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SOUTHEASTERN GEOLOGY

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BEACH CHANGES AT THE LOCATION OF LANDFALL OF HURRICANE ALMA*

By

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ABSTRACT

Within the past 5 years, several hurricanes have caused considerable damage to beaches in the low-energy environment of the Big Bend area of Florida. Of these, hurricane Betsy was the most destructive, although this storm did not touch the Big Bend directly. In contrast, hurricane Alma scored a direct hit, the eye passing over Florida State University's "Old" Marine Lab on Alligator Spit, but beach damage was relatively minor, compared to Betsy. Plane-table surveys, bracketed around the landfall of hurricane Alma, quantitatively revealed the beach loss and clearly showed the retreat of the forward-dune apron, a retreat which is irreversible at the survey site.

The discrepancy in beach retrogression caused by these hurricanes was largely determined by the presence respectively absence of a significant hurricane surge. Such surges, and the associated air-sea-land interactions are only partially understood and difficult to predict with accuracy. They are nevertheless of great interest to geologists, because they may have played a very significant role in the geologic past.

Surveys and observations on Alligator Spit over a period of several years revealed continuing beach retrogression in many places, but almost no systematic seasonal beach-profile changes. The dynamic characteristics of the investigated beaches are similar to those of the beaches on Sapelo Island, Georgia, studied by Pilkey and Richter (1964) and fundamentally different from those of the intensely investigated beaches in the high-energy environment of southern California. In view of the significant beach retrogression at many localities, and the ever increasing population pressure on coastal areas, continuing detailed studies of the mechanisms and trends of beach changes in the Southeast are needed.

*Florida State University, Department of Oceanography, Contribution No. 234.

INTRODUCTION

In the past 5 years, 4 hurricanes have caused damage to the coastal areas of the "Big Bend" of Florida. These hurricanes were: Dora and Hilda in the fall of 1964, Betsy in late summer 1965, and Alma in June 1966. The geomorphic work performed by these hurricanes was evaluated on one survey site near Florida State University's "Old" Marine Laboratory on Alligator Spit, about 60 km south of Tallahassee (Figure 1).

This site was first investigated during a series of terrain-analytical studies in low and "zero"-energy environments for the U. S. Army Corps of Engineers (Warnke, 1964, 1965). Because several of the beaches surveyed during this initial period seemed to be highly unstable, one of the sites, FSU 5, was continued to be studied, with surveys bracketed as closely as possible around hurricane surges. Surveys were carried out with a K & E self-indexing alidade. Details of the methodology and the history of beach retrogression from 1964 to 1966 are given by Warnke (1967).

Several morphological units comprise the investigated site, namely a dune ridge, a blow-out in the ridge, and the beach itself. The site is on the south side of Alligator Spit, facing the open Gulf (Figure 2). The area is classified as a low-energy environment, as defined by Tanner (1960). For a detailed description of the location, refer to Warnke (1967).

To summarize the previous findings: beach retrogression at the survey site was largely independent of the distance between the site and the eyes of the hurricanes at the "time of damage." Dora and Hilda reached the Tallahassee area, but only after they had travelled considerable distances over land, thereby losing energy (there is disagreement in the literature, however, over the exact path of hurricane Hilda after its landfall west of the Mississippi Delta). Hurricane Betsy did not touch the Big Bend area directly, but crossed the Gulf of Mexico in a gentle arc from the southern tip of Florida to the Mississippi Delta (Warnke, 1967, p. 54, Figure 6). Average wind speeds in the Tallahassee area during the days of damage were similar for all three hurricanes, about 6-7 m/sec; prevailing wind directions were 200° for Dora, 180° for Hilda, and 100° for Betsy.

Greatest damage to the coasts of the Big Bend was caused by hurricane Betsy, although neither wind speeds nor wave heights were excessive. However, the storm caused a surge, whose peak in the Big Bend area appeared to have been almost simultaneous with the astronomical high tide. The observed high tide in the afternoon on 9 September 1965 was 70 - 75 cm above normal. In this fashion, the available moderate wave energy was directly spent on the forward dune apron, causing its rapid retrogression and re-adjustment of the beach profile.

Permanent personnel, stationed at Florida State University's "Old" Marine Lab on Alligator Spit, noticed unusually low water in the

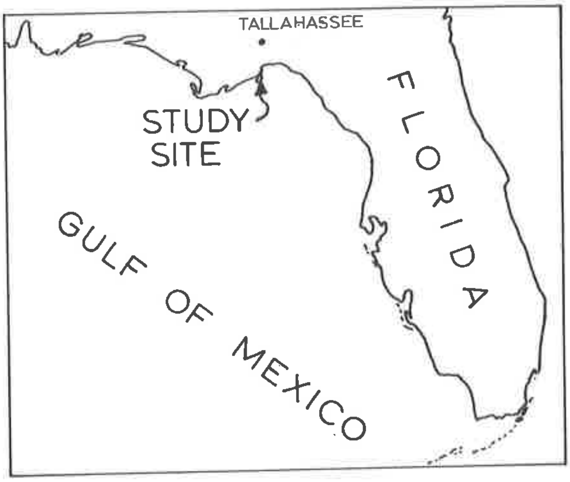

Figure 1. Index map.

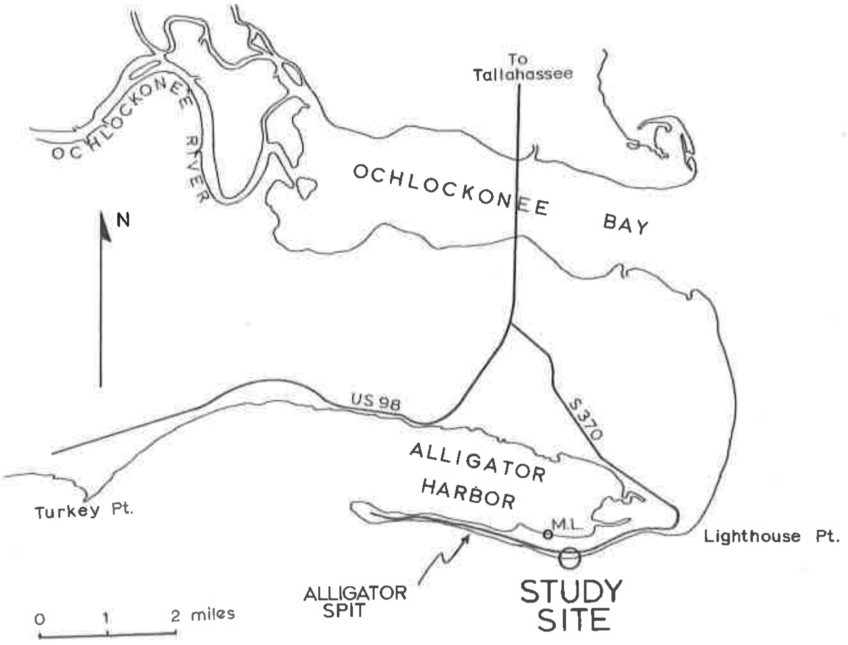

Figure 2. Alligator Spit and vicinity. M. L. = "Old" Marine Laboratory of Florida State University

evening of 8 September at the time of the expected low tide. It is also pertinent that Harris (1963), analyzing tide records from the Big Bend, found secondary oscillations of significant magnitude associated with hurricanes in 1926 and 1947, whose tracks were very similar to that of Betsy. These analyses and the above mentioned observations seemed to point to the possibility of positive interference between the tide wave and the storm surge (Warnke, 1967).

As tempting as it might be to speculate on the possible geologic significance of such interaction processes with regard to the geologic past, and as sinister as our conclusions might be concerning the possibility of large-scale flooding of the coastal area, extrapolations will have to wait until analyses of the tide records become available. Once the magnitude and progression of the hurricane surges become known, it will perhaps be possible to evaluate the role of the individual processes whose combination led to the retrogression at the survey site.

Acknowledgments

It is a pleasure to thank all those associates of the writer's who participated in the surveys, foremost among them Messrs. C. Early, V. Goldsmith, P. Grose, J. Holt, R. Kania, R. Murray, and J. Richter.

HURRICANE ALMA

Against this background it seemed desirable to observe the effect of a hurricane scoring a direct hit on the survey site. Nature provided Alma. On 9 June 1966, this hurricane crossed the Big Bend coast south of Tallahassee. At that time, the occurrence of a hurricane surge was expected at the time of the astronomical high tide in the early morning hours of 10 June 1966. This surge, however, did not materialize, even in the areas near the eye of the hurricane. Damage caused by Alma was minor, and beach retrogression was relatively small, at least in comparison with hurricanes Hilda and Betsy.

Figure 3 shows the track of hurricane Alma, paralleling the west coast of peninsular Florida before its landfall. The hurricane was predicted to cross inland to the west of Alligator Spit. Instead, it veered to the east, the left (western) periphery of the eye passing over the Spit. The synoptic situation on 9 June 1966, 1300 hrs. EST, at the time of landfall, is shown in Figure 4. This chart shows the typical hurricane-circulation pattern that still prevailed at the time of the landfall. For a satellite picture of this situation, refer to Anonymous (1966).

At the approach of the hurricane, a self-recording anemometer was set up at the end of the pier of the Marine Lab. This location is sufficiently far away from any buildings and obstructions so that the data can be taken as representative.

Wind speeds and directions associated with the passage of hurricane Alma are shown in Table 1. In this table, wind directions are

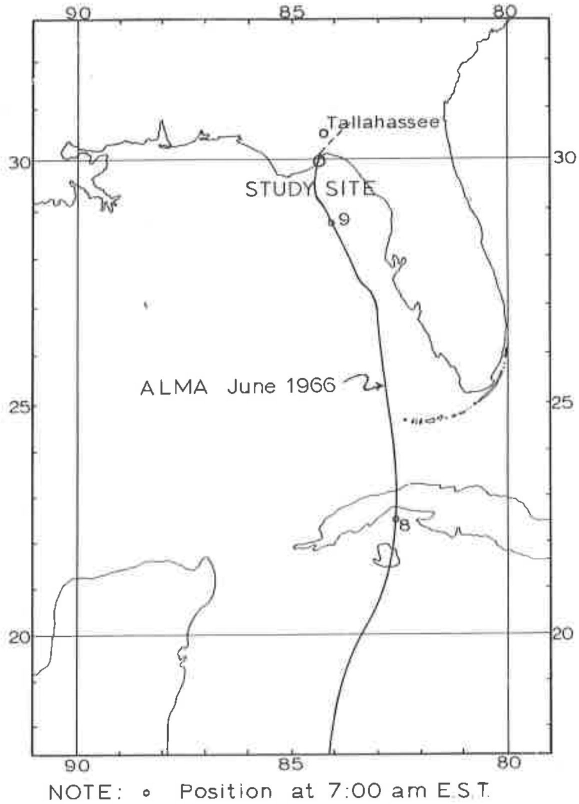

Figure 3. Track of hurricane Alma.

those indicated on the anemometer record at the time shown. Average wind speeds are given for the hourly intervals following the times shown in the table. These wind speeds are computed by averaging the "wind run" for the time interval involved (1 hour) and by applying the necessary correction using the nomogram supplied by the manufacturer. The passage of the eye over the Marine Lab at 1300 hours is clearly indicated in Table 1. For about 20-30 minutes, according to personnel stationed there, the usual calm prevailed, resulting in the relatively low average wind speed for that hour.

Maximum wind speeds of about 50 m/sec were observed just prior to the arrival of the eye of the hurricane. Wave height in the lagoon at that time was about 120 cm. These breaker heights are in excess of any observed during the passage of hurricanes in the previous 2 1/2 years. The northeasterly wind direction probably resulted in lower wave heights on the oceanward (lee) side of the spit, but direct observations are not available.

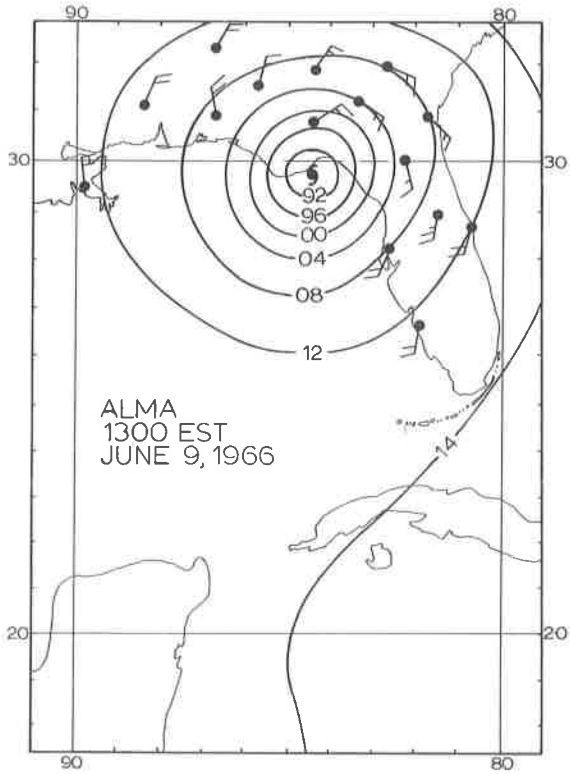

Figure 4. Synoptic chart at time of landfall of hurricane Alma. Drawn from U. S. Weather Bureau Facsimile.

BEACH RETROGRESSION

The amount of retrogression at the survey site is indicated in Figures 5 and 6. Maps and profiles labelled "Sept., 17, 1965" depict the situation on that date, 6 days after the passage of hurricane Betsy. Something resembling "equilibrium" had been re-established, and the profiles (Figure 6) show a weakly developed berm.

Maps and profiles of 5 May 1966 show the configuration of the site prior to the beginning of the hurricane season. A certain amount of apparent beach loss had occurred during the winter and spring months, but this particular change in the configuration of the beach is to a large extent a reflection of short-term phenomena, such as destruction and construction of the berm, and is not necessarily indicative of beach retrogression. The modification of the forward-dune apron (Figure 6, Profile A-A') is due to slumping after 17 September 1965, at which time the face was still oversteepened because of the erosion caused by hurricane Betsy.

Table 1. Wind Speeds at "Old" Marine Lab, Alligator Spit.

Hour	Direction	Speed (in m/s)	Hour	Direction	Speed (in m/s)
1600	75°	3.0	1800	285°	14.6
1700	105°	11.5	1900	270°	13.3
1800	90°	10.5	2000	270°	12.7
1900	85°	10.2	2100	270°	11.1
2000	60°	10.5	2200	270°	11.1
2100	65°	11.1	2300	250°	10.7
2200	75°	10.7	0000	275°	10.2
2300	60°	11.1	0100	270°	10.2
0000	75°	12.5	0200	270°	9.1
0100	45°	12.7	0300	275°	9.1
0200	40°	14.0	0400	285°	8.4
0300	45°	14.5	0500	285°	8.7
0400	35°	15.6	0600	300°	8.7
0500	35°	16.4	0700	300°	8.4
0600	45°	16.6	0800	295°	9.0
0700	50°	17.0	0900	300°	9.0
0800	85°	19.0	1000	325°	9.7
0900	70°	19.9	1100	310°	8.7
1000	60°	20.0	1200	310°	8.7
1100	60°	20.0	1300	300°	7.5
1200	45°	19.4	1400	310°	5.0
1300	45°	7.7	1500	310°	5.5
1400	315°	13.3	1600	240°	6.0
1500	290°	17.5	1700	255°	5.0
1600	285°	17.5	1800	260°	4.0
1700	275°	16.6	1900	270°	3.8
			2000	260°	

Profiles B-B', across a "blow-out" in the dune ridge show a general lowering of the surface, and this lowering, landward of the berm, may possibly have been permanent, although temporary fluctuations of similar magnitude had been observed earlier (Warnke, 1967, p. 52, Figure 5).

A survey, conducted on 11 June 1966, just after the passage of hurricane Alma, revealed the beach loss as shown in the maps and profiles of Figures 5 and 6. Especially the retreat of the forward-dune apron (Profile A-A') is clearly indicated. Such retreat of the forward-dune apron at the survey site is irreversible, regardless of the amount of beach restoration subsequent to the passage of a hurricane.

Contrasted to the beach retrogression caused by this hurricane, the damage caused by hurricane Betsy was far greater - although Betsy did not affect the area directly, and wind speeds and waves associated with her passage were not excessive (Warnke, 1967). The most im-

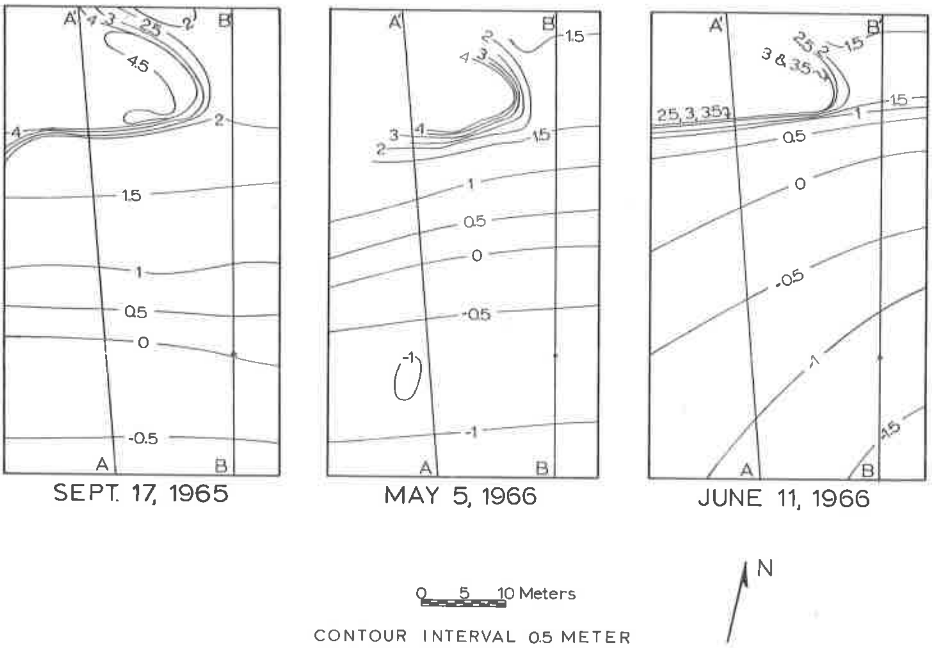

Figure 5. Maps of study site. Zero contour line approximates MSL. Small triangle indicates TBM.

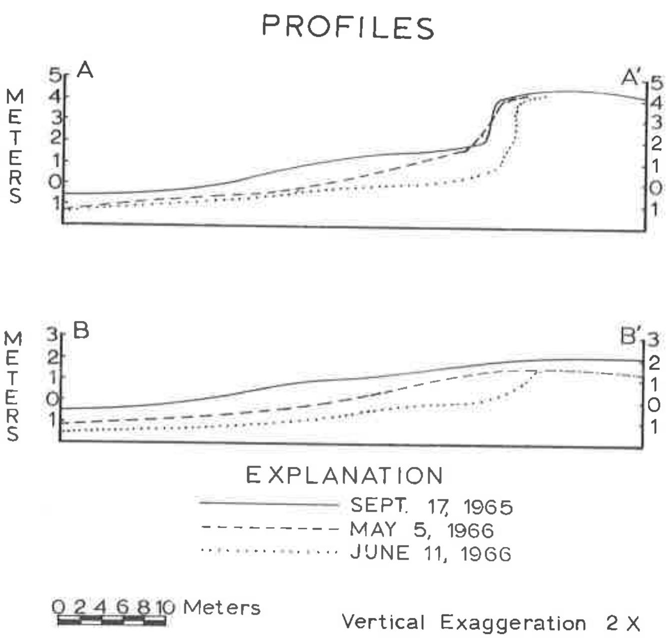

Figure 6. Profiles of study site.

portant determinant for the amount of retrogression was the presence resp. absence of a significant hurricane surge.[1] Whereas the surge associated with hurricane Betsy coincided (and perhaps interfered) with the high tide of an ill developed spring tide on the "day of damage," no large surge followed hurricane Alma, despite all warnings and predictions. Sea level rose perhaps 30-60 cm by witness accounts, but since this rise occurred during the period of an ill-developed neap tide (Table 2), erosion was minor and apparently restricted to a few hours.

