Upper Three Runs aquifer, and Figure 3 gives the percent sand, silt, and clay for 9 representative sand samples.

The Upper Three Runs is a subangular, lower coarse and medium grained, slightly gravelly, immature quartz sand. Gravel ranges from zero to 21.7% and averages 1.7 $\pm$ 0.4%. The gravel is pebble and granule size grains of rounded and subrounded quartz and quartzite. Sand averages 91.2 $\pm$ 0.9%, and ranges from 58.0 to 99.5%. Mud (silt + clay) averages 6.6 $\pm$ 0.7%, and ranges from 0.4 to more than 25% (Fig. 2). About 50% of the sampled sands contain less than 5% mud. Hydrometer analyses of the mud fractions of 9 Upper Three Runs sands indicate that clay-size particles are more abundant than silt-size grains (Fig. 3).

The average grain size of 90 Upper Three Runs sands is 1.69 $\pm$ 0.06ϕ (lower medium sand). Sands range from 0.57ϕ (upper coarse grained) to 3.58ϕ (very fine grained); mean

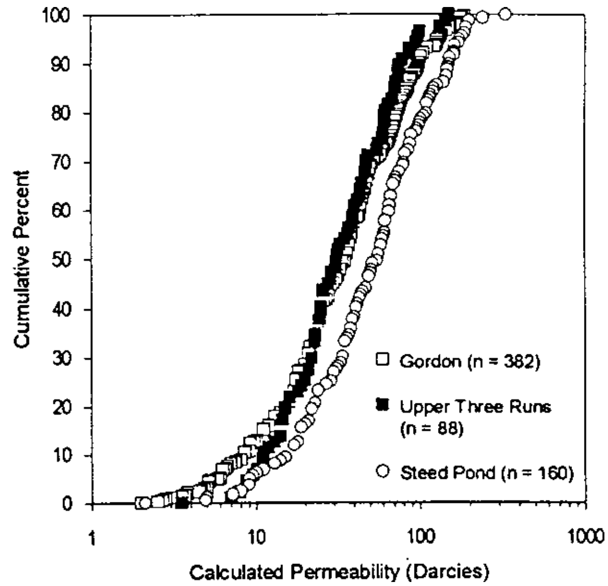

Figure 5. Cumulative frequency curves showing the distribution of mean permeability values for the Gordon, Upper Three Runs, and Steed Pond aquifer units.

size of slightly more than 50% of the sampled population is lower coarse and upper medium sands. The average sorting of Upper Three Runs aquifer sands is 1.14 $\pm$ 0.07ϕ, which is poorly sorted on the Folk and Ward (1957) verbal scale. Sorting ranges from 0.40 ϕ (well sorted) to 3.19ϕ (very poorly sorted). Almost 70% of the sampled population is moderately and poorly sorted, and about 25% is well and moderately well sorted. Sorting is controlled primarily by the amount of mud matrix in these sands. Typically, the greater the percentage of mud matrix the poorer the sorting. Upper Three Runs aquifer sands are fine-skewed (x = 0.13 $\pm$ 0.03); skewness ranges from –0.49 (strongly coarse-skewed) to 0.73 (strongly fine-skewed), and is controlled by the amount of mud and gravel in the sands. Sands with high mud contents are usually fine and very fine skewed, whereas those with high percentages of gravel are coarse and strongly coarse-skewed. Mean Kurtosis of 90 Upper Three Runs aquifer sands is 1.57 $\pm$ 0.08, which is very leptokurtic on the Folk and Ward (1957) scale. Kurtosis values range from 0.59 (very platykurtic) to 4.26 (extremely leptokurtic); most of the sampled sands are leptokurtic and very leptokurtic.

