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Abstract

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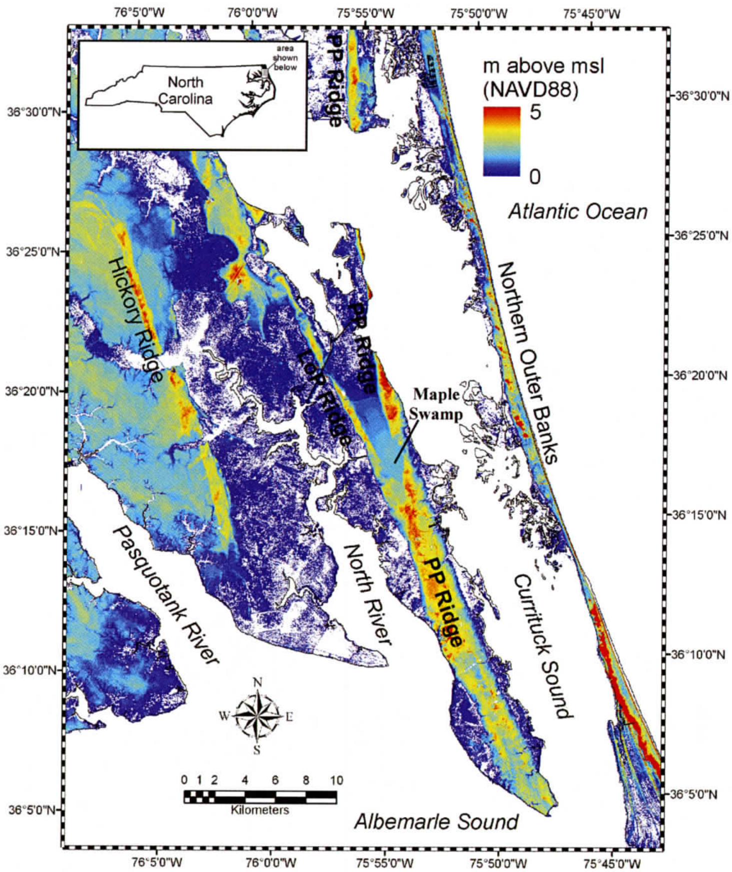

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GEOLOGIC FRAMEWORK OF THE CURRITUCK SAND RIDGES, NORTHEASTERN NORTH CAROLINA

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ABSTRACT

The morphologic, lithologic and geophysical characteristics of two sand ridges in southern Currituck County on the North Carolina coastal plain were investigated to determine their origin. Six radar facies and three lithofacies with six sub-lithofacies suggest that the sand ridges are paleoshorelines. Heavy mineral laminations, muddy sands, and organic units that correlate with radar facies and are interpreted as overwash, foreslope, and rollovers strengthen this determination. Micropaleontology and palynology results further support this interpretation. Geomorphic results indicate a dynamic coastal system with hiatuses, reactivations, and aeolian post-depositional processes.

Luminescence ages from a previous work suggest these ridges formed during MIS 3 highstands, suggesting significant glacio-isostatic adjustments, up to 20m, within the study area.

INTRODUCTION

Since the advent of geophysical techniques such as ground penetrating radar (GPR), geologists can quickly define the depositional environments of siliciclastic coastal deposits and place them in the context of past sea level and climate change. In North Carolina (NC), evidence of Pleistocene sea levels is preserved as a series of erosional scarps and terraces, or depositional ridges. Some of these features have been described as paleoshorelines by previous workers, based on their morphology, lithology, and fossil assemblages (where present) (Oaks, 1964; Eames, 1983; Muhs and others, 2004). Because of the low relief of the northeast NC coastal system, most of the late Pleistocene record occurs at elevations less than 15m, often as laterally adjacent landforms or as superposed deposits of variable thickness and continuity (Muhs and others, 2004). The North Carolina coastal plain, with its many erosional coastal scarps and beach ridges, may contain one of the best records of late Pleistocene sea-level highstands and climate change in North America (Muhs and others, 2004).

The purpose of this paper is to define the stratigraphy and depositional history of the sand units in southern Currituck County (SCC) NC (Figure 1) by correlating GPR and vibracore facies and relating the resulting stratigraphic record to past climatic and depositional environments.