Table 2. Expected Tides at St. Marks River Entrance.

Date	Time, EST	Expected Tides meters*
9 June, 1966	0012	0.12
	0700	0.79
	1136	0.58
	1754	0.91
10 June, 1966	0106	0.21
	0748	0.79
	1336	0.55
	1906	0.85

*At St. Marks, from Tide Tables, U. S. Dept. of Commerce, converted to metric units. Heights are reckoned from mean low water. Tides at study site about 20 min. later. Tidal range approximately the same.

This relatively minor amount of retrogression is due to several factors: the hurricane itself was not very strong, at least not in the Big Bend area. Nevertheless, it was still well defined at the time of landfall, as pointed out above. The geographic outline of the coastal area and the wind directions certainly had a diminishing effect: northeasterly wind directions just prior to landfall (Figure 4; Table 1) prevented a significant wind set-up because of limited fetch, and westerly and northwesterly directions after the passage of the eye similarly prevented a rise in sea-level due to set-up. Wind stress therefore to some degree counteracted the effect of the pressure field.

Since the hurricane had travelled the length of the West Florida Platform (shelf), parallel to the peninsular coast, certain surge-

1 Hurricane surges are highly complex phenomena. The interpretation given here is of necessity rather simplistic. For descriptions of characteristics of, and forecasting schemes for, hurricane surges, see Harris, 1956, 1959, 1963; Jelesnianski, 1966, i. a.

prediction schemes (see Jelesnianski, 1966) were not applicable, and this inapplicability at the present time makes futile any attempt to correlate quantitatively the geologic work performed by the hurricane surge with meteorologic conditions.

A mathematical model (Jelesnianski, 1966) for a geographic-meteorological situation not unlike the one under consideration suggests the following: A drop in sea level just preceding the center of the hurricane, followed by a large positive surge, followed in turn by resurgences. According to personnel stationed at the Marine Laboratory, sea level was about 15-30 cm below normal in the morning hours of 9 July 1966. This observation, and the minor height of the hurricane surge which followed (even at the time of the astronomical high tide), might perhaps suggest destructive interference between the surge and the tide wave, or at least with a partial tide. In the absence of appropriate tide-record analyses however, these ideas are speculative.

Nevertheless, the possibility of such interference phenomena should be kept in mind, and evidence for them should be looked for, because of the obvious implications for the geologic past: certain short-term transgressions, as evidenced for instance in the Triassic stratigraphy of Central Europe, might at least find a partial explanation in such interaction processes (for a review of the problem, and an alternate interpretation of the stratigraphic succession, see Wurster, 1965). Similarly, the enormous transport volumes and strong currents that could be set up by such processes in shallow epeiric seas might have played a significant role in the deposition of blanket sands and sand waves, known from the stratigraphic column. Such mechanisms should at least be considered as an alternate working hypothesis in addition to the one advanced by Merifield and Lamar (1968) who proposed strong tidal currents at the beginning of the earth-moon system, perhaps in the late Precambrian, as a possible transport mechanism.

LONG-TERM TRENDS AND SHORT-TERM CHANGES

Fifteen beaches along the west Florida Big Bend and Panhandle coast were investigated by Gorsline (1966). These studies were conducted at monthly intervals during 1962, and the results of these investigations seemed to indicate that most of the beaches were in "near equilibrium" (Gorsline, 1966, p. 199).

Our surveys which began in the fall of 1963, do not corroborate these findings. Continued surveys at the study site described herein, intermittent surveys at nearby locations, and inspections of locations investigated during the initial terrain-analysis (Warnke, 1964) revealed beach retrogression in many areas. Beach retrogression by itself does not necessarily indicate whether or not a beach is "in equilibrium," but the nature and magnitude of this retrogression point to the conclusion that the retrograding beaches have not yet attained equilibrium, at least not if long-period trends are considered.

After the passage of hurricane Alma, and up to the time of writing, 1968, retrogression at the study site has continued, although at a greatly reduced rate. This is a periodic phenomenon, associated with storm surges, windstau during periods of steady air-flow from the south (but otherwise "normal" weather conditions), and perhaps wave set-up on the beach. Some of this retrogression is compensated by beach progradation, for instance at the shoals off the western half of Alligator Spit (Warnke, 1967, Figure 7).

Short-term beach profile changes during the survey period seemed to be only dependent on local wave and tide conditions and revealed almost no systematic seasonal changes. This is in agreement with Gorsline's (1966) conclusions. Pilkey and Richter (1964) investigated seasonal beach-profile changes on Sapelo Island, Georgia. They concluded that most of their study area was being eroded, and that seasonal changes were almost negligible when compared to those occurring in high-energy environments, for instance in southern California. It seems that the dynamics of the Big Bend area beaches are similar to those on Sapelo Island, although there are of course differences, especially in average energy level. Nevertheless, both the Sapelo Island and the Big Bend beaches are fundamentally different from those on the West Coast.

Therefore, great caution has to be exercised in extending the results of beach-change studies in California to coastal areas in the Southeast. In view of the significant beach retrogression and the ever increasing population pressure on these coastal areas, detailed studies - on a regional scale - of the mechanisms and trends of beach changes in the Southeast are urgently needed.

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STRATIGRAPHY OF THE CAROLINA CRETACEOUS

By

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ABSTRACT

The Cretaceous section of the Carolina Coastal Plain comprises a seaward thickening wedge of clastic sediments that is exposed in a northeast trending belt 80 km wide by 140 km long on the nose of the Cape Fear Arch. It is readily divisible into three lithologic units. These have been named the Tuscaloosa Formation (pale sand with clay lenses), Black Creek Formation (dark, laminated clay interbedded with sand), and Peedee Formation, (dark, muddy sand). However, careful study shows that the most significant contact is within the "Tuscaloosa" Formation, which consists of a basal estuarine unit of early Cretaceous (?) age, here named the Cape Fear Formation, and an upper fluvial unit of Upper Cretaceous age, here named the Middendorf Formation. The Middendorf, Black Creek and Peedee are time-transgressing Upper Cretaceous facies which were respectively deposited by fluvial, estuarine, and open shelf environments of the transgressing late Cretaceous sea. The Middendorf - Black Creek contact appears to be an interfingering one. The Black Creek - Peedee contact is a ravinement, or disconformity cut by the transgressing Peedee sea. It is of negligable time value, except in the Cape Fear River valley where the *Exogyra cancellata* zone, elsewhere basal Peedee, may be missing. If it is in fact missing, ravinement may have transpired in this sector at a later time. The Snow Hill biozone is assigned in this report to the basal Peedee Formation, in accord with recent studies. It is proposed that the genetic integrity of the Middendorf-Black Creek-Peedee sequence be recognized by the formal application of the name Lumbee Group.

The Cretaceous-Tertiary boundary is, in most areas of outcrop, a disconformity. Where this upper Peedee is overlain by the basal Black Mingo the missing strata lie within the Danian and Maestrichtian stages. On the nose of the Cape Fear Arch, however, the Peedee is

overlain by 6 meters of Cretaceous limestone and quartz arenite, here informally designated the Rocky Point member of the Peedee Formation. The Rocky Point member is a littoral lithosome deposited during regression of the Peedee sea.

In the proximal subsurface, in northeastern North Carolina, the Peedee is overlain by the Paleocene Beaufort Formation composed of glauconitic sandstone and impure limestone. The relationship has been described as pseudo-offlap but is not adequately resolved by the water well logs. In the distal subsurface, as revealed in the coastal oil test wells, there is an apparent uninterrupted sequence of Cretaceous and Cenozoic sediments. Inspection of electric logs suggests that the Peedee rests directly on marine beds of Austin age or older, without the intervention of estuarine Black Creek of fluvial Middendorf. It is suggested that a decrease in the rate of sea level rise, or a reduction of paleoslope, or both, caused the relatively undifferentiated lithotopes of the lower Cretaceous to break up into the three well-defined lithotopes which gave rise to the formations of the Lumbee Group.

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INTRODUCTION

The most conspicuous structural element of the Carolina Coastal Plain is the Cape Fear Arch of North and South Carolina. Over the arch Tertiary sediments have been reduced by erosion to scattered patches, and the Cretaceous sediments, elsewhere mostly concealed, crop out from the Fall Line almost to the sea (Figures 1, 2) in an area greater even than the classic Cretaceous outcrop area of New Jersey. The wedge of Cretaceous thus exposed is readily divisible into three units. A pale, coarse, basal sand rests on the crystalline basement and has been correlated with the Tuscaloosa Formation of Alabama (Cooke, 1936). In this paper it is divided into the Cape Fear Formation (basal unit) and the Middendorf Formation (upper unit). Towards the sea, the Middendorf passes by facies change into the Black Creek

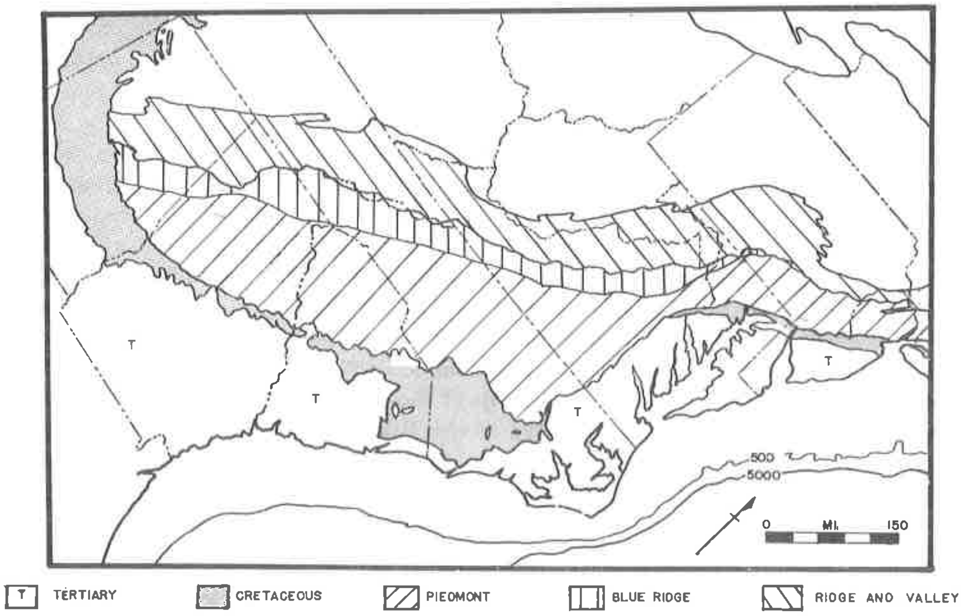

Figure 1. Outcrop area of the Atlantic Coast Cretaceous and its Appalachian sourceland. After Eardly, 1951.

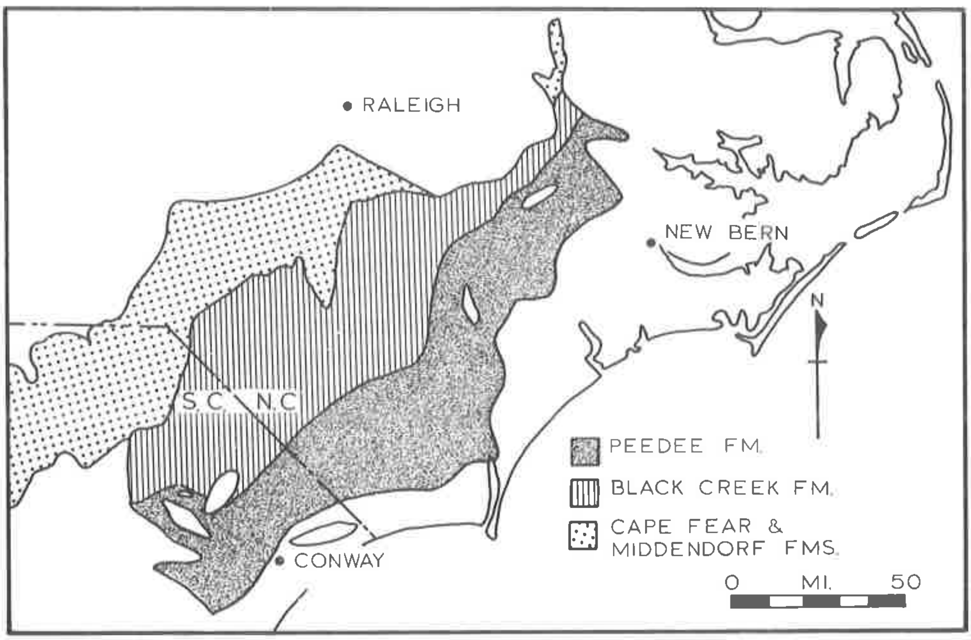

Figure 2. Outcrop areas of the Cretaceous formations in North and South Carolina.

Formation, comprising rhythmically interbedded pale sands and dark clays with little lateral continuity. Further seaward, the Black Creek passes in turn into the massive, dark gray, muddy sand of the Peedee Formation.

There has been no comprehensive study of this sequence since the publication of The Cretaceous Formations of North Carolina by Lloyd W. Stephenson in 1923. While this biostratigraphic analysis must remain the foundation for all further work, a re-evaluation of the Carolina Cretaceous in the light of modern sedimentological concepts is in order. To this end the authors have undertaken a detailed sedimentological and stratigraphic study of the Carolina Cretaceous. Analyses of the depositional environments of some of the component formations are being presented elsewhere (Swift and Heron, 1967; Heron, Swift and Dill, 1968; Swift, Heron, and Dill, 1969). Analyses of other formations are in preparation. This paper will systematically examine the stratigraphy of the entire Cretaceous section.

Acknowledgments

We gratefully acknowledge the advice and criticism of Walter W. Wheeler and Roy L. Ingram of the University of North Carolina. The paper has been critically read by Robert Jordan of the University of Delaware, Henry S. Johnson, Jr. of the Division of Geology, South Carolina State Development Board, and W. J. Furbish and Ronald Perkins of Duke University. We are grateful for the suggestions of these geologists but we assume full responsibility for the contents of this paper.

The studies were conducted with financial support from the North Carolina Department of Conservation and Development, the South Carolina State Development Board, the National Science Foundation, the Geological Society of America, the Society of Sigma Xi, the North Carolina Academy of Sciences, Duke University and the Smith Fund of the University of North Carolina. Wallace Fallaw and William D. Reeves served as field assistants. The authors express their appreciation and thanks to these organizations and individuals.

THE BASAL CRETACEOUS FORMATIONS

From New Jersey southwestward through Delaware, Maryland, Virginia, the Carolinas, Georgia, and westward into the Gulf Coastal Plain the oldest exposed Coastal Plain sediments are a group of sands and clays of similar origin and similar appearance. These sediments have been studied, subdivided, and correlated by practically every Coastal Plain stratigrapher from Fontaine's time (Fontaine, 1890) until today. The history of the terminology and correlation (Heron, 1958b) is long and complex and is filled with many examples of correlations

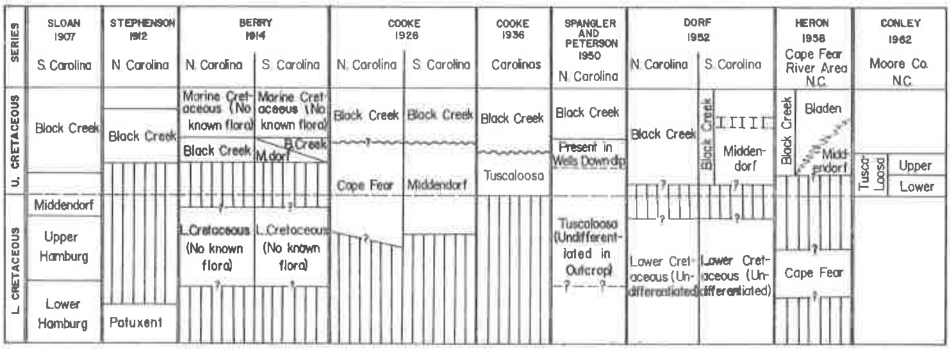

Figure 3. History of Cretaceous correlation in the Carolina Coastal Plain. From Heron, 1958.

made with a knowledge of the available but inadequate evidence and what H. H. Read (1952, p. 58) called "a generous species of low cunning." Most of the correlation and terminology problems with the basal Cretaceous sediments are caused by (1) virtual lack of fossils, (2) poor exposures, (3) similar lithologic characters, (4) lack of extensive unified studies, (5) failure of workers to utilize previous knowledge, (6) long distance correlation, and (7) failure to distinguish between rock stratigraphic and time stratigraphic units.

CAPE FEAR FORMATION

Prior to 1958 the outcropping basal Cretaceous sediments of North Carolina were grouped together into one formation variously called the Cape Fear (Stephenson, 1907; Cooke, 1926), the Patuxent (Stephenson, 1912), and the Tuscaloosa (Cooke, 1936). Heron (1958a) subdivided these sediments into two units and used names previously applied in North or South Carolina, the Cape Fear and the Middendorf (Figure 3).

The term Cape Fear as originally used by Stephenson (1907) included only the exposures on the Cape Fear River below Fayetteville and those on the Neuse River, Contentnea Creek and Tar River. In 1912 Stephenson grouped the Cape Fear with the sediment of the Sandhills of North Carolina into the Patuxent Formation. In 1926 Cooke believed that a local name was necessary for the beds in North Carolina, so he referred all of the Patuxent (the river exposures and the Sandhills) to the Cape Fear Formation. Later (1936) he correlated these sediments with the Tuscaloosa Formation of Alabama and designated the basal Cretaceous sediments of a part of Georgia, all of South Carolina and North Carolina as the Tuscaloosa Formation (Heron, 1958b).

Heron (1958a, 1960) and Heron and Wheeler (1959, 1964)

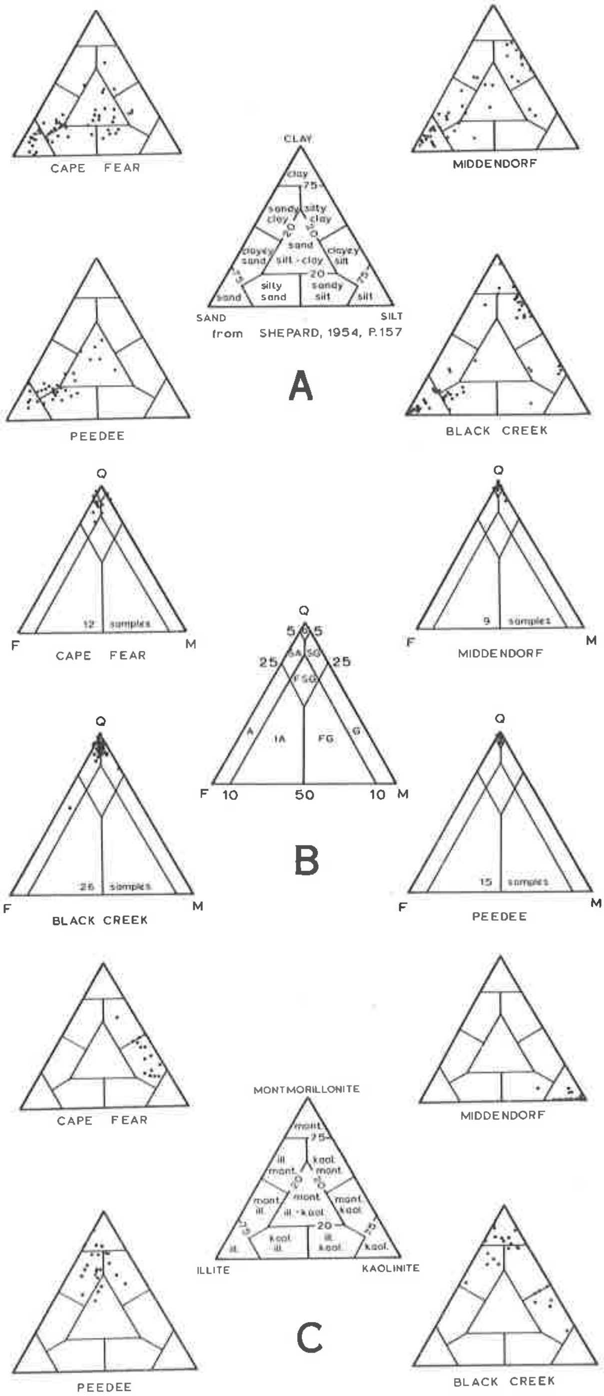

Figure 4. Textural and compositional data from the basal Cretaceous. A: Sand-silt-clay ratios. B: Sandstone compositions. C: Clay mineral suites.