Strom and Kaback (1992) determined the composition of 28 sand and muddy sand samples from SRS P-wells penetrating the Upper Three Runs aquifer. The sands consists of quarts with 2 to 40% detrital clay. Smectite and kaolinite are the dominant clay minerals with minor to trace quantities of illite. Trace amounts of chlorite, calcite, plagioclase, and K-feldspar were also reported. X-ray diffraction analysis of four mud samples from intra – aquifer confining layers shows that they consist of silt-size quartz and 52 – 64% clay, mainly kaolinite with minor to trace amounts of illite and smectite. Thin section study of six sand samples from the Upper Three Runs aquifer shows that they are quartzarenites composed of monocrystalline quartz with accessory polycrystalline quartz, muscovite, and heavy and opaque minerals. Trace quantities of K-feldspar, detrital kaolinite, and metamorphic rock fragments are also present (Thayer, 1992). The sands contain variable amounts of detrital matrix, ranging from less than 5% to 27%. Downdip, in the C-10 well, Upper Three Runs sands contain glauconite and 10 to 35% skeletal grains, including foraminifers, echinoderms, bryozoans, pelecypods, and broken skeletal debris.

Porosity and permeability of 88 Upper Three Runs aquifer sands containing less than 25% mud were determined from sieve analyses using the Beard and Weyl (1973) method. The porosity averages 35.3 ± 3.0% and ranges from 27.0 to 40.8%. The distribution of porosity values is approximately normal and closely follows that of the Gordon and Steed Pond aquifer units (Fig. 4). Calculated permeabilities of Upper Three Runs sands range from 3.5 to 150 D (8.5 to 366 ft/day) and follow a long normal distribution, being slightly skewed toward lower values (Fig. 5). Almost 60% of the permeability values lie between 16 and 64 D (39 and 156 ft/day). The geometric mean permeability of the 88 sand samples is 31.2 D (76 ft/day).

Porosity and permeability measurements have been done on ten samples from the Upper Three Runs aquifer (Bledsoe and others, 1990). The mean porosity of six sandy mud and muddy sand samples is 50.0 ±3.4%, and geometric mean permeability (vertical) is 3.77×10^{-8} D (1.19×10^{-3} ft/day). The geometric mean of five horizontal permeability measurements done on these samples is 2.74×10^{-3} D (1.79×10^{-3} ft/day). The average porosity of four mud samples from intra-aquifer confining layers in the Upper Three Runs is 45.0 ± 8.7%, and geometric mean permeability (vertical) is 4.63×10^{-8} D (1.13×10^{-7} ft/day). The geometric mean of three horizontal permeability measurements on the same mud samples is 1.72×10^{-2} D (4.19×10^{-2} ft/day).

STEED POND AQUIFER

In updip areas of the SRS regional, where the Gordon confining unit pinches out, the Gordon and Upper Three Runs aquifers coalesce to form the Steed Pond aquifer (Fig. 1). The Steed Pond includes sands from the water table to the top of the Corouch Branch confining unit, including strata of the Black Mingo, Orangeburg, and Barnwell Groups (Aadland and others, 1992).

The steed Pond aquifer consists of unconsolidated quartz sand that contains thin, discontinuous layers of sandy silt, sandy mud, and sandy clay. Figure 2 shows the percent gravel, sand, and mud for 173 Steed Pond aquifer samples, and Figure 3 shows the percent sand, silt, and clay for a subset of 15 representative samples. The Steed Pond is mainly a subangular, coarse and medium grained, slightly gravelly, submature quartz sand. Gravel averages 2.9 ± 0.5% and ranges from zero to 41.3% (Fig. 2). Most consists of subrounded to rounded grains of granule and lower pebble size quartz and quartzite. Sand size grains average 93.6 ± 0.6%, and range from 56.4 to 99.6%. Mud (silt + clay) averages 3.4 ± 0.4%, and ranges from 0.3 to 22.4% (Fig. 2). Nearly 75% of the sampled Steed Pond sands contain less than 3% mud. Hydrometer analyses of the mud fractions of 15 Steed Pond sands containing less than 25% mud show that clay size particles are usually twice as abundant as silt size grains (Fig. 3).