REGIONAL SETTING

Currituck County, the northeastern-most county in North Carolina, has two geographic regions, the mainland peninsula and the northern Outer Banks (Figure 1). The peninsula consists of two shore-parallel sand ridges, the Land of Promise Ridge (LoP) to the west and the Powells Point Ridge (PP) to the east, and is separated by a hardwood swamp forest known as the Maple Swamp (Oaks, 1964). These ridges appear to be relatively young, as they have not been significantly dissected by stream erosion. Furthermore, they are the most outboard ridges in NC, with the exception of the Holocene barrier islands. The western boundary of SCC is North River and the eastern boundary is the Currituck Sound. The shoreline of the county consists mainly of eroding fresh-water to low brackish-water marsh and hardwood swamp forest wetlands, except the few locations where

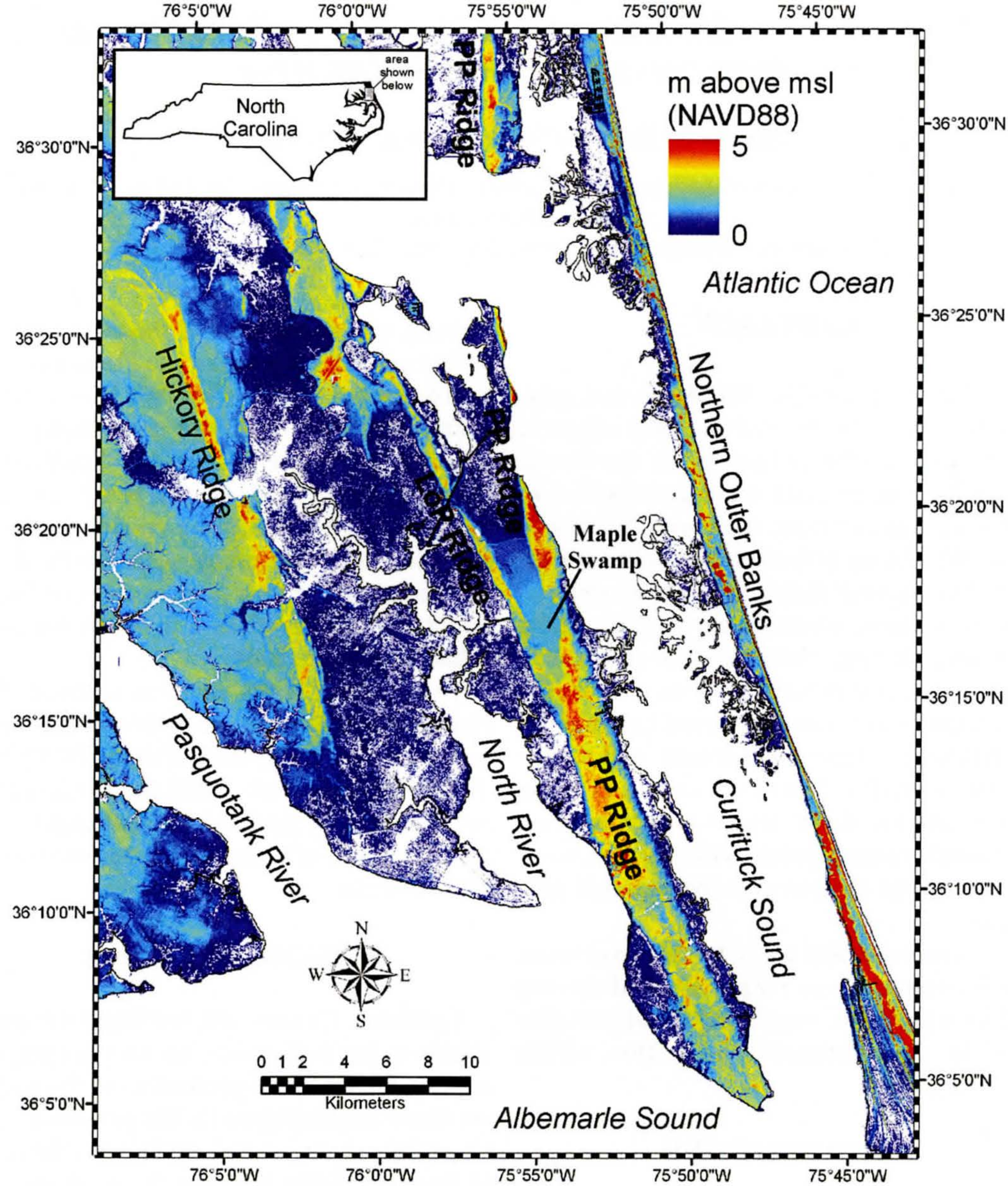