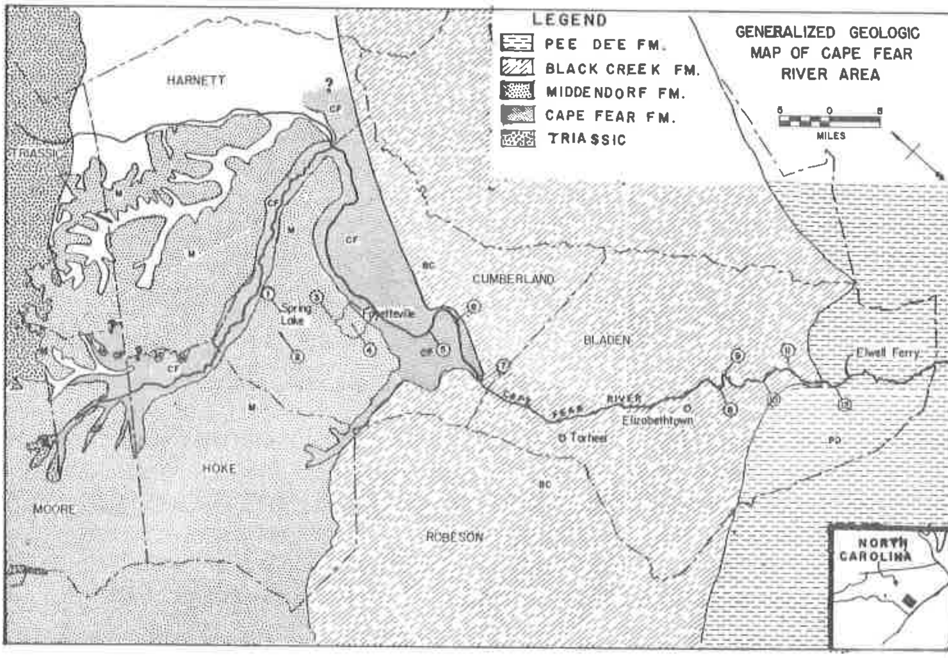

Figure 5. Outcrop area of the Cape Fear Formation (CF) in the Cape Fear River Valley. Numbers refer to localities in Heron and Wheeler, 1964.

recognized that the Tuscaloosa Formation in North Carolina is actually two genetically unrelated sedimentary units. The upper unit, designated the Middendorf Formation, consists of a heterogenous sequence of lenticular clays, muddy sands, clean sands, and pebbly sands. The clay minerals are mainly kaolinite (Figure 4). Beds are lenticular, with continuities of 100 meters or less (Heron, 1958a). A lower unit is easily distinguished in the Cape Fear Valley. It's beds are continuous for as much as two kilometers. They are composed of distinctive graded sand - sandy mud couplets, with pebbly bases. They are medium to light gray (N7-5) where fresh, but yellowish gray (5Y 7/2) and mottled red (5R 5/4) or yellowish orange (10YR 6/6) where weathered (Heron, Swift and Dill, 1968). The lower beds are less texturally differentiated than the upper sequence and lack its clean sands and silty clays. They contain a montmorillonitic kaolinitic clay mineral suite (Figure 4).

This lower unit is essentially the one designated "Cape Fear" by Stephenson (1907). It is here proposed that the name be reaccepted for these basal Cretaceous beds of the Cape Fear River Valley (Figure 5) distinguished by the criteria cited above. The bluff at the down-river side of the junction of Rockfish Creek with the Cape Fear River in Cumberland County is selected as a lectotype section (Figure 6). As defined, the Cape Fear Formation rests on the crystalline basement.

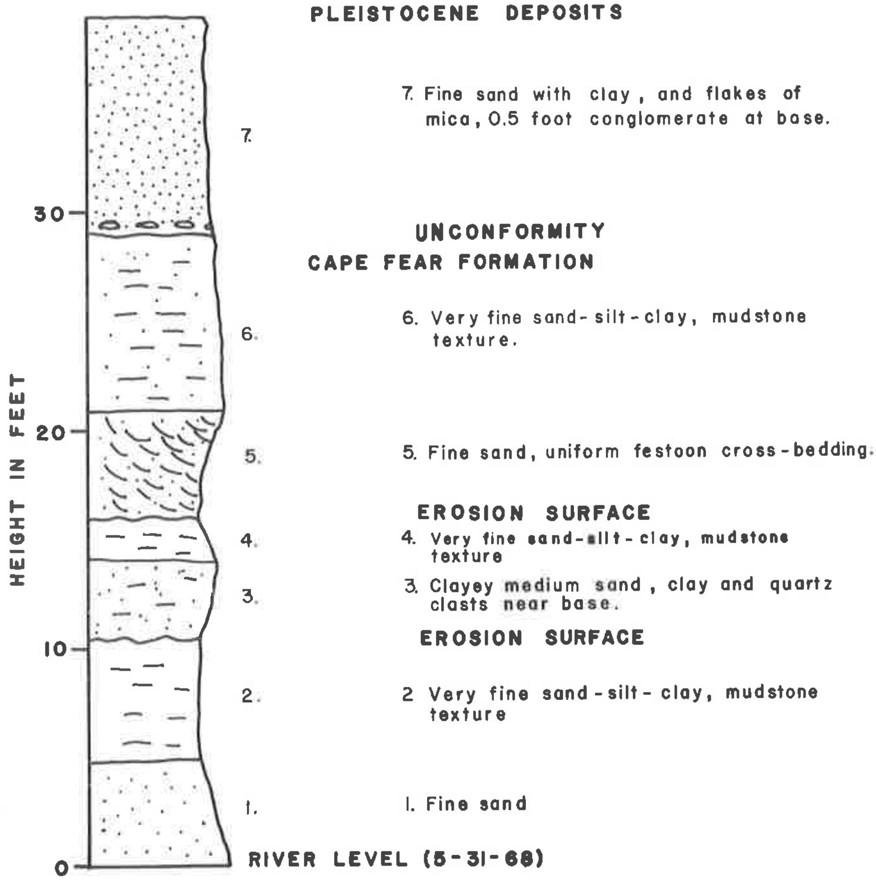

Figure 6. Lectotype section of the Cape Fear Formation, Cape Fear River about 0.4 mile downstream from mile board 109 at mouth of Rockfish Creek.

It is overlain by the Black Creek Formation in the Cape Fear River Valley (Figure 7). Conley (1962) described upper and lower Tuscaloosa units in Moore County, North Carolina. The lower unit is the up-dip extension of the Cape Fear Formation; here it is overlain by the Middendorf. The Cape Fear Formation has been studied in detail only in the Cape Fear River Valley. A similar unit appears in the river exposures to the northeast (Neuse, Tar, Roanoke). Brown (1962, 1963) has recognized an unnamed Lower Cretaceous unit in the adjacent subsurface of northeastern North Carolina with which we correlate the Cape Fear Formation. See Figures 8, 9, and 10 for regional stratigraphic relationships.

The Cape Fear pinches out against the Fall Line in Harnett and Moore Counties. It is presumed to thicken down-dip toward the

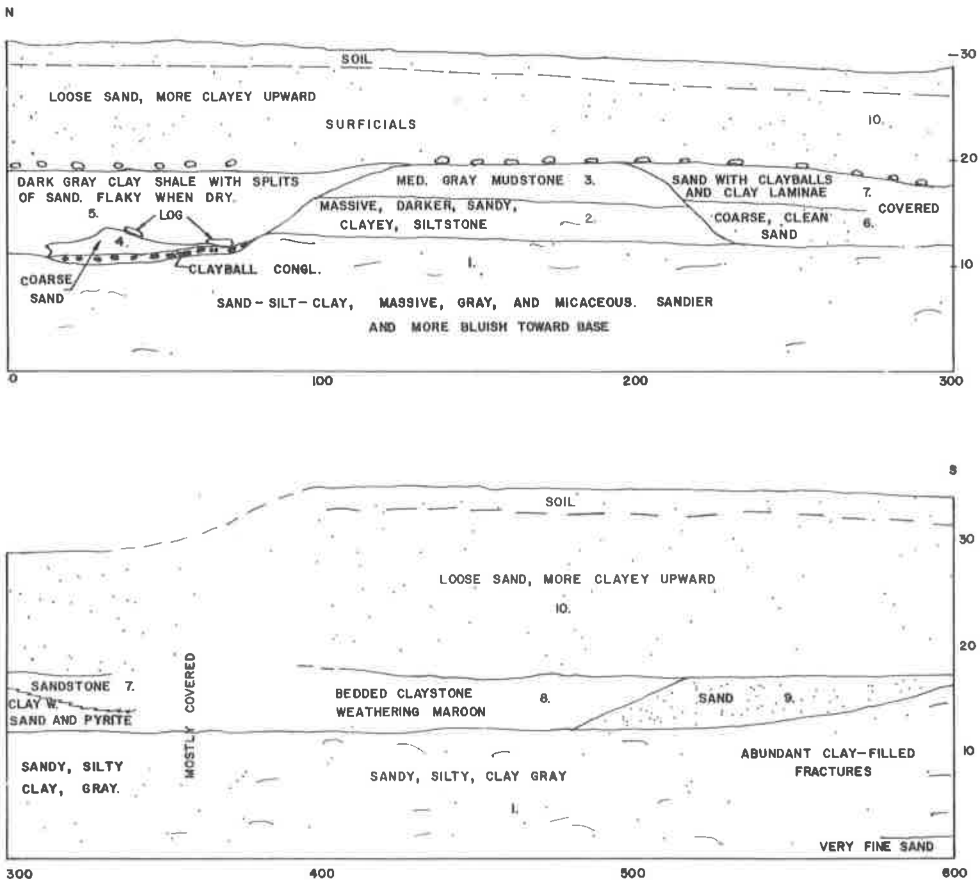

Figure 7. Black Creek - Cape Fear contact, east bank of the Cape Fear River 0.5 mile above mileboard 101. Beds 1-3 are Cape Fear Formation, beds 4-9 are Black Creek Formation, and bed 10 is Quaternary. Dimensions in feet. From Heron and Wheeler, 1964.

fossiliferous marine Lower Cretaceous of the coastal oil wells. It is estimated to be 15-70 meters thick where exposed in the Cape Fear River Valley.

The Cape Fear Formation is essentially non-fossiliferous. Some minor amounts of lignite are found as disseminated chunks in a few of the sand layers, and in at least one place large fragments of twigs and branches occur. About 92 samples from the Cape Fear Formation were washed, floated and examined for microfossils. One foraminifera of the genus Cibicides was found in an outcrop about one quarter mile up-stream from mileboard 109 on the Cape Fear River. The specimen was lost before specific identification could be made. Small lignite chunks

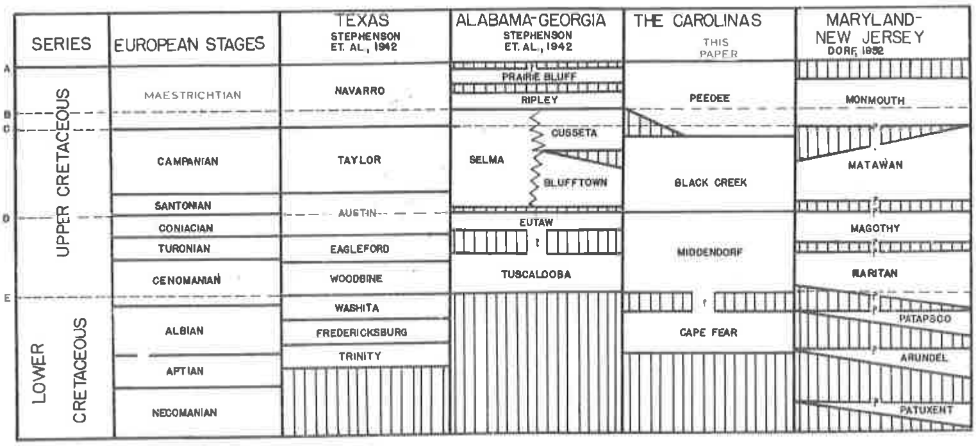

Figure 8. Correlation chart for the Carolina Cretaceous. A = top of Exogyra costata Zone. B = top of E. cancellata Subzone. C = base of E. costata Zone and E. cancellata Subzone, Top of E. ponderosa Zone. D = base of E. ponderosa Zone. E = upper Cretaceous Lower Cretaceous Boundary for the U. S. The section for the Carolinas is drawn parallel to the coast, hence the time transgressing nature of some units is not apparent.

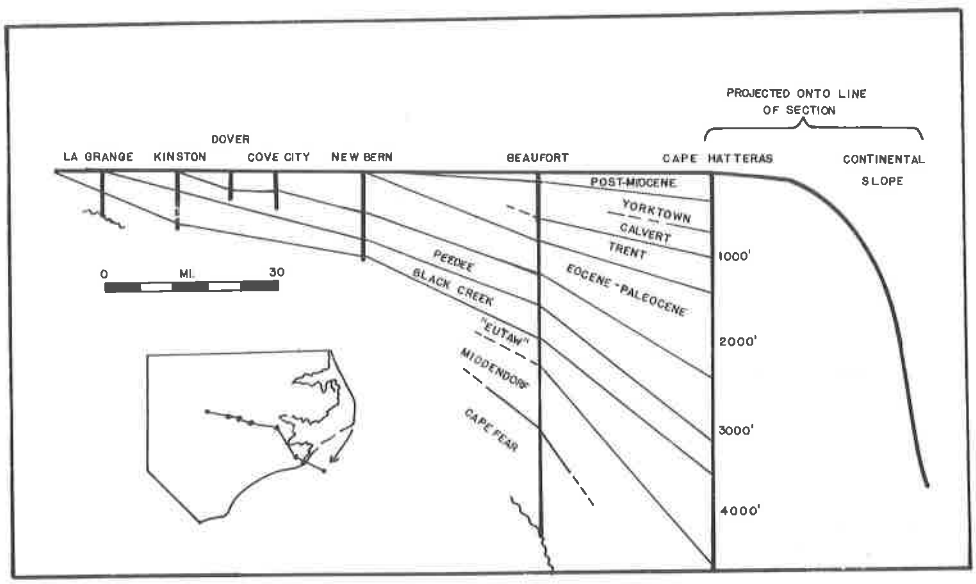

Figure 9. Cross-section through the Carolina Cretaceous. Data from Brown (1958) and Spangler (1950).

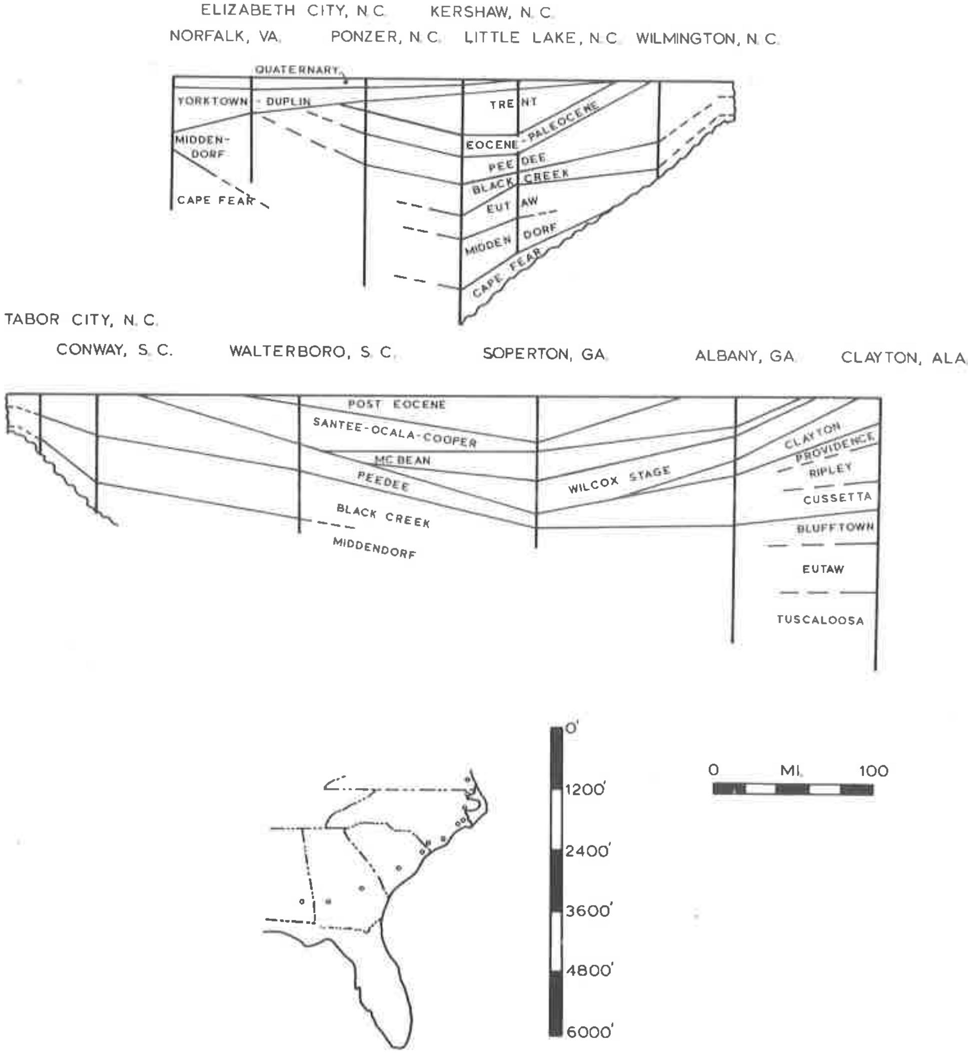

Figure 10. Longitudinal section through the Carolina Cretaceous and lateral equivalents. Data from Spangler (1950) and Richards (1945).

and amber particles were found in many samples. Insect parts and whole insects (possibly not fossil) were also relatively common. Two samples of the Cape Fear Formation were treated for plant spores. They were barren.

Although fossils are absent, the extremely continuous uniform nature of the bedding and lack of zones of mud-cracks, root casts, and disconformities mitigates against a fluvial origin. Since apparently equivalent horizons to the northeast (Brown, 1963) and southwest (Figure 12) are of lagoonal and estuarine origin, it is believed that the stratification may be the consequence of the periodic flushing of such restricted bodies of marine water by river floods (Heron, Swift, and Dill, 1968).