The average grain size of 165 Steed Pond aquifer sands is 1.35 ± 0.06ϕ (upper medium sand). The sands range fro –0.58ϕ (upper very coarse grained) to 3.95ϕ (very fine grained). About 75% of the sampled population falls between upper coarse and upper medium sand. The average sorting of 165 sands from the Steed Pond aquifer is 1.16 ± 0.05ϕ, which is poorly sorted on the Folk and Ward (1957) verbal scale. Sorting ranges from 0.41 ϕ (well sorted) to 4.93ϕ (extremely poorly sorted). Slightly more than 70% of the sampled population is moderately and poorly sorted. Generally, the sorting of Steed Pond aquifer sands is controlled by the amount of mud matrix. Usually, the greater the percentage of mud matrix the poorer the sorting of the sands. Mean skewness of Steed Pond sands is 0.16 ± 0.01 (fine skewed). Skewness ranges from –0.32 (strongly coarse skewed) to 0.63 (strongly fine skewed), and is controlled by the amount of mud and gravel in the sands. Sands with high mud contents are usually fine and very fine skewed, whereas those with high percentages of gravel are coarse and strongly coarse skewed. Mean kurtosis of 165 Steed Pond aquifer sands is 1.38 ± 0.04, which is leptokurtic on the Folk and Ward (1957) verbal scale. Kurtosis ranges from 0.72 (platykurtic) to 3.29 (extremely leptokurtic); most sands are leptokurtic and very leptokurtic.

Strom and Kaback (1992) determined the composition of eight sand samples from the Steed Pond aquifer using X-ray diffraction. Their results show that the sands consist mainly of quartz with less than 5% clay matrix. Smectite and kaolinite are the dominant clays with minor to trace amounts of illite. Petrographic analysis of five Steed Pond sands fro well C-2 indicate that they are quartzarenites composed of monocrystalline quartz with accessory polycrystalline quartz and minor sedimentary rock fragments, heavy and opaque minerals, muscovite, and detrital grains of kaolinite. Clay matrix ranges from 1.8 to 2.6% and consists of silt sized angular quartz, ground up micas, and allogenic clay.

Porosity and permeability of 160 Steed Pond aquifer sands containing less than 25% mud were determined fro sieve analyses using the Beard and Weyl (1973) method. The porosity of Steed Pond sands averages 34.8 ± 2.7% and ranges from 26.3 to 41.0% (Fig. 4). The distribution of calculated porosity values appears to follow a normal distribution, and is skewed slightly toward lower values (Fig. 4).

Calculated permeabilities of Steed Pond aquifer sands range from 2.1 to 330 D (5 to 805 ft/day); more than half of the permeability values fall between 32 and 128 D (Fig. 5). The geometric mean permeability of 160 sand samples is 47.9 D (117 ft/day).

Bledsoe and others (1990) measured the porosity and permeability of five samples from the Steed Pond aquifer. Mean porosity of three muddy sand samples is 48.7 $\pm$ 5.4%, and geometric mean permeability (vertical) is 5.74×10^{-7} D (1.4×10^{-6} ft/day). The geometric mean of two horizontal permeability measurements on these muddy sand samples is 1.14×10^{-3} D (2.78×10^{-3} ft/day). The average porosity of two mud samples from confining layers in the Steed Pond aquifer is 53.5 $\pm$ 3.5% and geometric mean permeability (vertical) is 5.44×10^{-9} D (1.33×10^{-8} ft/day). The geometric mean horizontal permeability of the mud samples is 2.23×10^{-4} D (5.68×10^{-4} ft/day).

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UPPER CLAIBORNIAN COASTAL MARINE SANDS OF EASTERN GEORGIA AND THE SAVANNAH RIVER AREA

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INTRODUCTION

Hetrick (1990) and Huddlestun and Hetirck (1991) named the Perry Sand for a distinctive formation west of the Ocmulgee River in Georgia. The Perry sand consists of stratified, relatively pure, well to very well sorted, fine to very fine grained quartz sand. All along its outcrop belt in Georgia, from Randolph County in the west to Houston County in the east, the Perry Sand occurs as a band not much greater than 10 miles (16 km) across (Fig. 1). Huddlestun and Hetrick (1991) correlated the Perry Sand with the Lisbon Formation on physical grounds. Except for local concentrations of burrows, the Perry Sand is not known to be fossiliferous. The Lisbon Formation occurs in the stratigraphic position of the Perry Sand in the shallow subsurface a few miles to the south of outcropping Perry Sand. Conversely, a few miles north of cores that contain Lisbon Formation and overlying and underlying units, only Perry Sand occurs in the stratigraphic position of the Lisbon.