Figure 1. Lidar topographic map showing the location of the study area and the dominant features discussed within this paper such as the Land of Promise Ridge (LoP) and the Powells Point Ridge (PP) as well as other features such as the Hickory Ridge and the Northern Outer Banks.

the ridges are eroding into the Currituck Sound.

METHODOLOGY AND SAMPLING STRATEGY

Ground Penetrating Radar

Sixty kilometers of ground penetrating radar (GPR) data were collected throughout the study area in order to define radar facies and reflectors that are indicative of depositional environments. Data were collected along three ridge-parallel (north-south) transects totaling 44 km and along five shore-normal (east-west) transects totaling 16 km (Figure 2). Transect lines were chosen by accessibility along state

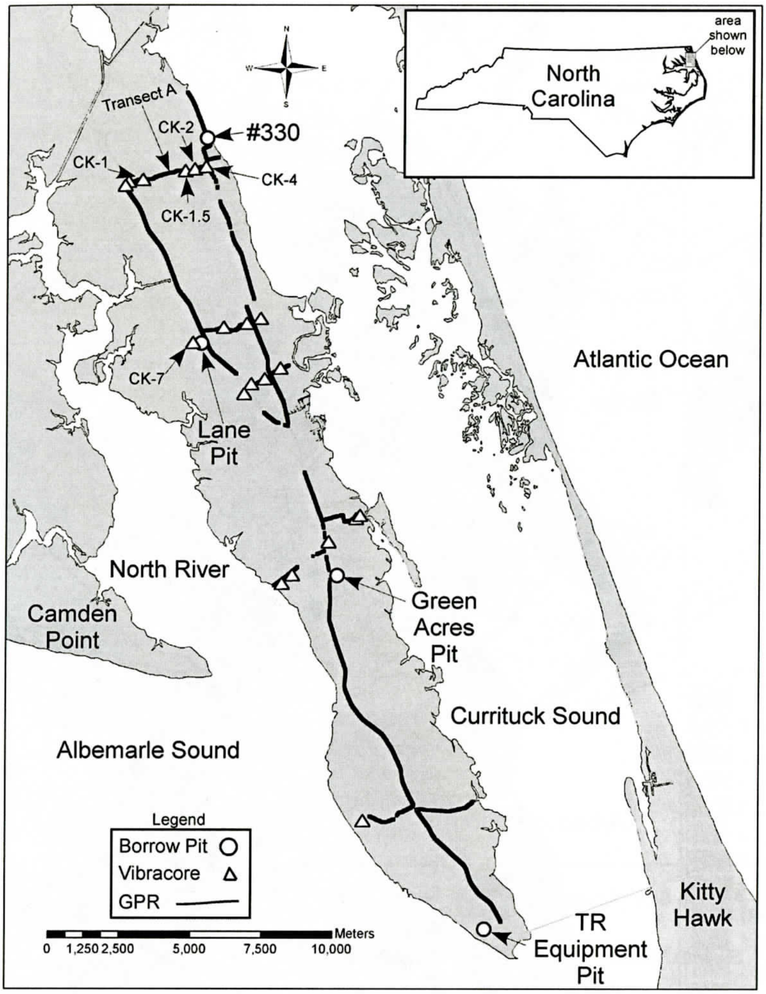


Figure 2. Location map of study area showing the 20 vibracore locations, 3 borrow pit locations, bluff, and 60 kilometers of GRP survey lines.

roads, which run parallel and perpendicular to the ridges of SCC.