MIDDENDORF FORMATION

The name "Middendorf Phase" was first used by Sloan (1904, 1907, 1908) in South Carolina for sands and kaolin clays lying between the Hamburg and overlying Black Creek Formation "phases". The term Middendorf has had a complex history (Figure 3). Berry (1914) relegated the Middendorf to member rank in the Black Creek Formation. Cooke (1926) raised it back to formational rank and included within it the Patuxent (Hamburg) of South Carolina. In 1936, Cooke discarded the term Middendorf in favor of the Tuscaloosa. Dorf (1952) advocated a return to Middendorf Member of the Black Creek Formation. Heron (1958a, 1960) and Heron and Wheeler (1959, 1964) favored a formational rank for the Middendorf. We propose that the Middendorf Formation, defined by criteria established in the previous section, be readopted for these strata.

Sloan did not designate a type section of the Middendorf Formation, but a railroad cut (Figure 11) on the Seaboard Railroad two miles east of Middendorf (Chesterfield County, South Carolina) is described by Sloan (1904, p. 108) and generally accepted as the type section. The general lithology at this outcrop has been traced southwest toward Columbia, South Carolina, and north at least as far as the Cape Fear River. The outcrop of the Middendorf approximately coincides with the Sandhills of the Carolinas, but the southeastern boundary of the Sandhills is the Citronelle Escarpment of Doering (1960) (Orangeburg Scarp, Colquhoun, 1962; Johnson and Du Bar, 1964), a Miocene shoreline feature unrelated to the Middendorf Formation. Near Columbia, South Carolina, the Middendorf is overlapped by Eocene sediments. To the northeast in Harnett and Johnson Counties, North Carolina, the Sandhills and most of the Middendorf is overlain by sands of the Miocene(?) Pinehurst Formation and by patches of Eocene sediments (Bartlett, et al., 1968). The Middendorf is estimated to be less than 70 meters thick where exposed. It is presumed to thicken seaward into the fossiliferous marine Cretaceous of the coastal wells.

The Middendorf Formation is locally overlain by Cenozoic sediments ranging in age from Eocene to Recent(?). Many of these younger sediments are distinctive enough in lithology to be easily differentiated from the Middendorf. Others are composed of reworked Middendorf gravels, sands, and clays that can easily be mistaken for Middendorf sediments. Often it is not clear whether a given outcrop is the Middendorf Formation, some local reworked sequence, or a more widespread unit.

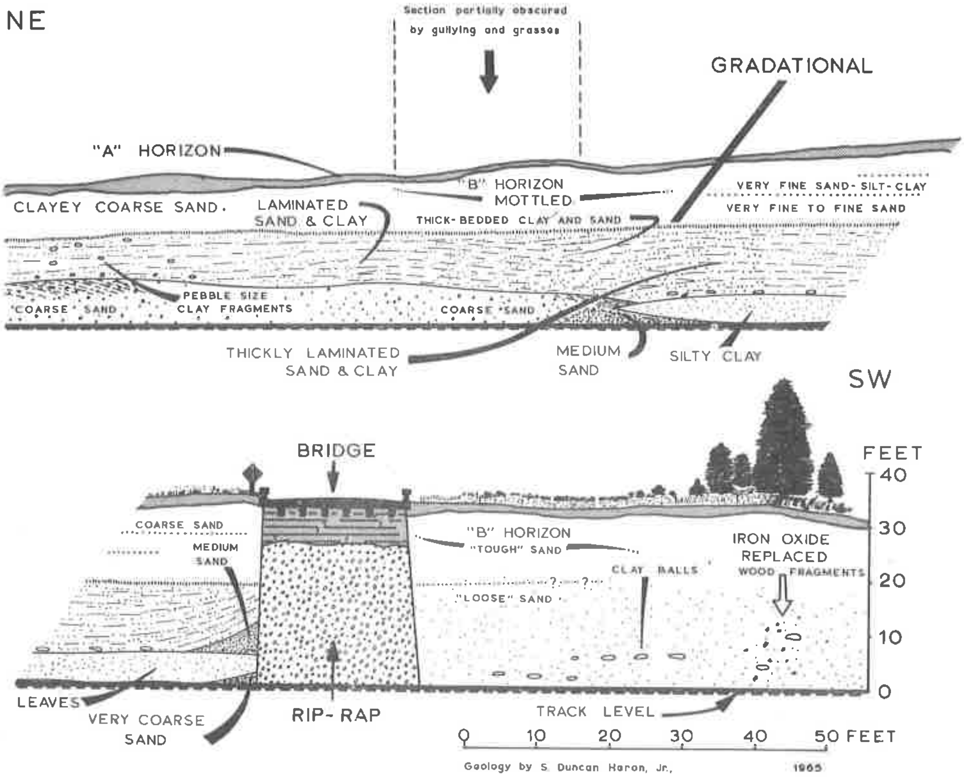

Figure 11. Type section of the Middendorf Formation on the Seaboard Coast Line Railroad, two miles east of Middendorf, Chesterfield County, South Carolina

The Middendorf Formation consists of loose to poorly indurated sands, thin layers and lenses of gritty mud to silty clay, and rare, laminated layers of sand and mud. Clay ball conglomerates are usually associated with the muds. As in the Cape Fear, Middendorf sands have poor framework sorting and a clay matrix, though they are not as extreme in these respects. Textural data are presented in Figure 4.

Middendorf muds are massive and lack any evidence of fissility. Pure clay size clays like those seen in the basal Cretaceous of Georgia and southwest South Carolina do not occur in the Middendorf of North Carolina and northeastern South Carolina. The purest clay found contains 74 percent clay, 25 percent silt, and 1 percent sand. Many of the muds are gritty from the quartz sand content. They are, however, more clayey than those of the Cape Fear.

Most of the sands and muds are light shades of neutral (N 6 to 9), but some muds are dark to medium gray (N 3 to 5). Oxidation is almost universal in the Middendorf Formation. The muds may be mottled dark yellowish orange (10 YR 6/6) and moderate red (5R 4/6) or occasionally pale red purple (5RP 6/2). The sands are of tan, irregularly stained, pale yellowish orange (10YR 8/6) or dark yellowish orange (10YR 6/6). Iron sesqui-oxide layers are common, especially in the sands immediately overlying mud layers. Part of the oxidation of the Middendorf sediments is post depositional, but a large part represents deposition in an oxidizing environment. The Middendorf Formation is well known for its fossil leaves (Berry, 1914; Dorf, 1952), but only a few localities have yielded the numerous species found. Forty-one species of plant mega-fossils have been described by Berry (1914) from the clay layer at the type locality of the formation. Twenty-four species are reported from localities as far south as Aiken, South Carolina. Most clay layers will yield one or two leaf impressions if searched diligently. In North Carolina, leaf impressions have been found at Spring Lake (Heron and Wheeler, 1964, p. 19) and elsewhere (Heron and Wheeler, 1959, p. 11).

At the type locality of the Middendorf Formation one microgastropod was found in a very coarse sand underlying the plant-bearing clay.

Middendorf materials are organized into massive, cross-bedded sands with good framework and overall sorting; discontinuous layers of mud; thick mud lenses set in relatively clean sands; and masses of laminated sand and mud. Fossil leaves, clay pebbles, channeling, and local disconformities are present. Point bar and channel fill deposits can be identified and the formation is believed to be of fluvial origin (Heron, 1958).

BLACK CREEK FORMATION

General

The formation was named Black Creek shale by Sloan (1907) for beds exposed along Black Creek in Darlington and Florence Counties, South Carolina (Figure 12). Stephenson (1907) proposed the name Bladen Formation for equivalent strata along the Cape Fear River in Bladen County, N. C. In 1912, he recognized the priority of Sloan's term. Berry redefined the Black Creek in 1914 to include a Middendorf "arkose member" at the base, at least in South Carolina. Stephenson (1923) regarded the upper 30 to 60 meters of the Black Creek Formation as the Snow Hill marl member.

The Black Creek Formation consists of laminated, medium dark gray to dark gray (N2-5) clay interbedded with medium gray (N-8) to yellow orange (10YR 5/2) sands. Laminae and thin to very thin beds (terms from Ingram, 1954) are grouped into sand-dominated or clay-dominated suites. Strata may be traced the length of the outcrop without significant variation, or they may swell, pinch, and bifurcate in such a manner that they "defy description" (Powers, 1951, p. 73). Estuarine and lagoonal lithosomes have been recognized on the basis of primary structures (Swift and Heron, 1967). Towards the top of the

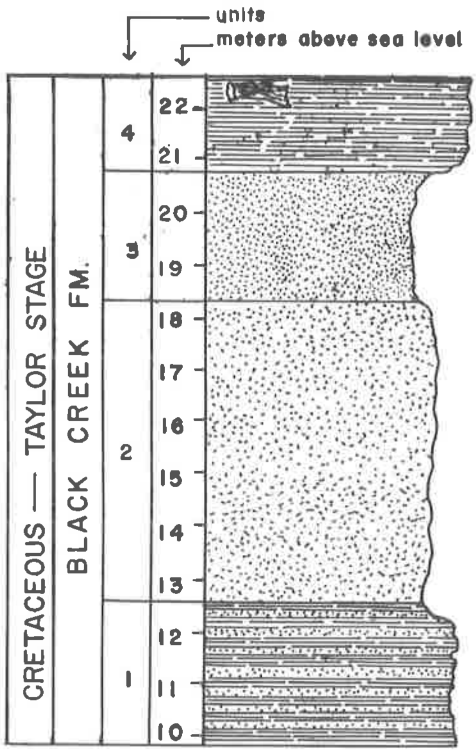

Figure 12. Outcrop from the type locality of the Black Creek Formation, south bank of the Black Creek, north of Florence, Darlington County, S. C. Sloan (1907) designated the general area, but not a particular outcrop. This section was described by Sloan on p. 357 of his Catalog of Mineral Localities of S. C. (1908).

formation, lenses and layers of well sorted sand are believed to be beach and nearshore deposits (Swift and Heron, 1967).

The Black Creek crops out in a belt just seaward of the Middendorf outcrop area, extending from the vicinity of Florence, South Carolina, to the Tar River, North Carolina. Powers (1951, p. 74) has estimated that the Black Creek was once 30 to 60 meters thick where it now outcrops along the Cape Fear River. The outcropping Black Creek contains a flora of Austin or Taylor age (Dorf, 1952), and towards the top a marine fauna of Taylor age (Brett and Wheeler, 1961).

Relationship of Middendorf and Black Creek Formations

Berry (1914) and Dorf (1952) have suggested that the Middendorf and Black Creek are at least in part equivalent. Berry described 41 species of plant megafossils in a claystone layer at the type locality of the Middendorf Formation, and reported 24 species at Aiken, South Carolina. He concluded that the flora was essentially synchronous with a Black Creek flora of up to 38 species from near Darlington, South Carolina, and at Courthouse Landing on the Cape Fear River, North Carolina. However, the synchroneity has so long a maximum possible extent (Woodbine through lower Taylor time) that the formations could be interpreted as sequential within this duration.

The Black Creek - Middendorf contact, though poorly exposed, tends to support the facies relationship rather than the sequential relationship. Between mileboards 100 and 101 on the Cape Fear River the Black Creek rests directly and disconformably on the Cape Fear Formation (Figure 7). Updip in the Little River area of Hoke County, North Carolina, and in Moore County, the Middendorf lies stratigraphically above the Cape Fear Formation. This contact has been mapped in detail in Moore County by Conley (1962), who reports a basal conglomerate separating the Cape Fear and Middendorf. "Outliers" of the Black Creek were mapped by Stephenson (1912) west of Fayetteville, North Carolina. In this area, masses of the typical estuarine lithology appear to rest on the Cape Fear Formation, though no good exposures of the contact have been found. When the strata are traced updip into the Fort Bragg area they change over to the typical Middendorf lithology but locally revert to a deposit similar to the fluviomarine lithosome (laminated sand with alternating light and dark layers).

The road between N. C. 87 near Bonnie Doone and N. C. 210 near Gardiners Chapel has two very enlightening roadcuts. A roadcut 0.3 mile northeast of N. C. 87 consists of typical Middendorf pale sands with minor pale clay lenses and layers. A second roadcut (0.6 mile from the intersection of N. C. 210) is 1.3 miles from the first and 15 meters lower. It contains a lens 4 meters thick of massive, dark gray clay with small particles of lignite; its surface is coated with sulphate bloom (Figure 13). Such an occurrence of Black Creek - like material at a stratigraphically lower position than the Middendorf can be explained by assuming intertonguing of the Middendorf and Black Creek. The shape of the lens is suggestive of a channel, but its three-dimensional extent is now known.

Pusey (1960) has found that in Sampson County, North Carolina, the subsurface occurrence of the Tuscaloosa and Black Creek suggests the interfingering of the two units.

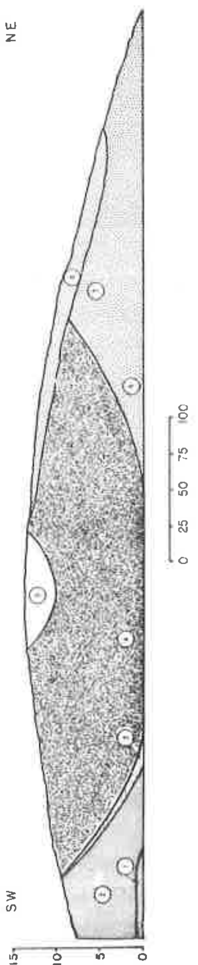

Figure 13. Tidal channel (?) filling of Black Creek lithology near the top of the Middendorf Formation, Country Club Road, Fayetteville, North Carolina.

PEEDEE FORMATION

General

Edmund Ruffin named the Peedee Formation in 1843. Sloan (1908, p. 443) designated a lectotype locality by referring to the same beds as the Burches Ferry phase, after a locality on the west bank of the Peedee River 10 miles south of the Route 301 Bridge over the Peedee River (Figure 14). Charles Lyell (1845), T. A. Conrad (1871), and W. C. Kerr (1875) referred to fossils from various North Carolina localities. The bulk of the Peedee Formation has not been subjected to the same nomenclatural wandering as the rest of the Cretaceous section, although differing viewpoints as to the nature, position, and name of the lower contact have resulted in a "Snow Hill Problem" (see below).

The Peedee is mainly a medium dark gray fine to very fine muddy sand, with horizons of sandy mud (Swift, *et al.*, 1969). It thickens from a feather edge to 260 meters in the Fort Caswell well at the mouth of the Cape Fear River (Stephenson, 1912) where it dips beneath the Tertiary cover. It crops out in a broad crescent from the Tar River, North Carolina, to Black Mingo Creek, in South Carolina.

Poorly defined bedding and indistinct mottling are the only sedimentary structures. The Peedee was deposited on an open shelf (Swift, *et al.*, 1969).

Snow Hill Problem

In 1923, Stephenson described "lenses and layers of more or less calcareous greensand and marine clay, some of which contain an abundant marine fauna" as being interstratified with the upper Black Creek Formation. He called these layers the Snow Hill Member, after outcrops near Snow Hill on Contentnea Creek, and assigned a Taylor age to them. Stephenson felt that the member marked "the transition from the more typical beds of the

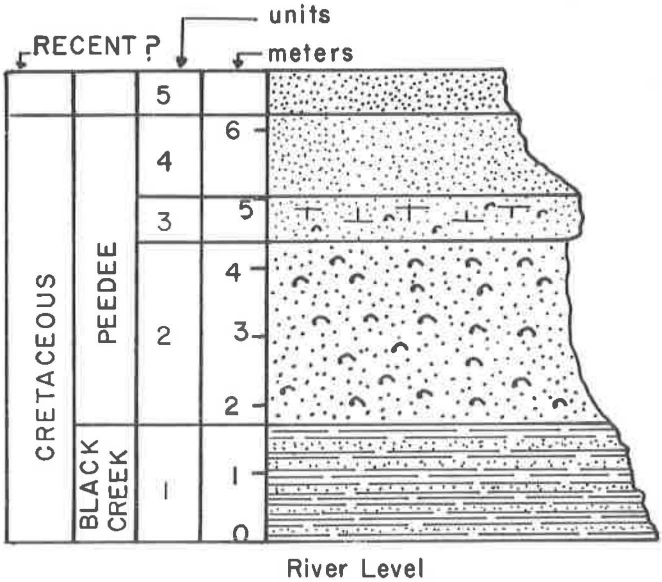

Figure 14. Lectotype locality of the Peedee Formation at Burches Ferry, South Carolina, on the Peedee River, west bank, 16 kilometers south of the Route 301 bridge. From Sloan, 1908, p. 311.

Black Creek Formation, which were probably laid down in very shallow marine waters or in sounds and estuaries, to deposits of deeper marine origin, which typify the Peedee formation". Stephenson used the term "lenses" in connection with the Snow Hill Member because "at Harrell Landing on Black River, a typical Black Creek flora was found above the upper most invertebrate-bearing stratum of the transition beds, which for this reason can logically be regarded as included within the Black Creek formation." Although tongues of Black Creek can be seen penetrating the Peedee at this and several other localities, such interfingering is minor. Most outcrops show the Snow Hill resting disconformably on the Black Creek, and apparently contiguous with the Peedee.

At two outcrops in the type area near Snow Hill, North Carolina, Stephenson (1923, p. 15) describes the Snow Hill lithology as "dark green, compact, argillaceous, micaceous, glauconitic sand." He similarly describes the Peedee (1912, p. 146-147) as consisting of "... dark green or gray, finely micaceous, more or less glauconitic and argillaceous sands... the materials as a whole are quite compact." Work by Brett and Wheeler (1961) and by the authors confirm the similarity of the respective lithologies. Minor differences do exist. The Snow Hill sands are mainly medium or fine sands. The overlying Peedee is more commonly fine or very fine sand. The silt to clay ratio is

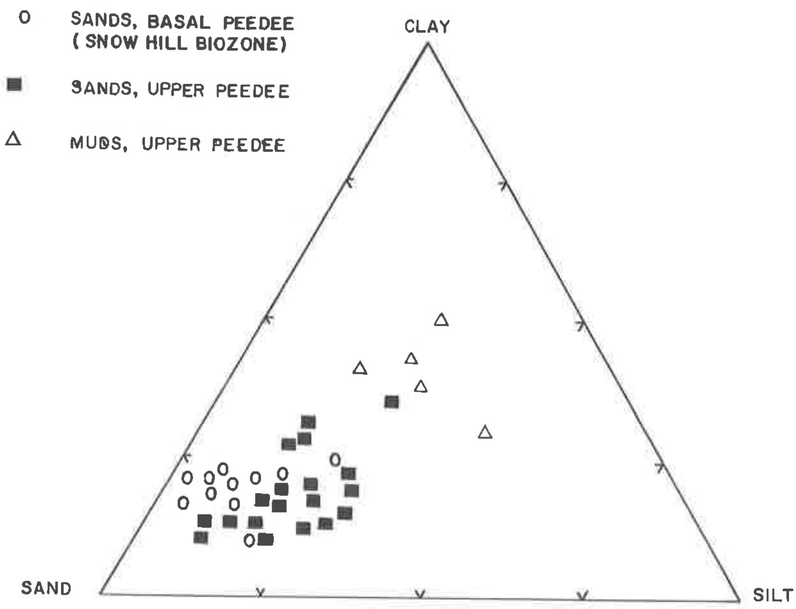

Figure 15. Comparison of sand-silt-clay ratios of the Snow Hill Biozone and overlying Peedee.

higher in the muddy matrix of the Peedee than it is in that of Snow Hill (Figure 15), but these characteristics can be determined only by textural analysis. The Snow Hill is often conglomeratic with megaclasts of molluscan fragments (Snow Hill fauna), clay wafers, rounded bone and lignite fragments, calcareous and phosphate concretions, and rarely, quartz pebbles. Both the Snow Hill and overlying Peedee beds are characterized by poorly defined bedding and distinct to indistinct mottling. Bedding, however, becomes thicker up column, and mottling less noticeable (Swift, 1964). The only exception to these observations is found at Mars Bluff on the Peedee River, South Carolina, just south of the Route 301 Bridge, where the Snow Hill fauna occurs in dark laminated clays and pale clean sands characteristic of the Black Creek Formation.