The Perry Sand is considered to be a coastal marine lithofacies of the inner to middle neritic Lisbon Formation. In west central Georgia, the facies change is abrupt and there appears to no transgressive or regressive facies relationships between the Perry and the Lisbon.

The Perry Sand can be traced in outcrop as far east as the vicinity of the Ocmulgee River in Georgia (between the south side of Warner Robins and the brewery north of Clinchfield). We could not trace it farther east because, if the Perry lithofacies is a mappable unit east of the Ocmulgee River, it occurs only in the shallow subsurface where we currently have no core control (Fig. 1).

In west central Georgia, the Perry Sand grades laterally updip (landward) into the Mossy Creek Sand of Huddlestun and Hetrick (1991). The Mossy Creek Sand is lithologically more variable than the Perry Sand. In its finer grained lithofacies, the Mossy Creek Sand resembles the Perry Sand but is coarser grained (generally medium grained sand), is less well sorted, and the bedding is larger in scale and more crude. In its coarsest lithofacies, the Mossy Creek occurs as coarse grained, poorly sorted, tidal channel deposits with large scale cross bedding and common clay (kaolin) rip up clasts. Typical *Ophiomorpha nodosa* and bioturbation occur locally in this facies. The Mossy Creek Sand is also a coastal marine formation, deposited landward of the Perry Sand and, in places, the coarser facies of the Mossy Creek Sand strongly resembles the coarser facies of the younger Tobacco Road Sand in Georgia. In west central, Georgia, the areal extent of the Mossy Creek is much broader than that of the Perry and geometrically is a blanket deposit.

The Mossy Creek Sand grades laterally eastward across the Ocmulgee River into the Tertiary hard kaolin or Claiborne kaolin (Jeffersonville member of the Huber Formation of Huddlestun and Hetrick (1991) [informal name]). I have seen upper Claibornian Mossy Creek sand lithofacies in only a few mines between the Ocmulgee and Oconee Rivers in Georgia. However, the coarse grained and intensely cross bedded channel lithofacies facies of the upper Claibornian may not be easy to distinguish from the Lower Paleocene Marion Member of the Huber Formation of Huddlestun and Hetrick (1991) or from the basal Upper Eocene channel sands (LaMoreaux, 1946; Huddlestun and Hetrick, 1991). The upper part of the type section of the Huber Formation as described by Buie (1978) may be Claibornian and consists in part of cross-bedded, poorly sorted, coarse-grained sands (see Huddlestun and Hetrick, 1991, p. 117 – 118). Unfortunately the type section of the Huber Formation has been excavated and is not longer accessible. I also have not identified any sand lithofacies of the exposed Claibornian east of the Oconee River in Washington County, Georgia. In that area, it appears that the Barnwell Group overlies the Marion member of the Huber Formation, Claiborne hard kaolin, or Upper Eocene channel sands.

In outcrop in the Savannah River area in Georgia, the only deposits of probable late Claibornian age that I have identified (also pers. Com., J. Hetrick, 1992) fall within the range of the lithologies of the Jeffersonville member of the Huber Formation. Neither the Perry nor Mossy Creek Sands have been identified in outcrop in the Savannah River area of Georgia.