GPR data were acquired using a truck or a Polaris two-seater all terrain vehicle (ATV) traveling between 3-5 miles per hour. A Geophysical Survey Systems Inc.© (GSSI) 100 MHz antenna was towed behind the ATV while the passenger monitored the readout on the Subsurface Interface Radar (SIR) 2000 and collected notes. Data were collected at 16 bits/sample, 512 samples/scan, and 8 scans/second (approximately 6 scans/meter). Navigation data, recorded in WGS84 format, were obtained using a Trimble Differential Global Positioning System (GPS) unit, which the driver monitored. Waypoints were recorded simultaneously on the GPR and GPS systems.

The raw GPR data were processed using Radan software©, which included bandpass filtering (75-125 MHz), gain adjustment, stacking (3x), and surface normalization. Processed data were exported as bitmap files into Canvas©. The major reflectors were traced and separated from the GPR line to help visualize depositional groups and define radar facies.

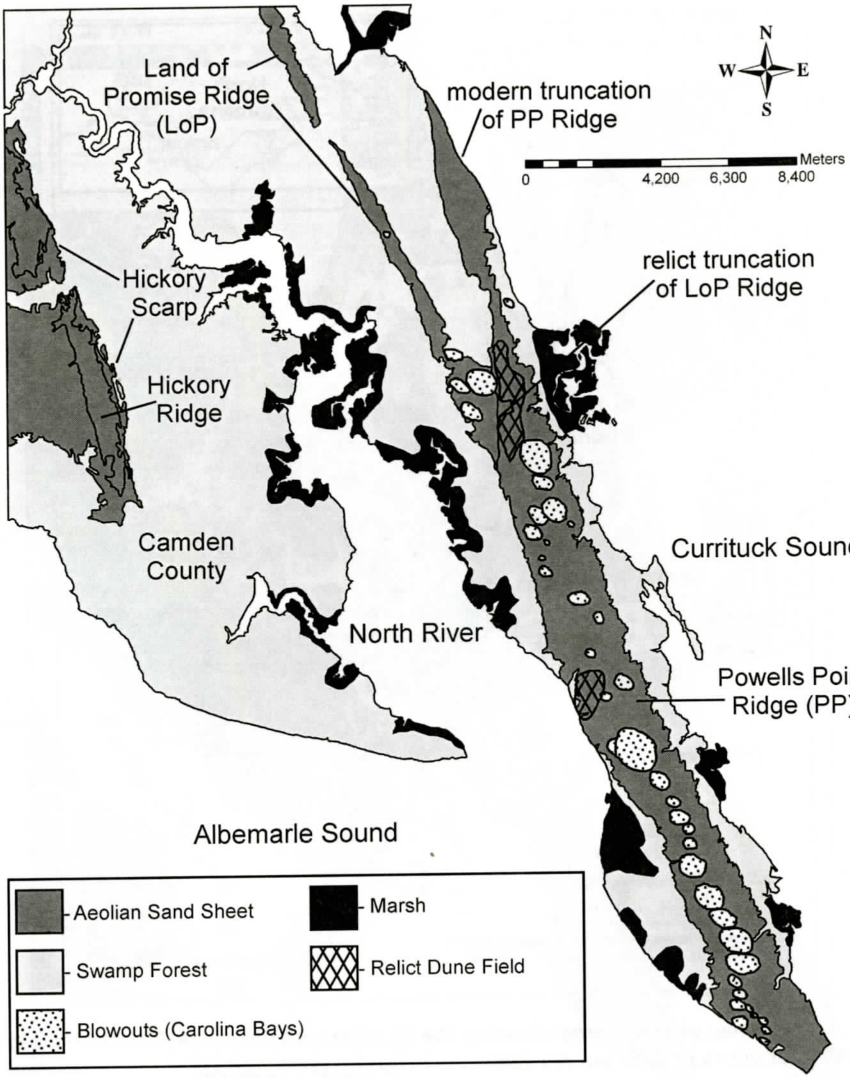


Figure 3. Geomorphic map of southern Currituck County illustrating the major features of the study area. The Blowouts (Carolina Bays) mapped in the field area were only detectable using Lidar. The relict dune fields indicate sand movement during cooler dryer climates.