Both the megascopic and microscopic differences described above serve to show that the Snow Hill beds are basal to the Peedee sequence, rather than terminal to the Black Creek depositional episode. Stephenson, in fact, separated the member from the rest of the Peedee mainly to preserve the unity of the Exogyra ponderosa zone as defined by him (Stephenson, 1912). He stated (Stephenson, 1923, p. 10) "on account of the numerous localities in the transitional beds which have yielded invertebrate fossils, it is necessary for convenience of reference to apply a name to this part of the section." The top of the member was defined as "the top of the transition beds carrying the Snow Hill fauna, or at the point where the materials finally become as defined, the unit is clearly an assemblage zone of a true marine character." The Code of Stratigraphic Nomenclature states (Cohee, 1956, p. 2004) that formations be designated on the basis of lithologic characteristics and not on the basis of enclosed fossils unless they are important lithologic components. We therefore support the conclusion of Brett and Wheeler (1961, p. 105) who proposed that Stephenson's term "Snow Hill calcareous member" be abandoned and that the beds it described be assigned to the basal Peedee.

Significance of the Peedee - Black Creek Contact

Previous writers have suggested that a disconformity separates the Peedee and Black Creek Formations in North Carolina (Brett and Wheeler, 1961, p. 114) and in South Carolina (Stephenson, 1923). The following evidence confirms their statements.

1. The Black Creek - Peedee contact is commonly sharp, occurring over several millimeters.
2. Where the Black Creek strata have a slight initial dip, an angular unconformity is present.
3. Muddy shelf sands and laminated fluviomarine clays are commonly juxtaposed without the intervention of clean nearshore sands.
4. The basal Peedee is commonly conglomeratic. Megaclasts are largely intrabasinal and include clay chips from the underlying Black Creek, abraded lignite and bone fragments, and lenses of molluscan shells.
5. Interfingering between the Black Creek and Peedee Formations is rare.

All features may be observed at the Black Creek - Peedee outcrop at Burches Ferry, Peedee River, South Carolina, or at Mossy Log Landing, Black River, North Carolina.

L. D. Stamp (1922) has pointed out that the surf zone of a transgressing sea may bevel the surface being transgressed. Stamp called the resulting disconformity a ravinement. Fischer (1961) has shown that the modern New Jersey coast is undergoing ravinement as a consequence of a post-Pleistocene rise in sea level. He states that in the ravinement process the sea destroys part or all of its own marginal record of low energy marsh and lagoon deposits and high energy barrier island sands. On the New Jersey coast, evidence of this destruction is afforded by the molluscan shells found on the outer beaches of the barrier islands. They are a mixture of fresh- appearing surf zone forms and leached, stained, lagoonal forms. The latter are exhumed as the barrier island transgresses the lagoon, and lagoonal deposits become exposed to wave action at the foot of the beach face.

The various features suggestive of a disconformity at the base of the Peedee are best explained by the ravinement process (Swift, 1968). Particularly interesting is the resemblance between Fischer's mechanically mixed fauna and the complex Snow Hill fauna of the basal Peedee. Stephenson (1923) has recorded 140 species in the Snow Hill assemblage zone, versus 54 for the rest of the Peedee. Brett and Wheeler (1961, p. 117) have determined that the Snow Hill fauna has "open lagoonal" affinities. Its matrix, however, is the shelf lithosome of this paper. The development of open lagoons by the drowning of barriers is in harmony with the concept to be developed here. It is suggested, however, that where the Snow Hill fauna occurs in the basal Peedee its lagoonal component has at least in part been winnowed from the underlying Black Creek Formation and that its diversity is a consequence of the mechanical mixing of the fauna from various shelf and transition zone subenvironments. The Black Creek - Peedee Contact in the vicinity of the Black River, N. C. and on the Cape Fear River, N. C. is shown schematically in Figures 16 and 17.

Ravinement in the Peedee River Valley

The preceding section has shown that the disconformity between the Black Creek and Peedee Formations is a consequence of the ravinement process. The ravinement alone is responsible for the disconformity in North Carolina. Brett and Wheeler (1961, p. 114) noting the physical criteria, have cited the disconformity, while Stephenson (1923, p. 12), concerned more with biostratigraphic data, states that in North Carolina the Peedee rests directly on the Black Creek. Stephenson does, however, note an unconformity "... in South Carolina there is evidence of an unconformity of appreciable time importance at one locality in Florence County... ". He refers the reader to page 32 where the description of the Jeffreys Creek outcrop includes an "undulating unconformity" between the Black Creek and Peedee Formations. On page 51, he states:

> ... the Exogyra cancellata subzone has not been recognized in South Carolina, and there is both paleontologic and physical evidence that it is wanting here, being represented by an unconformity which separates the Black Creek formation and the beds of the Peedee formation, which occupy a position about midway of the Exogyra costata zone.

Paleontologic evidence that the Exogyra cancellata Subzone (Figure 18) is wanting appears to consist of the absence of the index fossils Exogyra cancellata and Anomia tellinoides. Correlations based on the absence of index fossils are considered dubious by some authors; Weller (1960, p. 548) states that "the fossil's... absence does not prove that the strata under consideration occupy a position outside the range of the index fossil."

A decision concerning the presence or absence of the Exogyra cancellata subzone in the Peedee River Valley must be based on outcrops which are in the part of section that might be expected to carry the fauna, which are fossiliferous, and in which the fossils have been

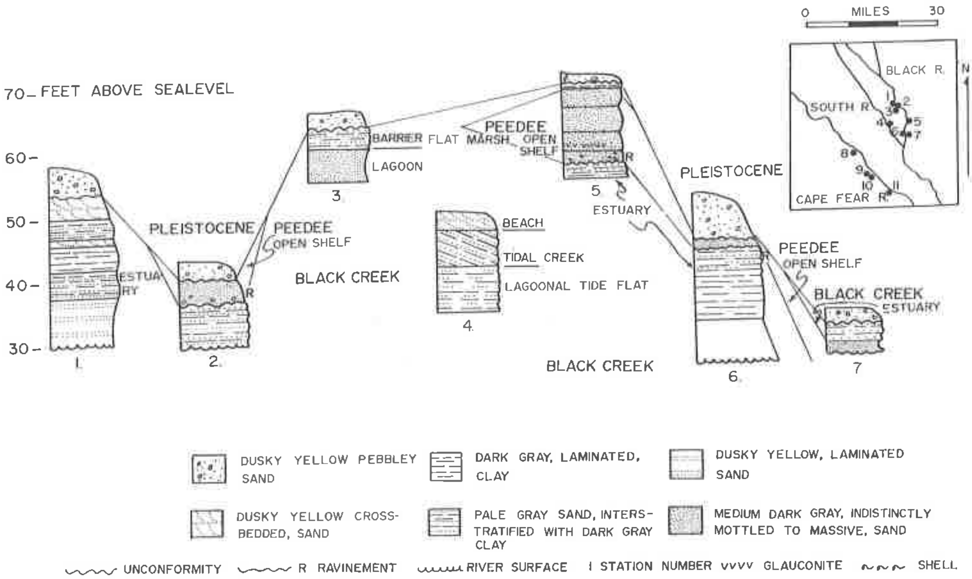

Figure 16. Black Creek - Peedee contact in the vicinity of the Black River, North Carolina.

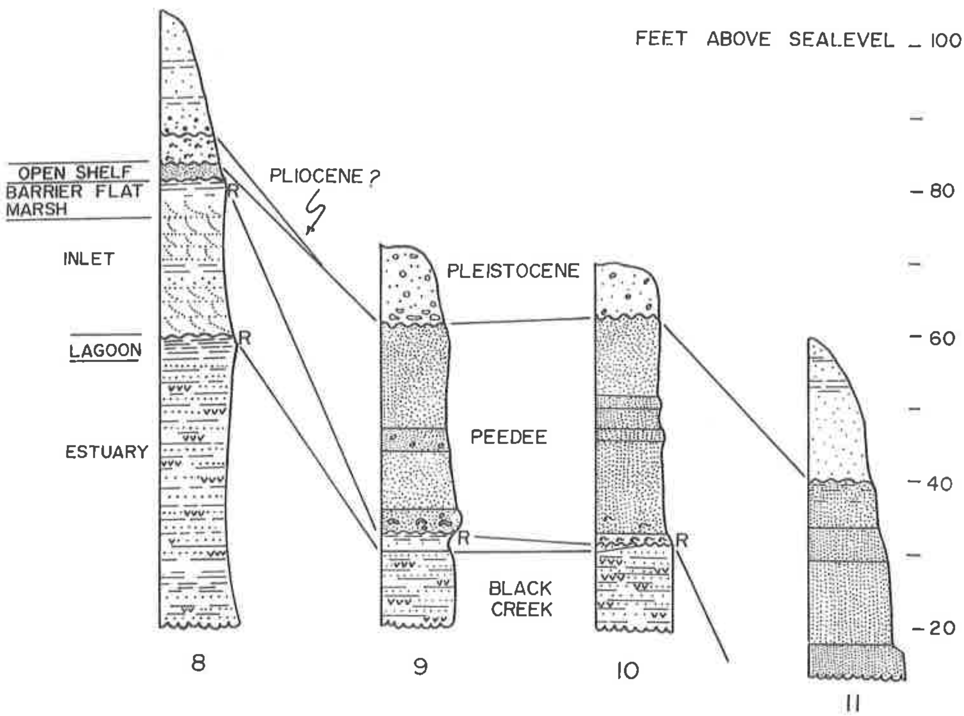

Figure 17. Black Creek - Peedee contact on the Cape Fear River, North Carolina. See above figure for location map and legend.

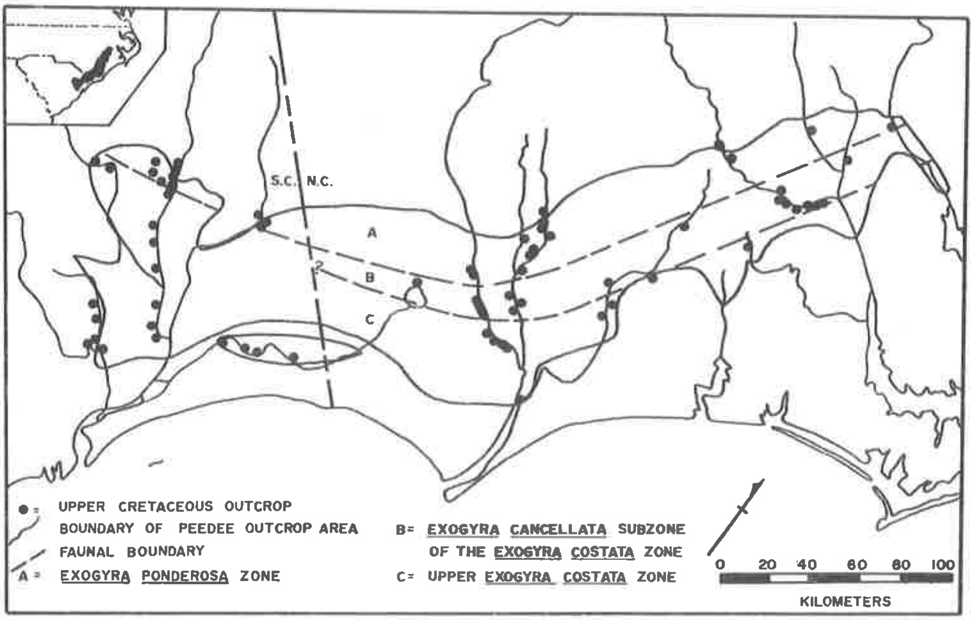

Figure 18. Faunal zones of the Peedee Formation.

identified. The only outcrops which satisfy these conditions are:

1. Burches Ferry, Peedee River (upper Black Creek and basal Peedee Formation).
2. Jeffreys Creek (upper Black Creek and basal Peedee Formations).
3. Cains Landing, Peedee River (basal Peedee Formation).
4. Mars Bluff, Peedee River (upper Black Creek Formation).

The fauna of these outcrops and their ranges in the Gulf and Atlantic Coastal Plains are presented in Figure 19. All data is taken from Stephenson (1923). Peedee species, with the possible exception of Trigonia enfaulensis, have, according to Stephenson, a range of at least "Exogyra costata zone". Stephenson reports all but T. enfaulensis from the Selma Formation, and he considers this unit to lie below the top of the Exogyra cancellata subzone.

While it is possible that the Exogyra cancellata Subzone is missing in the Peedee River Valley, Figure 17 suggests that positive assertion on the subject is carrying the available evidence beyond its limit of resolution. Conceivably, any evidence based on such conservative forms as pelecypods is, in this problem, at the limit of resolution. Weller (1960, p. 558) suggests that under ideal conditions correlation by invertebrate fossils yields an accuracy of about three million years. If the space provided for the Exogyra cancellata Subzone on Stephenson's correlation chart (Stephenson, et al., 1952) approximates its absolute time span, then the span is about three million years. The problem of the Exogyra cancellata Subzone awaits detailed quantitive analysis of

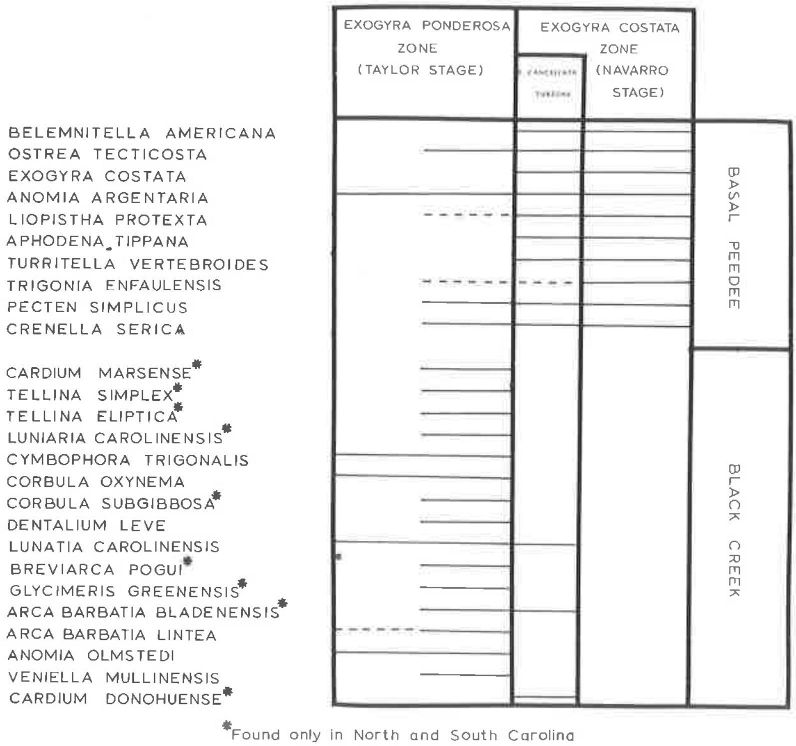

Figure 19. Macrofauna of the Peedee-Black Creek contact, Peedee River Valley.

large samples of fossils collected at carefully determined stratigraphic levels throughout the Carolinas.

Should the Exogyra cancellata fauna be in fact missing in the Peedee River Valley, the following are possible explanations:

1. A suitable environment was not present, subsequent to ravinement.
2. The area was briefly emergent during Exogyra cancellata time, subsequent to the main ravinement.
3. The transition zone persisted in this area through Exogyra cancellata time; ravinement did not begin until upper Exogyra costata time.

Since the environmental requirements of the fauna are known only in a general way, the first explanation cannot be evaluated. The second explanation is reasonable; the numerous diastems of the Upper Cretaceous section in Georgia and Alabama (Stephenson and Monroe, 1938) are best explained as due to epirogenic movements. The third explanation is the simplest, and fits what little is known concerning crustal stability in the Carolinas during the Upper Cretaceous. Well data (Figure 25) suggest that the Navarro Stage thickens over the Cape Fear Arch; the "arch" has apparently been a zone of instability rather than a persistently positive feature and was negative during Navarro time. Transgression then, may have transpired earlier in North Carolina than in South Carolina; and basal Peedee beds in South Carolina might be expected to contain a slightly younger fauna.

If this is the correct explanation for the apparent lack of the Exogyra cancellata fauna, then an important segment of the faunal sequence is obscured within the generally barren Black Creek deposits. Should a fossiliferous Black Creek outcrop be found stratigraphically higher than the Mars Bluff outcrop it might reveal the missing fauna. It is also possible that the Exogyra cancellata forms could tolerate only open shelf conditions; in this case, some modification of the rather provincial Snow Hill fauna might have persisted as long as its transition zone environment was available. It then would have been replaced by the upper Exogyra costata fauna and the intermediate Exogyra cancellata fauna would be omitted from the paleontologic record. An outcrop worthy of further study in this regard is the Route 301 roadcut, stratigraphically intermediate between the Mars Bluff and Jeffreys Creek outcrops. It contains a fossil assemblage which has not been studied.

LUMBEE GROUP

The preceding pages have shown that superficial examination will resolve the outcropping Carolina Cretaceous into a basal sand, an intermediate sand with laminated clay beds, and an overlying muddy sand. More careful observation reveals that the basal sand consists of two distinct units. The lower one is a fragment of a marine marginal sedimentation system of probable early Cretaceous age. The upper part of the basal sand, redefined in this paper as the Middendorf Formation, plus the overlying Black Creek and Peedee Formations constitute a cogenetic transgressive sequence (Figure 20). In Figure 21 the size frequency distributions of Upper Cretaceous sediments are seen to be responses to the transport system that linked the Middendorf, Black Creek and Peedee environments. Each depositional environment through which the sediment passed subtracted certain size distributions whose characteristics reflect specific depositional subenvironments. The results of this grading are apparent in Figure 22 where median diameter and the first percentile are plotted against distance from the Fall Line for Cretaceous samples from the Cape Fear River Valley. At each stage, the coarsest fraction of the traction load was preferentially deposited in low-energy sediment sinks adjacent to the main sediment pathways. Such grading was marked in the inner portion of the sediment transport system, where the paleoslope flattened rapidly through fluvial, tidal, and wave base levels, and the environments were rigidly partitioned into channel and interchannel zones. It was more subtle on the broad, gentle Peedee shelf where energy gradients were low, and transport was accomplished by the repeated shifting and spreading of sediment by storm-generated wind drift currents. Exceptions to the

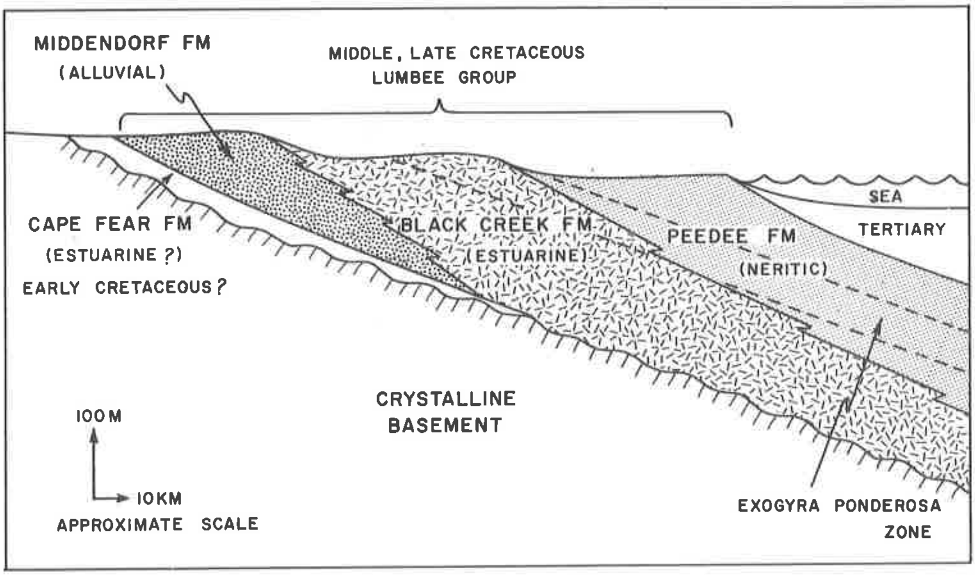

Figure 20. Schematic cross-section through the Carolina Cretaceous. Modified from Brett and Wheeler, 1961.