In western South Carolina, on the other hand, there are two exposures of Perry like sand that I am familiar with: one being deposits identified as Huber Formation at Stop 7 of Nystrom and others (1982). The upper sand overlying the Cretaceous kaolin at the Bell kaolin pit in western Aiken county is, to me, indistinguishable from the finer grained lithofacies of the Mossy Creek Sand. These three sand exposures contain the appropriate lithologies and occur in the same stratigraphic positions of the Perry Sand and Mossy Creek Sand of southwestern and central west Georgia. The question is whether these sand bodies are continuous fro

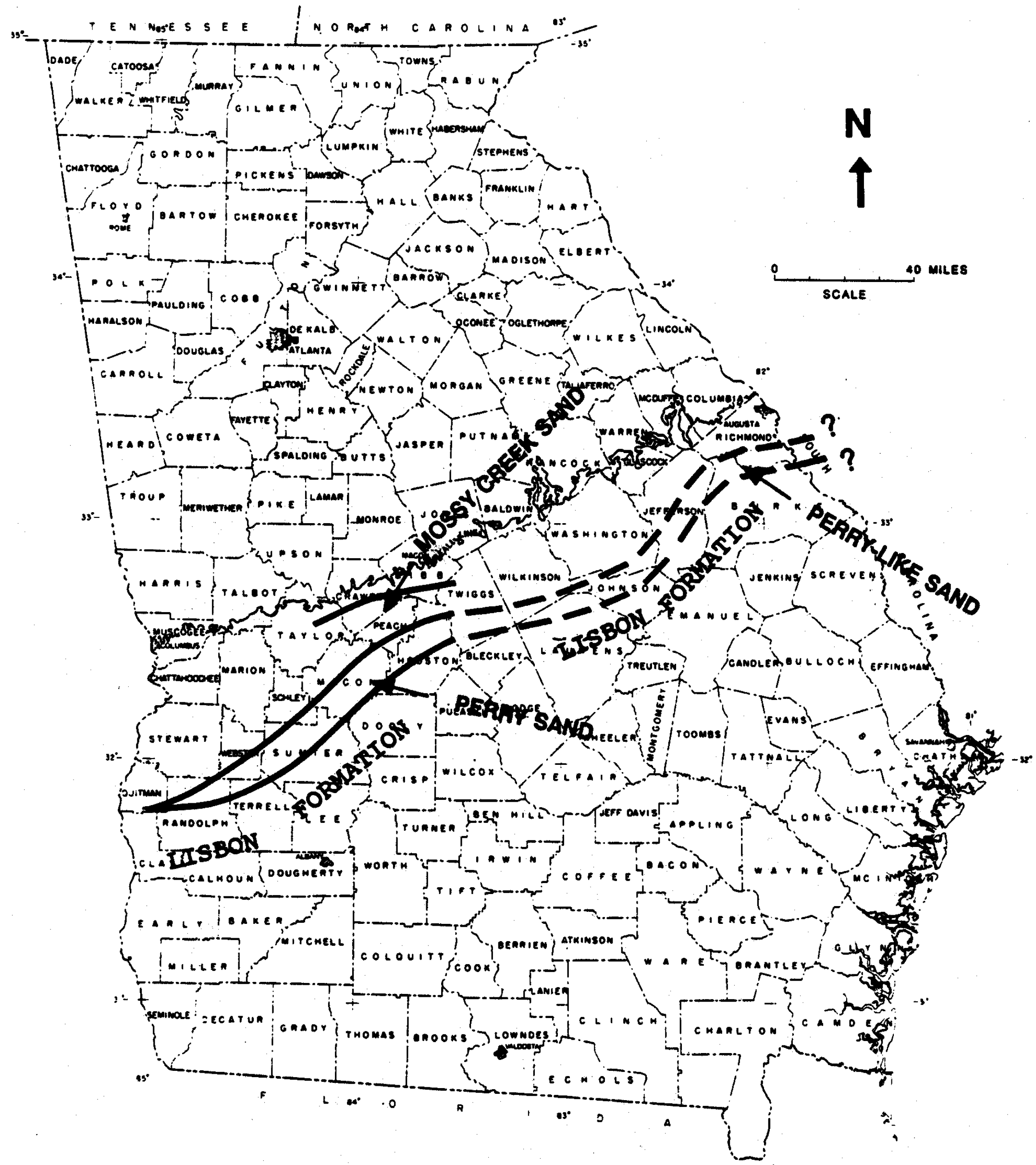

Figure 1. Location of Perry Sand and Perry-like sand.

central Georgia into South Carolina or whether they constitute lenses or beds within a larger unrecognized, upper Claibornian formation (much as Twiggs-type clay occurs as lenses or beds within the Dry Branch Formation of eastern Georgia and western South Carolina).