Geomorphic Analysis

Geomorphic mapping was accomplished using light detection and ranging (LiDAR) data and 1998 color-infrared digital orthophoto quarter-quadrangle (DOQQ) obtained from the North Carolina Geological Survey. Raw LiDAR data were downloaded from the North Carolina Floodplains Mapping Program website (www.ncfloodmaps.com) and the North Carolina Department of Transportation website (www.ncdot.org).

LiDAR is an active sensor that emits laser pulses and measures the return time for each beam to travel between the sensor and a target using ultra-accurate clocks (Suarez and others, 2005). The location of every laser return is achieved by using differential GPS and an inertial measurement unit obtains orientation parameters. The majority of commercial LiDAR systems can collect between 20,000 and 75,000 records per second and are capable of achieving

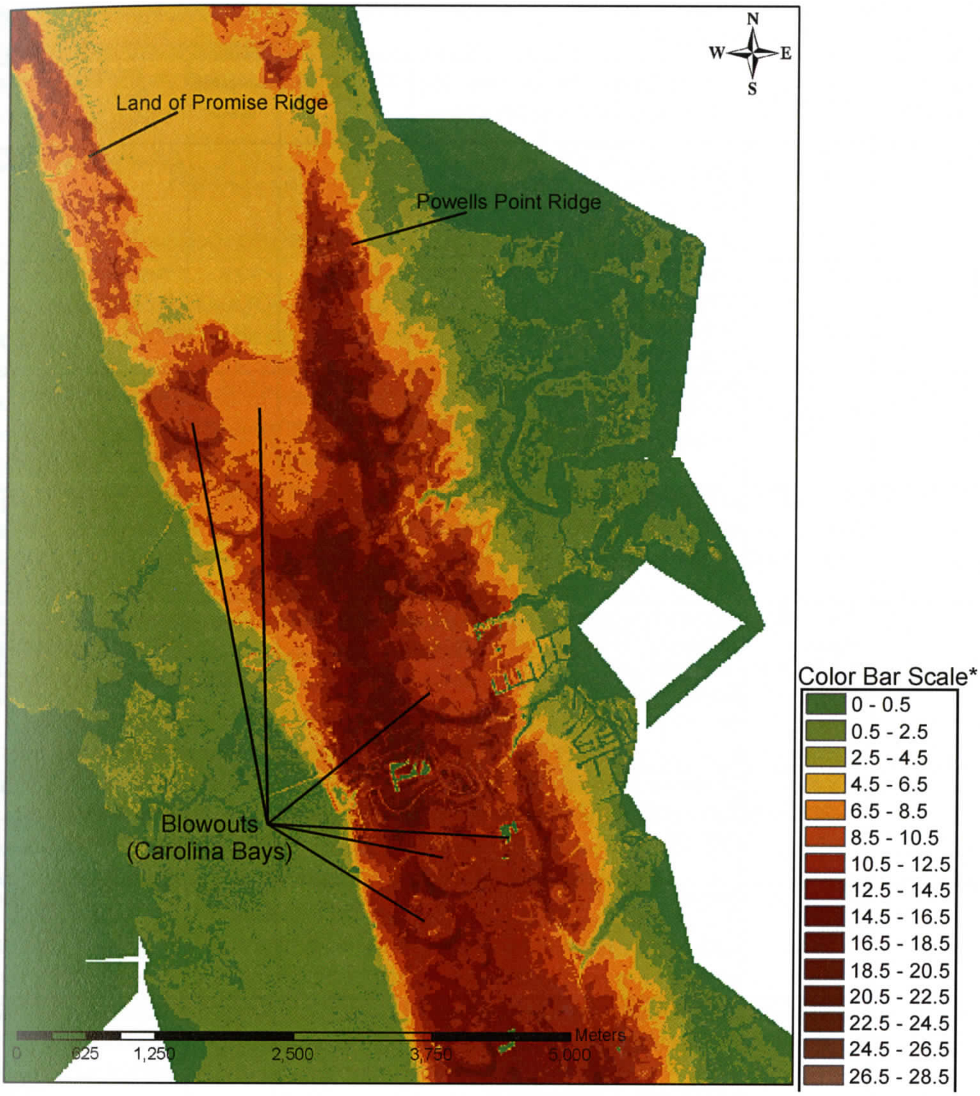


Figure 4. Lidar topographic map illustrating the relict truncation of the LoP Ridge. This truncation indicates the sand ridges were formed by two individual fluctuations in sea level and is identified in Figure 3. *Elevations are in feet.