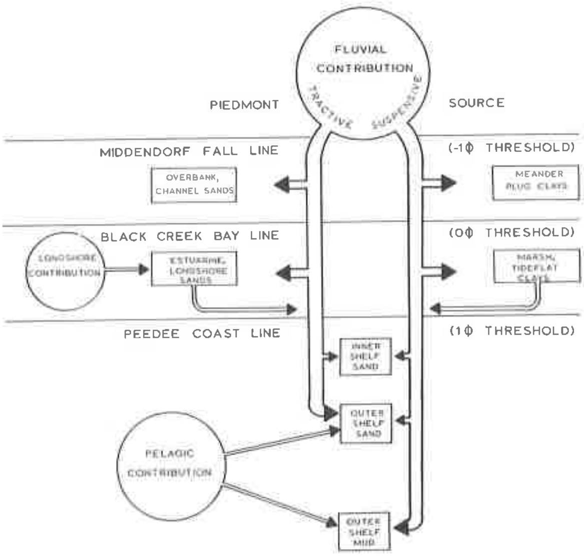

Figure 21. Schematic diagram of sediment transport through the Upper Cretaceous lithotopes.

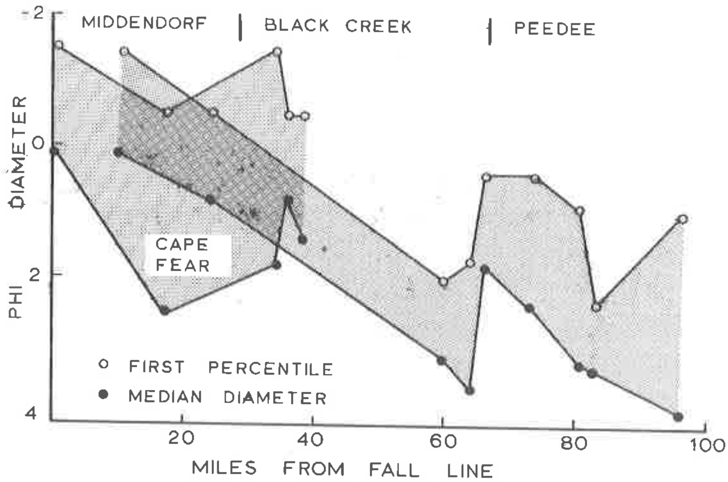

Figure 22. C-M profiles of Cape Fear Formation and Lumbee Group in Cape Fear River Valley. Marked break in median diameter of Lumbee Group occurs in the nearshore lithosome of the Black Creek Formation. Irregular behavior of the first percentile in the Peedee Formation is due to the advent of the coarse intrabasinal fraction.

prevailing equilibrium were restricted to the contacts between environments; notably the late Cretaceous shoreline where the ravinement process transpired. The late Cretaceous transport system is considered more fully elsewhere (Swift, Heron, and Dill, 1969).

It is proposed that the integrity of this outcropping Upper Cretaceous sequence be formally recognized by the application of the name Lumbee Group in accordance with the Code of Stratigraphic Nomenclature (1961). The name is that of a coastal plain Indian tribe, which formerly occupied the area of Upper Cretaceous outcrop.

The type section consists of the type sections of the component formations. The lectotype section for the Cape Fear Formation is the bluff at the down-river side of the junction of Rockfish Creek with the Cape Fear River in Cumberland County, North Carolina (Figure 6). The generally accepted type section for the Middendorf is the railroad cut (Figure 11), two miles east of Middendorf, Chesterfield County, South Carolina (Sloan, 1904, p. 108). The type locality of the Black Creek Formation is the banks of Black Creek (Figure 12) in Darlington and Florence Counties, South Carolina (Sloan, 1907). The Peedee lectotype locality is Burches Ferry on the west bank of the Peedee River, 2 miles south of the Route 301 bridge over the Peedee River (Figure 14). An important reference locality for the entire Lumbee Group is the Cape Fear River Valley. Heron and Wheeler (1964) have described outcrops from this area.

The morphology of the group is well known only in its outcrop area (Figures 9 and 10). Here it is a seaward-thickening wedge with its axis parallel to the coast. Its lower surface in this area is an unconformity, below which lie the Lower Cretaceous(?) Cape Fear Formation, Triassic redbeds, or contorted crystallines of Paleozoic(?) age. Its upper surface is a surface of erosion of Paleocene to Recent age, upon which rests a discontinuous veneer of Cenozoic sands and gravels. Its northwestern margin is a feather edge produced by recent erosion. Its southeastern or submarine termination remains to be determined; future work may show that the group is more truly a prism wedging out toward the base of the continental slope. To the northeast the group wedges out beneath a pre-Miocene unconformity; to the southwest of the Carolinas it passes by facies change into the Cretaceous section of Georgia and Alabama (Richards, 1967). The precise definition of this facies change awaits detailed subsurface study.

CRETACEOUS-TERTIARY BOUNDARY

Peedee-Black Mingo Contact

Throughout most of its outcrop area, thin patches of fine muddy sand, fine calcareous sands and coquinas of Tertiary age occupy basin-like depressions in the undulating surface of the Peedee, and both Cretaceous and Tertiary are mantled by Quaternary surficials of fluvial and littoral marine origin. The magnitude of the disconformity between Mesozoic and Cenozoic is least on the western flank of the Cape Fear Arch, at the junction of Black Mingo Creek and the Black River. Here, at Brown's Ferry, (Figure 23), a medium dark gray (N4) silt attributed to the basal Tertiary Black Mingo Formation (Sloan, 1907) carries a lower Midway (Danian) microfauna, as defined by Globoterinoides daujergensis (Broniman), a guide fossil of the Danian (lower Paleocene) in Europe, the East Coast and Gulf States, and the Carribbean (Loeblich and Tappan, 1957). It rests on medium dark gray (N4), very fine grained, muddy sand of the Peedee Formation. The latter carries a typical Navarro state microfauna.

On the east flank of the Cape Fear Arch, at West Landing on the Neuse River (Figure 23) a small outlier of Black Mingo with a Danian microfauna again overlies Peedee with a Navarro microfauna. Here the disconformably surface has 5 meters of relief and the basal Black Mingo is conglomeratic with terrigenous clasts and fragments of Peedee lithology.

Cretaceous Limestone at Castle Hayne

The boundary becomes more obscure on the nose of the Cape Fear Arch, at the mouth of the Cape Fear River. Earlier workers

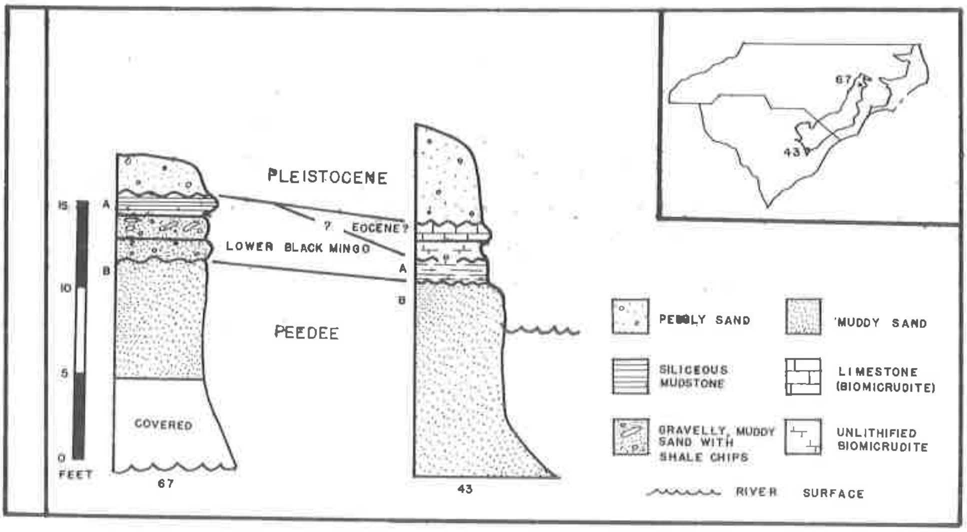

Figure 23. The Black Mingo-Peedee contact at Brown's Ferry, South Carolina, and West Landing, North Carolina.

(Tuomey, 1848; Clark, 1890; Stanton, 1891) noted that in the vicinity of Castle Hayne, near Wilmington at the junction of the Cape Fear River and the Northeast Cape Fear River, there are limestone strata overlying the typical Peedee lithology with a "co-mingling" of Cretaceous and Tertiary faunas. Clark (1890) suggested that the faunas were mechanically mixed. Stanton, however, was able to divide the limestone strata into two units at Castle Hayne and at Rocky Point twenty miles to the north. The units were separated by a phosphatized surface. Stanton identified a lower unit one to two meters thick as Cretaceous and a one meter upper unit as Tertiary (Eocene). He stated that a phosphate pebble conglomerate at the base of the upper unit was the layer in which the mechanical "co-mingling" occurred. In 1910 and 1912 Miller named the Eocene upper unit and its phosphatic basal conglomerate the Castle Hayne Formation. He wasn't able to observe the lower unit. More recently, Fallaw and Wheeler (1963) examined both units in a quarry one mile southwest of Castle Hayne. They reconfirmed Tuomey's findings and identified the Cretaceous mollusks Trigonia haynesis Stephenson, Exogyra costata Say, Ostrea subspatulata Forbes, Cardium pendenses Stephenson, and Cardium spillmani Stephenson in the lower unit.

Several years after Fallaw and Wheeler's study, the Superior Stone Company opened a new quarry 3.4 miles N 65° E of Castle Hayne. It exposed 6 meters of typical Castle Hayne and 12 meters of the problematic unit bearing Cretaceous fossils. The stratigraphic aspects of this quarry have been studied by Johnson (South Carolina Geological

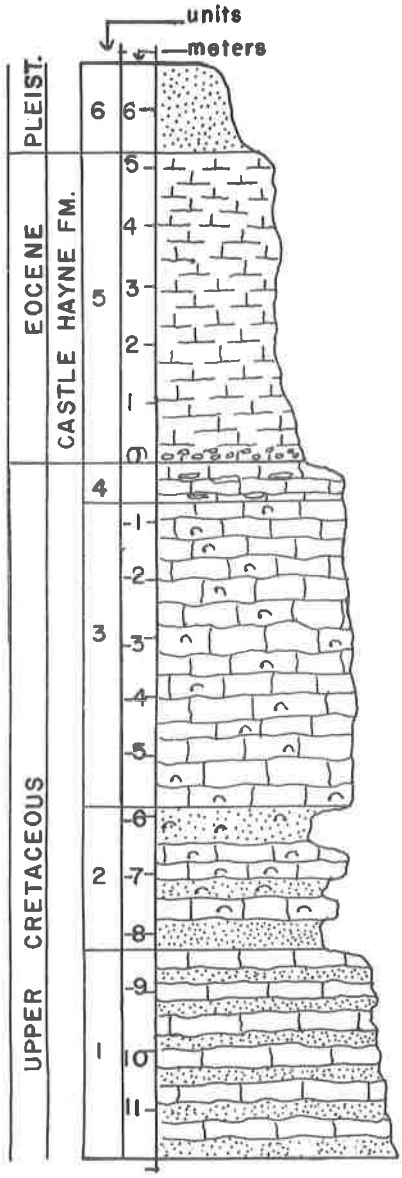

Figure 24. Type section of the Rocky Point member of the Peedee Formation, Superior Stone Company Castle Hayne Quarry. South bank of Northeast Cape Fear River, 3.4 mi. N 64° E of Castle Hayne, North Carolina. Composite section measured by Henry S. Johnson, Jr., and S. D. Heron, Jr., December 1966.

Survey) and Heron. Petrographic and stratigraphic aspects of the units have been analysed by Cunliff and Textoris (1968) and Wheeler and Curran (1969).

Field examination confirms the presence of two distinct units separated by a phosphatized disconformity (Figure 24). The depth of this quarry has revealed that the Cretaceous unit consists of 3 sub-units; an upper one noted by earlier workers and two lower ones seen here for the first time. The lowest sub-unit consists of lumpy thin-bedded (thickness term from Ingram, 1964), medium light gray (N6), sandy limestone to calcareous sandstone alternating with thin-bedded, loose, well sorted to very well sorted, medium to fine grained very light gray (N8) sand. The limestone is fossiliferous to very fossiliferous, but the fossils consists of casts and molds, the shell material probably having migrated to form the carbonate cement (Textoris, personal communication). The loose sand is also fossiliferous; fossils here are the original shells. These are mainly individual specimens or pockets and lenses of the Cretaceous oyster, Ostrea subspatulata. The shells are badly worn.

The central sub-unit consists of the same two lithologies arranged in medium beds. Medium scale, high-angle, tabular cross-strata sets (McKee and Wier, 1953) are abundant in both lithologies. In addition, the same units locally contain abundant invertebrate burrowing. The general aspect of the central sub-unit is that of a beach - surf zone lithosome.

The uppermost sub-unit consists entirely of the sandy limestone lithology. Loose sand is not present. Its top meter is phosphatized and is referred to as "cap rock" by the quarry men.

The upper unit is medium gray (N5) unconsolidated limestone. Fossils are abundant and consist of the original shells, unusually unbroken and unworn. The texture of the unit is muddy sand to sand mud. The upper unit is typical Castle Hayne Limestone as described by Miller (1910).

Age of the Cretaceous Limestone

Stanton (1891) describes the unit as full of Cretaceous fossils and the source of the reworked Cretaceous fossils in the overlying Castle Hayne. Fallaw and Wheeler (1963) found megafossils of late Cretaceous age. Wheeler and Curran (1969) report additional megafossils of Cretaceous age as well as planktonic and benthonic foraminifera.

Relationship to Peedee Formation

The problem of the relationship of the Cretaceous limestone to the Peedee Formation is a difficult one in part because the contact between the two lithologies has not been observed, and therefore can not be assessed as conformable or disconformable. Fallaw and Wheeler (1963) note that "Peedee limestone beds occur elsewhere near Castle Hayne and have been reported lower in the Peedee Formation." They conclude that the Cretaceous limestone is a limestone facies of the Peedee Formation. It should be noted that the Peedee limestone beds occurring elsewhere near Castle Hayne are part of the horizon in question and these cannot be used to relate this unit to the rest of the Peedee. Limestone beds up to one meter thick do occur in the lower Peedee, on the Peedee River at Cain's and Allison's Landing and in the subsurface (Brown, 1958). The surface beds are like the Cretaceous limestone in that much or all of the carbonate appears to be due to dissolution, movement, and precipitation of shell material. The terrigenous fraction, however, is always a muddy sand; clean sands with a littoral aspect like those of the Cretaceous limestone are found only at the base of the Peedee and here are not calcareous.

This unit should have a specific name because its lithology is distinct from that of the underlying Peedee and the overlying Eocene Castle Hayne Limestone. However, the authors have not studied the unit in detail and have not mapped its extent. For these reasons, we do not propose a formal name for the unit. We have informally called the unit the Rocky Point member of the Peedee Formation. We consider the section exposed in the Superior Stone Castle Hayne quarry (Figure 24) as the type section for this informal unit.

The significance of the Rocky Point member depends on whether or not it rests conformably on the Peedee. A 325 foot drill hole (Table 1) two miles north of Southport and 30 miles south-southwest of the type locality indicates that the Rocky Point member is interbedded with the Peedee Formation. It is reasonable to assume that the Rocky Point member simply represents the withdrawal of the Peedee Sea.

Table 1. Log of Core Drill Hole 2 Miles North of Southport, N. C.

Depth Feet	Description
0-31	No core.
31-53	Clay, silty, micaceous, slightly to moderately calcareous, dark gray.
53-77	Sand, C-VC, well sorted, gray white.
77-115	Clay, silty, sandy, micaceous, slightly to moderately calcareous, gray black.
115-123	Limestone, dense, hard, fossiliferous, gray; abundant casts and molds of fossil shells, similar to Rocky Point member in Superior Stone Company Castle Hayne Quarry.
123-153	Limestone, coquinoid, soft, crumbly, fossiliferous, cast and mold, leached, oxidized, yellowish cream to yellowish brown; thin interbedded layers of dense gray case and mold limestone similar to 115-123' above; grades downward into underlying unit.
153-215	Limestone, calcarenite, silty, marly, very calcareous, light to medium gray; grades downward into underlying unit.
215-325	Limestone, calcarenite, silty to clayey, marly, medium to dark gray.

The lithology below 123 feet is similar to the typical Peedee lithology. Logged by H. S. Johnson, Jr., March, 1968.

SUBSURFACE STRATIGRAPHY OF THE CAROLINA CRETACEOUS

General

Investigations of the subsurface stratigraphy of the Carolina Cretaceous began with logs of water wells presented by Stephenson (1912, 1914). Mansfield (1925, 1937) and Mundorf (1944) logged more water wells and some early test holes for oil. In 1945, Richards compiled well data of the Atlantic Coastal Plain from New Jersey to Georgia. Berryhill (1948) analyzed the stratigraphy and foraminifera of the Esso test well, Hatteras Light Number One. In 1950, Spangler presented a synthesis of the downdip stratigraphy of the Carolina Coastal Plain based on coastal oil wells drilled during the preceeding decade.

Swain (1947, 1951, and 1952) offered a somewhat different interpretation of the coast subsurface based on his analyses of ostracods from the Hatteras well. In 1958 and 1959, Brown filled the blank space between the outcropping Cretaceous and the deep wells by publishing detailed analyses of 82 water wells from the updip section. Finally, in 1965, Maher synthesized previous subsurface data pertaining to the Atlantic Coastal Plain.

Limitations inherent in these studies of subsurface Cretaceous stratigraphy render correlation with the outcropping strata difficult. Perusal of Brown's data shows that even in the case of these carefully prepared analyses, it is generally not possible for water well logs to resolve strata less than one meter thick. Surface units such as the Black Creek and Cape Fear Formations which are diagnosed partly or largely on the basis of laminations or other primary structures are therefore difficult to trace into the subsurface.

The problem is intensified by basic philosophical differences between surface and subsurface investigators. Recent surface investigations have correlated formations and members on the basis of lithic characteristics rather than on the basis of enclosed fossils, in accord with the Code of Stratigraphic Nomenclature (Cohee, 1956, p. 2004). Subsurface workers on the contrary have been oriented towards faunal analysis. They apply lithic criteria but give this method priority mainly when fossils are absent. As a result, their units are commonly equivalent to stages, but may transgress time lines when fossils are absent. Since these units are generally called formations and named after updip lithostratigraphic units, considerable semantic confusion results when surface to subsurface correlations are attempted.