The Occurrence of Perry Like Sand in Eastern Georgia

A total of eight cores were examined that had been taken over the years for different projects from Jefferson, Richmond, and northern Burke Counties, Georgia (Fig. 1). These include the following: Richmond 2, (C-2) (GGS-3181), Richmond 3, (C-5) (Bath) (GGS-3184), Richmond 4, Pine Hill, (GGS-3760), Richmond 5, Blythe, (GGS-3762), Jefferson 2, Wrens, (GGS-3761), Burke 5, Ga. Power 1, (GGS-3674), Burke 6, McBean, (GGS-3757), Burke 7, Millers Pond, (GGS-3758).

Perry Sand, or a variant thereof, was identified in four of the cores: the Richmond 5 (GGS-3762) (Blythe), the Jefferson 2 (GGS-3761) (Wrens), the Burke 5 (GGS-3674) (Georgia Power 1), and the Richmond 4 were taken too far up dip and only Jeffersonville like lithologies directly underlie the Barnwell Group in that area. These three cores constrain the width of the possible belt of coastal marine, Perry like sand to no more than approximately 6 miles. The Perry like lithology is inexplicably absent in the Burke 7 (GGS-3758) (Millers Pond), perhaps because this core site is located near the downdip limits of the sand and the transgressing coastal marine deposits of the Upper Claibornian only filled topographic lows.

With the available information, a few conclusions can be tentatively reached. 1) The predominant sand lithofacies present in the four cores in the upper Claibornian stratigraphic position is that of the Perry Sand. 2) Typical Perry like sand is generally present but there are minor lithologic distinctions. 3) The sand lithofacies identified appears to occur in a band that roughly trends eastward from the vicinity of Wrens in Jefferson County through northernmost Burke County and to southern Richmond County (Fig. 1). Wrens, Georgia, appears to occur in the downdip (offshore) part of the band; Blythe, Georgia, within the bad; and the McBean Creek area of Richmond and Burke Counties near the downdip (offshore) part of the band. The core near Hephzibah (Richmond 4 [GGS-3760]) occurs north of the belt of Perry like sand. 4) If the continuity of the coastal marine sand lithofacies of the Upper Calibornian is real, then there appears to be little or no Mossy Creek type sands in eastern Georgia between a downdip Perry-like sand and the exposed Huber Formation (Jeffersonville member) (pers. Com., J.H. Hetrick, 1992). 5) There appears to have been a broad "embayment" during the late Claibornian in northern Jefferson and western Richmond Counties, Georgia or, conversely, a lobe of siliciclastics to the west in the Oconee River area (Fig. 1). If the projection of the trend of the Perry Sand – Perry-like sand were linear across Georgia to the Savannah River area, then Louisville in Jefferson County should occur along that trend (Fig. 1). This interpretation of an "embayment" is consistent with the well logs of Herrick (1961, p. 236 – 241) where the Lisbon Formation occurs in the upper part of the Claibornian section (Perry stratigraphic position) in the vicinity of Louisville.

The Perry-like sand of eastern Georgia is the same as that of the type area in Georgia in that much of it consists of thinly stratified, very well sorted, fine to very fine grained sand. Particular differences between the Perry Sand of the type area and the lithologically similar sands of eastern Georgia are: 1) There are more structureless and massive bedded intervals in the Perry-like sand. 2) The Perry-like sand of eastern Georgia tends to be slightly micaceous whereas either little mica or no mica is present in the Perry Sand in southwestern and central west Georgia. 3) There are more clay laminae that define bedding planes in the Perry-like sand. 4) There is fine carbonaceous or lignitic debris along bedding planes in some intervals in the Perry-like sand that is not know to occur in the Perry Sand of southwestern Georgia. 5) Gypsum-bloom occurs in some stratigraphic intervals on the surfaces of cores in the Perry-like sand whereas no gypsum of any sort has been observed on the surfaces of cores in the Perry Sand. In regard to the last two differences, in southwestern Georgia the Perry Sand generally occurs at the tops of the sections and is weathered to varying degrees. In eastern Georgia, the similar sands do not occur at the tops of the sections and are more deeply buried and, therefore are less susceptible to weathering and oxidation.