Such correlations are further hindered by fundamental differences in updip and downdip lithosomes. Throughout its history, the Coastal Plain has received mainly coarse, pebbly non-fossiliferous sand on its inner margin, and fine, muddy shelly sand on its outer margin. Lithologies on either side of a contact, such as the Middendorf-Cape Fear contact, are locally so similar as to render them paraconformities. The zones of interfingering between adjacent lithosomes are far easier to detect than the equally important contacts between vertically successive lithosomes. The updip facies are thin, discontinuous, and are transected by numerous disconformities; the downdip facies are vastly thicker and contain many units with no updip equivalents. Therefore, time correlation of the surface and subsurface Cretaceous presents a misleading picture of litho-stratigraphic relationships, and hinders reconstruction of depositional regimes. An attempt will be made on following pages to clarify this situation.

The Proximal Subsurface

The proximal subsurface is defined mainly by water wells. They are rarely more than one hundred meters deep, and most bottom in the

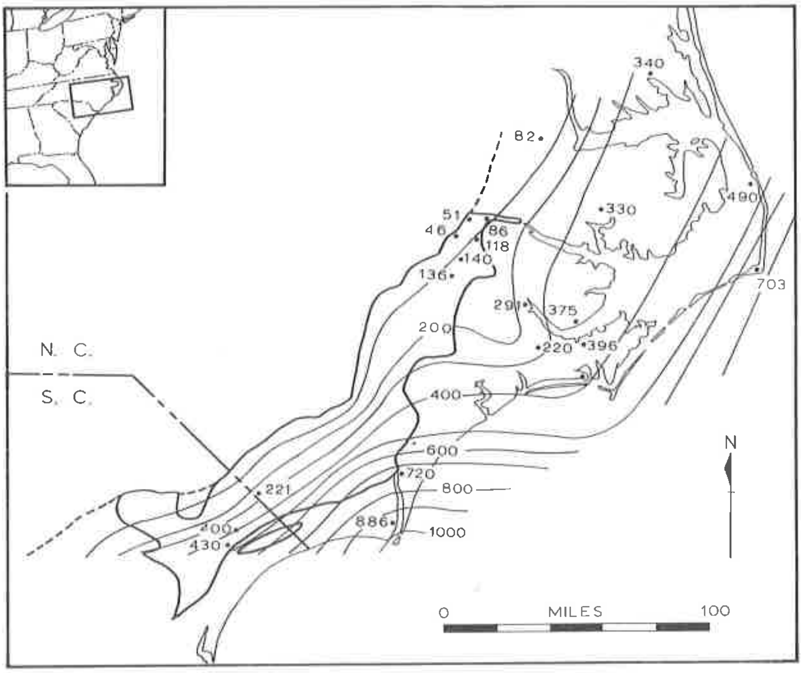

Figure 25. Isopach map of the Navarro stage in the Carolinas. Data from Brown, 1958; Spangler, 1950, and Richards, 1945.

Peedee or Black Creek Formation. Consequently, this discussion deals largely with the geometry of the Peedee Formation.

An isopach map of this unit reveals a wedge-shaped mass of sediments thickening seaward (Figure 25). Control is poor but suffices to show that the Peedee thickens over the Cape Fear Arch in contrast to the Black Creek Formation which thins across the arch (see also Figure 10). The thickening of the Peedee tends to be masked in the outcrop area, where many of the upper strata have been removed, but is quite noticeable on the coast. Apparently the Cape Fear Arch has been a zone of crustal mobility rather than a consistently positive zone. Brown (1958, Table 1) suggests that the Peedee sediments on the Cape Fear axis were deposited in deeper water than those on the shelf to the northeast. If so, the Cape Fear axis was a bathymetric as well as a structural depression during upper Cretaceous time.

Brown, (1958, p. 27) reports a deltaic facies of Navarro and Midway age near the North Carolina-Virginia border. He assigns it mainly to the Peedee Formation on the basis of age, but inspection of the well logs suggests that the lithology more closely resembles that of the Black Creek Formation. Tongues of Middendorf lithology may also be present (pink, mottled feldspathic sands and brick-red clays). Brown's data indicates that in this area the rate of subsidence was in equilibrium with the rate of sedimentation, resulting in a stabilized shoreline throughout Navarro time. Middendorf and Black Creek facies of Navarro age are absent south of Bertie County, North Carolina. While still stand was established in the north, transgression continued along the Cape Fear axis, extending these facies far enough west to be destroyed by post-Cretaceous erosion. The apparent absence of the Exogyra cancellata zone in South Carolina, described on previous pages, may reflect the southern margin of this Peedee embayment of Navarro time.

Throughout its outcrop area, the Peedee is disconformably overlain by buff or pale gray sands, clays, coquinas, muds, and limestones of Tertiary age. The differing aspects of the Mesozoic and Tertiary lithologies in most areas indicate that two are products of distinctly different sedimentary regimes. In Craven County the disconformity is equivalent in magnitude to part of the Paleocene stage (Brown, 1958; p. 6); in most parts of the outcrop area, it is greater.

Northeast of its outcrop area, the subsurface Peedee is overlain by the Paleocene Beaufort Formation (Brown, 1959, p. 25). The Beaufort resembles the Peedee but is generally coarser, less clayey, and more glauconitic. Brown (1959, p. 8) states that the glauconite concentration may reach 90 percent. Grains are sometimes rounded and "water polished," while Peedee grains are usually sub-angular (Brown, 1958, p. 78). Gorsline (1963) has traced this subsurface unit south onto the continental shelf.

The composition and stratigraphic position of this unit suggest that it was deposited during a period of restricted supply of terrigenous sediment and of shoaling waters, when bottom sediments were being reworked and glauconite concentrated. Brown (1959, p. 7) believes that "the Beaufort lies unconformably on the Peedee and exhibits a pseudo-offlap relation to that formation". However, Brown's published well data consist of descriptions of cuttings. The data do not permit resolution of the contact sufficient to indicate whether it is conformable or not. In the same article (p. 63-64) Brown describes a subsurface deltaic deposit on the inner margin of the Coastal Plain, in which Paleocene and Cretaceous strata cannot be differentiated. If sedimentation crossed the era boundary without a detectable break in the coastal environment, it seems reasonable to conclude that it was also continuous on the adjacent shelf. The Beaufort Formation may therefore mark the regression of the Peedee Sea. If so, its basal portion would be represented by the disconformity beneath the Black Mingo outlier at West Landing on the Neuse River, North Carolina, and the disconformity beneath the Black Mingo Formation at Brown's Ferry, South Carolina. In this case, erosion would have been occurring over the Cape Fear

Arch during early Danian time, while sedimentation would have been occurring in the basin to the northeast. Alternatively, a disconformity may exist at the base of both the Beaufort Formation and the base of the deltaic Paleocene and these units may be correlated directly with the Black Mingo. All would then bear a pseudo-offlap relationship with the Peedee, and the disconformity separating them might be a ravinement, an erosional record of the transgressive phase of Paleocene sedimentation. In this case only the Rocky Point member is left as a possible deposit of the withdrawing Lumbee Sea.

The Distal Subsurface

The Cretaceous sequence of the coastal oil well tests as described by Swain (1951, 1952) and Spangler (1950) form a distinctive suite of limestone, chalk, and clay. Inspection of the electric logs (Spangler, 1950, Fig. 4; Maher, 1965, Plate 5; this paper, Figure 26) and lithic logs (Swain, 1952) indicates the presence of three major lithologic units. The basal unit, over 900 meters thick in the Hatteras well, is assigned to Jurassic(?) through Austin time. The sequence starts with arkosic, gravelly sand and varicolored clays of possible non-marine origin. (Spangler, 1950, p. 123-130). Gravelly sands reappear at the top of the sequence, possibly indicating the completion of a transgressive-regressive cycle. Swain, whose well logs are the most detailed, infers an angular unconformity at the Lower Cretaceous - Upper Cretaceous. However, lithologies do not change markedly across this boundary. This sequence has a characteristic spikey self-potential and resistivity pattern owing to the well-defined alternation of clay, limestone, and sand.

The overlying unit, consisting of clay with minor sand and chalk beds, has more uniform electrical log characteristics. It has been assigned a Taylor-Austin age. The relatively thin uppermost unit, described as a coarser sand by Swain, reverts to the spikey electric log pattern.

The Navarro, Taylor, and Austin stages have been designated the Peedee, Black Creek, and Eutaw Formations respectively by Spangler (1950). This is unfortunate as the Eutaw is a formation defined by outcrops in a neighboring sedimentary basin (southwest Georgia embayment) 400 kilometers away. Further, Spangler correlates his downdip Black Creek with that portion of the updip Black Creek (Snow Hill member) now assigned to the basal Peedee.

Despite the confusing nomenclature, Spangler's correlation of the homogenous, fine-grained Navarro and Taylor stages of the subsurface with the similar lithology of these stages in surface outcrops is easy to accept. His correlation of the dark, estuarine Black Creek of the outcrop area with the fully marine downdip Austin is awkward, however. This downdip unit consists of "varicolored sands, gravelly sands, and clay shales" (Spangler, 1950, p. 130). Swain (1952, p. 62) reports

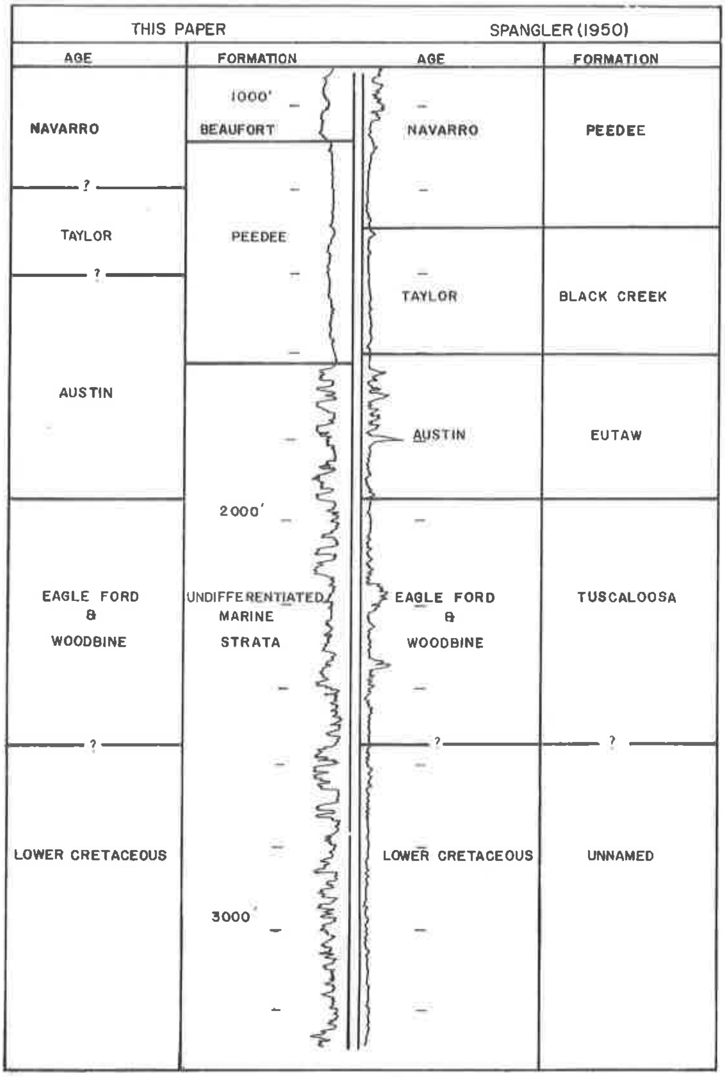

Figure 26. Interpretation of the electric log at Atlas Plywood number 1. Data from Spangler, 1950.

white to light gray sandstone to conglomeratic sandstone whose upper portion is limonitic. It is very difficult to see how such material could be bypassed by the non-conglomeratic, darkly pigmented Black Creek estuarine beds lithotope. It is easier to assume that the Black Creek pinches out beneath the Peedee, so that in the distal subsurface the fully marine Peedee lithology rests directly on the fully marine Austin beds.

This lithostratigraphic relationship is more easily accepted when it is realized that considerable difficulty was encountered by subsurface workers in picking the Cretaceous stage boundaries (Spangler, 1950, p. 109). The Navarro-Taylor boundary appears to have caused particular trouble. Spangler (1950, p. 116) picked the top of his downdip Taylor stage by the occurrence of Vaginulina regina. He remarked that in the Gulf Coastal area, this form is found no higher than upper Austin. However, he accepts a Taylor age for this species in the Carolinas because in one well it is associated with a macrofauna identified as younger than Austin-Taylor. But if the microfauna were presumed to be more trustworthy than the macrofauna in this ambiguous case, then the Taylor-Navarro boundary may be higher than Spangler placed it; that is, within the Peedee Formation, rather than at its base. The Austin-Taylor boundary seems likewise capable of being moved upwards, since Spangler (1950, p. 116) defines this time horizon largely on the basis of "the first appearance of Eutaw lithology". If these boundaries actually occur at horizons higher than those picked by Spangler, then the Lumbee Group would fit the classic picture of a transgressive sequence by "climbing in the section", e. g., becoming progressively younger when traced updip. See Figure 27. It is hoped that exploratory drilling now in progress on the Carolina Coast (Ingram, personal communication) will resolve this problem.

The preceding discussion has demonstrated that in addition to the vertical division into an updip and downdip facies, the Carolina Cretaceous is divided by a horizontal boundary into lower and upper rock-stratigraphic sequences, reflecting two distinct sedimentary regimes (Figure 27). A fragment of the basal system outcrops on the inner Coastal Plain as the Cape Fear Formation, believed to have been deposited in coastal marine basins during the early Cretaceous (Heron, Swift, and Dill, 1968). In the downdip section, beds of Austin(?) through Jurassic(?) age appear to have been deposited by the same system. The late Cretaceous sedimentary regime is represented updip by the three-fold Lumbee sequence and downdip by a massive, fine-grained section most nearly equivalent to the updip Peedee.

A commonly offered explanation for two-fold sequences of this sort is that each represents an advance and retreat of the sea, separated by a period of erosion. However, a simpler explanation is that the two-fold sequence is a result of a reduction in paleoslope. Lower Cretaceous strata were deposited on an immature continental shelf formed by the foundering of the Appalachian Mountain system at the beginning of the Mesozoic. Textural analysis of the Cape Fear Formation (Heron, Swift, and Dill, 1968) suggests that during this period the marine marginal environments had little effect on sediments passing through them. By the end of Austin time, however, a broad construction shelf, the core of the modern one, had been formed. The resulting reduction of slope, perhaps aided by a reduced rate of sea level rise, slowed sedimentation to the extent that the coastal environment could modify the character of the sediment passing through it. The homogenous Early Cretaceous depositional environment broke up into well differentiated fluvial, estuarine, and shelf lithologies by means of separation of the Early Cretaceous shoreline into a fall line, a bay line (line separating

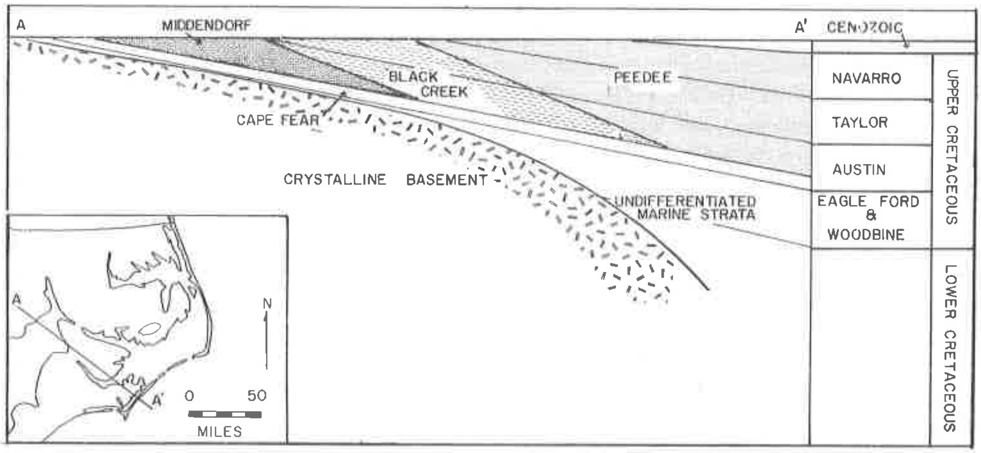

Figure 27. Schematic cross-section of the Carolina Cretaceous.

heads of bays; Lohse, 1955), and an outer shoreline. Thus established, the Middendorf, Black Creek, and Peedee lithotopes began a shoreward migration in response to continued sea level rise through the remainder of Upper Cretaceous time.

SUMMARY AND CONCLUSIONS

The Cape Fear Arch of North and South Carolina brings to the surface a seaward thickening wedge of Cretaceous sediment whose outcrop area is approximately 200 by 400 kilometers. The wedge thickens from an irregular feather edge at the Fall Line to over 1,000 meters in the Hatteras Well. The outcropping strata are readily divisible into three lithosomes. A basal unit of heterogeneous, pale sands and clayey sands has generally been referred to as the Tuscaloosa Formation and has been assigned a continental origin. The overlying Black Creek Formation consists of interbedded pale sand and dark laminated clay. It is mainly of lagoonal and estuarine origin, with littoral sands in its upper most portion. The uppermost Peedee Formation is a homogeneous, medium dark gray, fine to very fine, clayey sand that was deposited on an open shelf.

Careful reassessment of this sequence suggests that the most significant internal boundary lies within the basal "Tuscaloosa" lithosome. The lower "Tuscaloosa" has been re-assigned its original name of "Cape Fear," and has been raised to formational rank. It appears to be of marine marginal (fluvio-estuarine?) origin, and may be of early Cretaceous age. The upper Tuscaloosa has been re-assigned its original name of Middendorf, and has also been raised to formational rank. It is of fluvial origin. The Middendorf, Black Creek, and Peedee are the time-transgressing lithosomes of the late Cretaceous marine transgression of the Carolinas. We recognize their genetic relationship by designating them the Lumbee Group.

Correlation of the outcropping Cretaceous strata with the subsurface Cretaceous strata is difficult. Subsurface data is sparse. The two sections are inherently different, since throughout its history the inner Coastal Plain has received intermittent thin, discontinuous washes of coarse continental sand, while the outer Coastal Plain has received thick, nearly continuous, sequences of marine sediment. Finally, surface and subsurface workers have used different techniques. Surface workers have been mainly concerned with tracing rock stratigraphic units, while subsurface workers, owing to the limitations on their data, have been concerned primarily with rock-time units. However, three gross lithostratigraphic units may be discerned. A heterogeneous sequence of sand and clay strata with a spikey electric log pattern persists throughout the Cretaceous into Austin time. It is followed by a fine probably clayey sand with relatively uniform electric log characteristics, lasting from Austin into Navarro time. This is followed in turn by a coarser, more heterogeneous sand with a spikey electric log pattern. The subsurface section appears to be primarily marine, and bears little apparent relationship to the outcropping section. The most probable lithostratigraphic correlation appears to be a correlation of the entire intermediate subsurface sequence (fine, clayey sand) with the outcropping Peedee. It would appear that during Austin time, a reduction in the paleoslope or in the rate of sea level rise, or both, caused the earlier Cretaceous coastal lithotope (Cape Fear lithotope?) to break up into three well-defined lithotopes. As these fluvial, estuarine and shelf lithotopes moved inland in response to the continuing rise in sea level they respectively generated the Middendorf, Black Creek, and Peedee Formations.

At its most seaward point, the outcropping Peedee is overlain by more than 17 meters of interbedded clean sand and sparry sandy limestone. The sequence contains oysters characteristic of the late Cretaceous, and appears to be a shore facies. If it rests conformably on the Peedee, then it could be designated the uppermost unit of the Lumbee Group, which would then constitute an asymmetrical transgressive-regressive cycle. Elsewhere the Lumbee Group is overlain by Cenozoic sediments of Danian to Pleistocene age.

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RUBIDIUM-STRONTIUM AGE STUDY OF MIDDLE DEVONIAN TIOGA BENTONITE

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ABSTRACT

Twenty-two whole-rock samples of Middle Devonian Tioga Bentonite were analyzed for Rb, Sr and Sr isotopic composition. All analyzed samples exhibit significant alteration of the original minerals. Fifteen of the twenty-two samples analyzed lie on a 310 m. y. isochron. The average "age" of all samples is 302 m. y. This average "age" is approximately 70-80 m. y., or only about 20 percent, younger than expected for rocks of Middle Devonian age. Consequently, these results provide support for our previous suggestion that useful Rb-Sr age data might be obtained on weathered rocks of unknown age from areas where it is impossible to obtain fresh samples.

INTRODUCTION

Whole-rock samples of Middle Devonian Tioga Bentonite have been analyzed for rubidium, strontium, and strontium isotopic composition. These results are part of a continuing study on the effect of weathering on Rb-Sr whole-rock ages.

In a previous investigation (Bottino and Fullagar, 1968), comparison was made of the Rb-Sr ages of fresh and weathered whole-rock samples of the Cape Ann Granite, Massachusetts, and the Petersburg Granite, Virginia. The Cape Ann Granite samples were weathered to the extent of being slightly friable. These weathered samples had an average Rb-Sr age only 10 percent younger than the isochron age for fresh samples of the Cape Ann Granite. The age of saprolite samples from the Petersburg Granite was only 8-15 percent younger than the age of the fresh samples.

If weathering lowers Rb-Sr ages only slightly, meaningful age data might be obtained even if only weathered rock samples can be obtained. To test this suggestion, we are analyzing additional suites of weathered samples.

The Tioga Bentonite has a well-defined stratigraphic position and thus a good estimate of its age may be obtained from published time scales. Comparison of our results on samples of weathered Tioga Bentonite with the expected age permits an evaluation of the effect of weathering on the Rb-Sr age for this lithologic unit.

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TIOGA BENTONITE

By definition, the Devonian Tioga Bentonite marks the top of the Onesquethaw Stage (Dennison, 1961); this age assignment is used in the Devonian standard section of New York (Rickard, 1964) and elsewhere in the Appalachian basin (Oliver et al., 1967). Interpolation of time scale estimates indicate that the Tioga Bentonite was deposited 380 ± 10 m.y. ago (Holmes, 1960; Kulp, 1961; Harland et al., 1964; Afanassyef et al., 1964; Faul, 1966). The bentonite is found in outcrops, most of which are in Virginia, West Virginia, Maryland, Pennsylvania and New York and wells throughout the middle and northern Appalachian basin. All analyzed specimens came from outcrops. Sample locations are given in the Appendix. The bentonite has been studied in detail by Dennison (1961) and Dennison and Textoris (1968), who collected or aided in collecting the samples used for this geochronological study.

The following description of the Tioga was provided by Dennison and Textoris from a manuscript in preparation.

> "In west-central Virginia the bentonite has its greatest thickness and consists of several tuffaceous layers. A distinctive coarse mica zone is the most extensive layer of the Tioga, and most samples analyzed in this study came from this zone. Samples analyzed range from coarse crystal-vitric and crystal tuffs to tuffaceous shale. Vitric

portions probably were glass dust and have devitrified to illite, microcrystalline quartz and montmorillonite. The most common crystals are biotite, and these are up to 1.5 mm in diameter. Other crystals are plagioclase and quartz; these crystals generally are smaller than the biotite crystals. There is a general decrease in grain size away from west-central Virginia."

The coarseness of the crystals and the thickness of the tuffaceous layers suggested to Dennison and Textoris that the source volcano(s) was in west-central or central Virginia.

"In all thin sections of the Tioga Bentonite, feldspar and, to a lesser extent, biotite exhibit considerable alteration. Diagenesis (which includes weathering) has produced authigenic illite, pyrite, gypsum, basaluminite, limonite, calcite and chloritoid. These minerals have replaced and filled considerable portions of the very porous and permeable bentonite."

ANALYTICAL PROCEDURES

The Rb-Sr method of age determination is based on the radioactive decay of Rb^{87} to Sr^{87} by beta-emission. Using an indirect method, Aldrich et al. (1956) determined that the half-life for Rb^{87} is 5.0×10^{10} years ($\lambda Rb^{87} = 1.39 \times 10^{-11}$ years^{-1}). This half-life and decay constant are used for the age calculations in this paper.

The equation used for calculating Rb-Sr whole-rock ages is as follows:

$$(Sr^{87}/Sr^{86})_p = (Sr^{87}/Sr^{86})_o + (Rb^{87}/Sr^{86}) \lambda t$$

where

$(Sr^{87}/Sr^{86})_p$ is the present Sr isotopic ratio in a sample and this value is measured during analysis;

$(Sr^{87}/Sr^{86})_o$ is the ratio of the original or initial strontium in the sample;

(Rb^{87}/Sr^{86}) is the present ratio in the sample and is measured during analysis;

λ is the decay content for Rb^{87}; t is the age of the rock.

Analysis of a single whole-rock sample is not sufficient to solve the age equation, as the equation still would contain two unknowns, $(Sr^{87}/Sr^{86})_o$ and t. To sclve for both unknowns, a number of samples with different Rb/Sr ratios are analyzed. The results are evaluated by plotting $(Sr^{87}/Sr^{86})_p$ versus (Rb^{87}/Sr^{86}). The results ideally plot in a straight line, which is called an isochron. The slope of the isochron is proportional to the age (t) of the rock, and the intercept gives the $(Sr^{87}/Sr^{86})_o$ of the primary strontium. The validity of an age determined from an isochron plot is based on the following conditions:

1. All samples must have the same $(Sr^{87}/Sr^{86})_o$.

2. All samples must be of the same age.
3. Each whole-rock sample must have acted as a closed system with respect to Rb and Sr.

Detailed discussions of the Rb-Sr method are given by Moorbath (1964) and Hamilton (1965). The significance of the initial Sr^{87}/Sr^{86} ratio is discussed by Faure and Hurley (1963).

Whole-rock samples were prepared by crushing 30-50 grams of rock. Biotite was hand separated from portions of three bentonite samples. The biotite crystals obtained were approximately 1 mm in diameter.

The samples were dissolved in reagent grade HF and vycor-distilled H_2SO_4. The solutions were passed through cation exchange columns to concentrate Rb and Sr. Rubidium and strontium concentrations were measured by isotope dilution techniques. Most of the isotope dilution analyses were done using a Sr^{86} spike; for each of these samples, the Sr isotopic composition was measured on a separate unspiked solution. A few samples were spiked with Sr^{84}, permitting both the Sr isotopic composition and Sr concentration to be determined from the same analysis. (These samples are indicated in Table 1). All mass spectrometry was done at Goddard Space Flight Center using a 12-inch radius of curvature, solid-source mass spectrometer.

ANALYTICAL RESULTS

Twenty-two whole-rock samples of bentonite were analyzed. The Rb and Sr concentrations and Sr isotopic composition are given in Table 1. (The Sr^{87}/Sr^{86} ratios have been normalized to Sr^{86}/Sr^{88} = 0.1194; explanation of this normalization procedure is given by Faure and Hurley, 1963). With one exception, the analytical results are plotted in Figure 1; the Rb^{87}/Sr^{86} ratio for sample #314 is too large to permit the results for this sample to be plotted in the figure. The $(Sr^{87}/Sr^{86})_N$ and Rb^{87}/Sr^{86} ratios are plotted with uncertainties of $\pm$ 0.4 percent and $\pm$3 percent respectively. These estimates of analytical uncertainties are based upon our replicate analyses in this and other studies.

The results for most of the bentonite samples plot on or near a visual best-fit isochron of 310 m.y. (Figure 1). Specifically, 15 of the 22 results plot on this isochron. Of the 7 remaining samples, 5 are below the isochron and 2 are above. In spite of this scatter, 11 of the first 12 samples analyzed plotted on the 310 m.y. isochron (#314 was the exception). Since the Tioga Bentonite is significantly older than 310 m.y., these results emphasize that care must be taken in evaluating isochrons established by relatively few points.

Figure 1 indicates that the Tioga Bentonite has an initial Sr^{87}/Sr^{86} ratio of 0.707. Using this value, an "age" has been calculated for each bentonite sample. The "ages" average 302 m.y., and range

Table 1. Rb-Sr Analytical Data.

Sample	Rb ppm	Sr ppm	Average $(Rb/Sr)_{wt}$	Average Rb^{87}/Sr^{86}	Sr^{86}/Sr^{88}	$(Sr^{87}/Sr^{86})_N$
Bentonite						
#300	156.6	36.1	4.34	12.63	0.1198	0.7609
#301	93.3	45.2	2.06	5.98	0.1202	0.7338
#302	80.1	62.6	1.28	3.77	0.1197	0.7253
#303	117.2	80.1	1.46	4.24	0.1202	0.7245
#304	62.8	20.4	3.08	8.95	0.1203	0.7454
#305	99.1	100.8	0.98	2.84	0.1204	0.7208
#306	95.3	72.9	1.31	3.80	0.1195	0.7259
#308	64.9	69.2	0.94	2.73	0.1196	0.7193
#309	78.0	90.3	0.86	2.49	0.1202	0.7181
#310	120.8	65.0	1.86	5.40	0.1199	0.7297
#311	168.7	12.6	13.39	39.44	0.1200	0.8744
#312	97.6	32.5	3.03	8.79	0.1198	0.7312
	97.5	31.8			0.1201	0.7311
#313	83.5	49.4	1.69	4.90	0.1197	0.7273
#314	277.4	8.85			0.1196	0.8965
	276.6	8.34	32.65	95.73		
	284.5	8.49				
#315	112.1	41.0	2.73	7.93	0.1196	0.7403
#346	134.8	6.81	19.79	58.60	0.1197	0.9393
#487	73.5	18.5	3.97	11.54	0.1198	0.7492
#488	110.6	17.5	6.32	18.43	0.1202	0.7798
#489	142.3	42.5	3.32	9.66	0.1196	0.7572
	142.7	43.3*			0.1200*	0.7560*
#492	97.3	31.1	3.13	9.10	0.1197	0.7450
#501	88.2	17.6	5.01	14.59	0.1196	0.7681
#503	54.9	15.6	3.55	10.34	0.1197	0.7661
	55.8	15.6*			0.1199*	0.7675*
Biotite						
#488B	168.4	18.1*	9.30	27.13	0.1201*	0.7823*
#492B	116.3	45.7*	2.54	7.39	0.1199*	0.7511*
#501B	93.4	16.8*	5.56	16.20	0.1197*	0.7711*
Glauconite						
#299	185.6	113.0	1.64	4.76	0.1198	0.7419
#350	104.9	30.0	3.50	10.19	0.1203	0.7615
#351	179.4	75.9	2.36	6.86	0.1201	0.7475

* Sr^{84} spike used in analysis

between 142 m.y. and 416 m.y. Figure 2 shows a plot of the distribution of these "ages".

Biotite was separated from portions of bentonite samples #488, #492 and #501. The analytical results for these three samples are given in Table 1 and are plotted in Figure 1. One of the biotites plots above the 310 m.y. isochron, one slightly below it and one well below it. (These biotites and the corresponding whole-rock samples are numbered in Figure 1.) Obviously, the biotite results show no consistent pattern.

At several locations in West Virginia and Virginia, a glauconitic sandstone unit occurs within 10 feet stratigraphically below the coarse mica zone of the Tioga Bentonite. The glauconite is from the Bob's Ridge Member of the Huntersville Chert (Dennison, 1961). Three whole-rock samples from this glauconitic layer were analyzed. Thin sections indicate that these samples contain 60-80 percent glauconite;

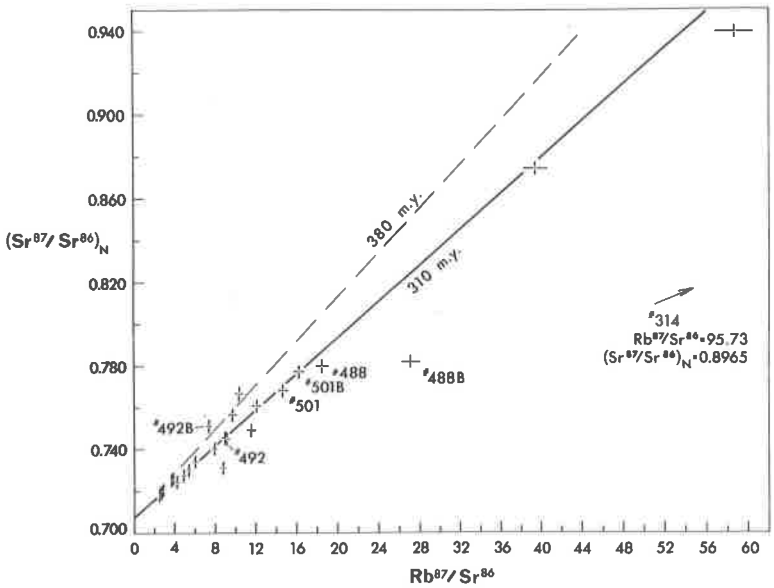

Figure 1. Plot of $(Sr^{87}/Sr^{86})_N$ versus Rb^{87}/Sr^{86} for Tioga Bentonite whole-rock and biotite samples.

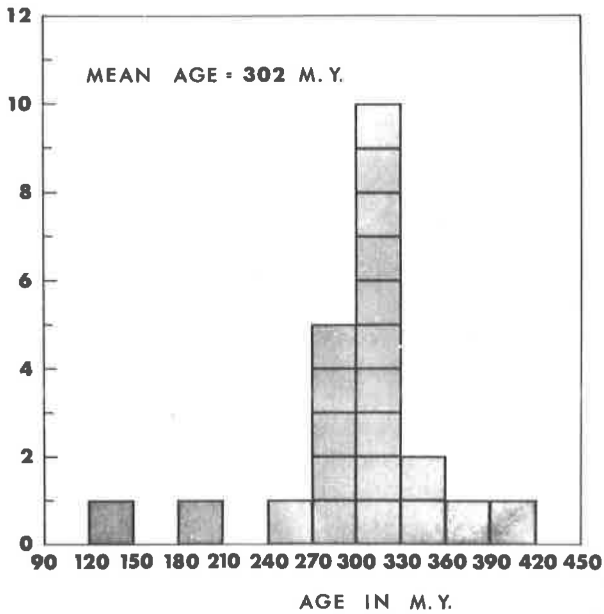

Figure 2. Distribution of Rb-Sr ages of whole-rock Tioga Bentonite samples.

most of the remainder is quartz. The analytical results are given in Table 1, but are not plotted in Figure 1. Inspection shows that the results for these samples would plot above the 310 m. y. isochron, and have an apparent age of 305 m. y.

DISCUSSION AND CONCLUSIONS

Figures 1 and 2 show a pattern of results for the whole-rock samples of Tioga Bentonite. Most of the analyzed whole-rock samples indicate an isochron "age" of approximately 310 m. y. All twenty-two samples have an average "age" of 302 m. y. This "age" is approximately 70-80 m. y. younger than that expected for the lower Middle Devonian. It is not surprising that analyses of the bentonite samples indicate an anomalous age; the bentonite exhibits considerable alteration of the original minerals. In spite of this alteration, this "age" is only about 20 percent too young. (For comparison, the position of a 380 m. y. isochron has been indicated in Figure 1.)

The data for the three glauconite samples are difficult to evaluate because of too few samples and a limited spread in the Rb/Sr ratios of these samples. An isochron established by the glauconite data would indicate a maximum "age" of approximately 305 m. y. This "age" might be the results of weathering or it might be fortuitous.

Biotite often contains a high percentage of the radiogenic Sr^{87} in a whole-rock sample. We therefore considered the possibility that biotite had managed to retain an "age" close to actual age of approximately 380 m. y. If this had happened, the biotite could be the cause of the observed whole-rock age pattern. The three biotites separated from the bentonite and analyzed did not support this hypothesis. Biotites #488 and #501 plot below the 310 m. y. isochron, thus having "ages" less than 310 m. y. Biotite #492 is above the 380 m. y. isochron, suggesting an "age" in excess of 380 m. y. The biotite clearly can not be responsible for the observed whole-rock age pattern. In a study pertinent to our results, Marvin et al., 1965, analyzed biotite samples from a Middle Jurassic bentonite layer in Utah, and found some of the Rb-Sr (and K-Ar) ages to be too young. They suggested that alteration of biotite by groundwater might account for the low ages. This suggestion would seem to apply equally well to the results for the Tioga Bentonite since it is a relatively permeable unit, and most outcrops are marked by a damp zone or a line of ground water seep.

We do not yet have an explanation for the whole-rock age pattern. As we continue our study of weathered rocks, we intend to investigate the possibility that a cation exchange mechanism involving clay minerals might produce this type of age pattern. Perhaps the clay minerals trapped much of the Rb initially present in the bentonite as well as subsequent radiogenic Sr. Such a mechanism also might explain the Rb-Sr ages of saprolitic Petersburg Granite; weathered samples average only approximately 15 percent younger than the average age of fresh samples (Bottino and Fullagar, 1968). In that paper, we suggested that the relatively unweathered biotite might explain, at least in part, the close agreement between the average ages of the fresh and weathered samples (580 m.y. and 495 m.y. respectively). However, our recent analyses of biotite separated from saprolitic and fresh Petersburg Granite give Rb-Sr ages of 180 m.y. and 380 m.y. respectively. The age of the fresh biotite sample probably reflects a thermal event. With ages approximating 180 m.y., biotite from saprolite certainly could not account for the close agreement of ages between the fresh and weathered granite.

The results for the Tioga Bentonite support our earlier suggestion (Bottino and Fullagar, 1968) that useful Rb-Sr age data might be obtained on weathered rocks in situations where ages are unknown and it is impossible to obtain fresh samples.

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APPENDIX: SAMPLE LOCATIONS

Bentonite

West Virginia

#301	Hardy County, 1.7 miles west of Wardensville along W. Va. route 55
#302	Same as #301
#303	Grant County, one mile south-southwest of Hopeville along W. Va. routes 28 and 4
#305	Mineral County, one mile east of Keyser
#308	Hardy County, 1.3 miles southwest of Wardensville
#309	Berkeley County, Allensville
#310	Same as #309
#311	Same as #310
#315	Berkeley County, Tomahawk
#487	Grant County, Whip Gap
#489	Pendleton County, Ketterman Knob

Virginia

#314	Tazewell County, Bluefield
#346	Highland County, two miles northeast of Monterey
#492	Frederick County, Hayfield

Pennsylvania

#304 Fulton County, Anthony Ford
#312 Same as #304
#313 Northumberland County, Selinsgrove Junction
#488 Blair County, one mile south of Tyrone along U. S. route 220
#501 Bedford County, four miles west of Bedford along Pennsylvania Turnpike
#503 Carbon County, West Bowmans

New York

#300 Onondaga County, Warren Bros. quarry three miles north-northeast of Fayette
#306 Onondaga County, Penitentiary quarry, Jamesville

Glauconite

West Virginia

#299 Pocahontas County, Greenbank
#350 Greenbrier County, two miles northeast of White Sulfur Springs
#351 Same as #350