Very little typical Mossy Creek lithology is seen in the four cores in Georgia. Most of the coarser sands (generally medium-grained) in this stratigraphic position are lithologically intermediate with the very fine grained Perry-like sand. That Mossy Creek sand lithology does occur sporadically in western South Carolina in the Mossy Creek-Perry stratigraphic position is evidenced by typical Mossy Creek type sand overlying the Cretaceous kaolin (Buffalo Creek Member of the Gaillard Formation? Of Huddlestun and Hetrick [1991] also seen Pickering and Hurst 1989]) at the Bell kaolin pit in western Aiken County. Sands of Mossy Creek appearance occur at other sites in western South Carolina. Nystrom and others (1986, p. 27-31) referred to these sands in western South Carolina as "surficial sand deposits" or to the Pinehurst Formation, a sand of eolian origin and considered variously to be of pre-Pleistocene to Holocene in age (for discussion, see Nystrom and others, 1986). However, the intricate layering, cross-bedding and burrows in these sands in western South Carolina more closely resemble an aqueous, coastal marine sand deposit than an eolian sand deposit. The occurrence of Mossy Creek like sands at varying elevations in South Carolina is similar to that of the Mossy Creek Sand near the Fall line in the vicinity of the Flint River in Georgia. In Georgia, there are significant cut-outs and topography on the tops of all formations near the Fall line. Entire formations may be missing locally. However, in western South Carolina the origin of Mossy Creek like sands is still controversial and there is as yet on consensus as to their age or origin.

CONCLUSIONS

Perry Sand crops out in a narrow band across southwestern Georgia eastward to the vicinity of the Ocmulgee River. The Perry Sand does not crop out between the Ocmulgee and Savannah Rivers but there are four cores from Jefferson, northern Burke, and Richmond Counties, Georgia, where Perry-like sand occurs in the Perry stratigraphic position in the shallow subsurface. This Perry-like sand occurs immediately north of the Lisbon Formation and in the Lisbon stratigraphic position. Therefore, the Perry-like sand appears to be continuous in the shallow subsurface in Jefferson, Burke, and Richmond Counties. The occurrence of Perry-like sand in the Perry-Lisbon stratigraphic position in Aiken County, South Carolina, also indicates that the Perry-like sand may be continuous from eastern Georgia into South Carolina. Whether the Perry Sand occurs in the shallow subsurface between the Ocmulgee River and Wrens is unknown due to the lack of data.

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SILVER BLUFF: A VERY CELEBRATED PLACE

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Aiken, South Carolina

Silver Bluff, located in the Coastal Plain on the Savannah River in Aiken County, South Carolina (Jackson, SC-GA 7 ½’ quadrangle, longitude 81 °51;08” W, latitude 33^{o} 18’ 40”N) is the highest point on the South Carolina bank of the Savannah for many miles, rising approximately 30 ft above water level on the cut bank of a meander. Exposed in the bluff is a section of yellowish-gray clay and bluish-gray, lignitic lay overlain by mottled, yellow and reddish, poorly sorted, pebbly sand and clay. We sent samples of lignitic clay from near the base of the section to two commercial palynological laboratories. By one the material was dated as Cretaceous (?) from one poorly preserved specimen, and by the other it was dated as Pleistocene(?) from numerous specimens. The sediments are probably terrace deposits (Newell and others, Fig. 9).

According to some (Stokes, 1951, p. 20; Faust, 1982, p. 69), DeSoto’s expedition found a thriving Indian settlement at Silver Bluff in 1540. The name of the locality derives from two possible sources. One idea is that it came from a metallic sheen on the outcrop caused by muscovite (Faust, 1982 p. 69). There is also a story that Spaniards operated a silver mine there [Bartram, 1791 (Harper, ed., 1958, p. 315)]. They may have actually been mining, for the manufacture of gunpowder, concretions of iron sulfide which occur in the lignitic clay. According to the story, having mined down to water level, they decided to dig a channel through the neck of the meander loop and divert the Savannah. On the Jackson quadrangle map based on aerial photographs taken in 1963, a meander cutoff named Spanish Cut appears to have been widened and straightened over a distance of almost 400 ft., approximately 1000 ft short of the goal.

William Bartram passed through Silver Bluff, “a very celebrated place” [Bartram, 1791 (Harper, ed., 1958, p. 199)], several times in the latter part of the eighteenth century, the locality being on a well-traveled trading path from the coast to the Indian settlements to the west. In his famous book (1791), he described in detail a Silver Bluff stratigraphic section containing belemnites. Belemnites indicate a Cretaceous age in the Carolinas, but the nearest occurrence of Cretaceous marine megafossils known to the authors in 33.5 mi to the southeast near Allendale, South Carolina, where they were found in a well core. Bartram published his book many years after his expeditions through the area, and he apparently confused his notes from the Silver Bluff section with his description of outcrops on the Cape Fear River in North Carolina, approximately 225 mi to the northeast, where Cretaceous sediments of the Black Creek and Peedee formations are exposed. Many of the same words and phrases in Bartram’s description of Silver Bluff reappear identically in his accurate account of the North Carolina Cretaceous outcrops.

In 1831 Silver Bluff became the site of the plantation of James Hammond, a leading southern intellectual, governor of South Carolina from 1842 to 1844, and U.S. senator fro 1857 to 1860 (Faust, 1982). Hammond, interested in increasing the productivity of his land, decided to experiment with marl. This had been recommended by Edmund Ruffin, a plantation owner and member of the Virginia aristocracy (Ruffin, 1843, p. xvii) who promoted application of limestone to the exhausted soils of the southeast. Hammond, using slave labor, barged limestone from Shell Bluff, on the Georgia side of the Savannah, upstream to Silver Bluff, approximately 11 mi by the present course of the river, to apply to his fields where shell fragments can still be seen. The famous outcrop at Shell Bluff has been visited by many geologists, including Charles Lyell (Lyell, 1845, p. 158).

As governor, Hammond was instrumental in getting Ruffin to come to South Carolina to find limestone and encourage its use, and the two agricultural experimenters became close friends, Ruffin being a frequent visitor to Silver Bluff (Faust, 1982, p. 114 – 116). Ruffin was such an enthusiast that a newspaper stated “During his late exploration of soil through South Carolina, it was remarked of him, that he was so full of calcareous manures, that if you poured any sort of acid, acetic, or nitric, on his head he would effervesce, and indicate the presence of lime” (Mitchell, 1981, p.

48). As a result of his exploration for limestone, Ruffin published one of the early reports on geology of South Carolina (Ruffin, 1843) and was referred to by Hammond as South Carolina's greatest benefactor (Mitchell, 1981, p. 48).

The Virginian was an ardent secessionist. He is reported to have fired one of the first shots a Fort Sumter, perhaps the one that narrowly missed Abner Doubleday, who is said by some to have fired the first return shot (Halsey, 1963, p. 29). Ruffin then traveled north to take part in the first battle of Bull Run as an infantryman. At the time, he was 67 years old. A few months after Lee's surrender, Ruffin, deciding that he was unable to live under the rule of the "perfidious, malignant, & vile Yankee race", shot himself (Mitchell, 1981, p. 256).

Upon the election of Lincoln, Hammond resigned from the U.S. Senate. His term as governor had also ended on an unpleasant not when it became known that he had been indulging in improper behavior with four teenage sisters of Wade Hampton III (Faust, 1982, p. 241 – 245), Civil War general, governor of South Carolina from 1877 to 1879, and U.S. senator, 1879 to 1891.

Silver Bluff is now deserted.

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