high vertical (between +/- 15 to 20 cm) and horizontal (between +/- 20 to 30 cm) accuracies (Suarez and others, 2005). The LiDAR data in this investigation have a conservative vertical error of ±25 cm. Pixel size is 5 m.

Raw LiDAR data were downloaded from the websites and manipulated using ArcGIS 9© (application of hillshade, slope aspect, etc.). The LiDAR map was exported from ArcGIS 9© in jpeg form, then imported into Canvas©. The geomorphic features were digitized and interpreted to produce a geomorphic map.

Lithology

Twenty vibracore locations were chosen using the GPR data in an attempt to recover multiple lithofacies in a single core (Figure 2). Vibracoring induces high frequency vibrations onto a 3-inch diameter aluminum irrigation pipe, which allows the pipe to penetrate into the ground. Typical cores measure 4 to 6 meters be-

Table 1. Summary table of lithofacies, specific characteristics, and interpreted depositional environments defined in this study.

Major Lithofacies	Sub-facies	Sediment Description	Sedimentary Structures	Percent Organic Material	Percent Mud	Interpreted Depositional Environments
Sandy Mud (sM)		Light olive gray (5Y 5/2) to brownish black (5YR 2/1); Micaeous	Massively bedded	<10%	>50%	Estuary/Back-Barrier
Organic Peat (P)		Dusky yellowish brown (10YR 2/2); fibric to sapric organic deposit	Bioturbated and structureless	>20%	<10%	Freshwater marsh, Hardwood Swamp Forest
Sand (S)	Rooted Sand (rS)	Dusky brown (5YR 2/2) to dusky yellowish brown (10YR 2/2)	Bioturbated with in situ roots and rhizomes	<10%	<10%	Topsoil/paleosol
	Massively Bedded Sand (mass)	Medium dark gray (N4) to pale yellowish orange (10YR 8/6)	Massively bedded w/ occ. Mud lam & mottling	<10%	<10%	Flood tidal delta complex, Interior tidal flat, Back-barrier sand flats, Aeolian Dune
	Heavy Mineral Laminated Sand (hlS)	Moderate yellowish brown (10YR 5/4) to dark yellowish orange (10YR 6/6)	Heavy mineral laminations	<10%	<10%	Flood tidal delta complex, Barrier interior tidal channel, Distal overwash barrier flat, Back-barrier berm (aeolian)
	Slightly Muddy Sand (smS)	Moderate yellowish brown (10YR 5/4) to dark gray (N3)	Massively bedded w/ occ mottling & burrowing	<10%	10-20%	Flood tidal delta complex, Back-barrier sand flats
	Muddy Sand (mS)	Brownish black (5YR 2/1) to dark yellowish brown (10YR 6/6)	Massively bedded w/ occ mottling & burrowing	<10%	21-50%	Flood tidal delta complex, Back-barrier sand flats
	Laminated Sand (lS)	Dark yellowish orange (10YR 6/6) to pale yellowish brown (10YR 6/2); laminations are pale yellowish brown (10YR 6/2) to grayish orange (10YR 7/4) quartz sand	Laminated sand; Varve-like appearance	<10%	<10%	Lake, Shallow body of water (back-barrier lagoon)

low the ground surface. Precise measurement of core penetration depth, recovered core length, and sediment lost were recorded in the field. Vibracore locations were documented using a Trimble Differential GPS unit.

In the lab, the cores were cut in half using a circular saw. One half was sampled and the other half was archived. The archived half was photographed at 35 cm intervals with a Nikon D100 digital camera. The cores were visually logged and sampled for lithology, microfossils (foraminifera and diatoms, pollen), and ^{14}C dating. Texture of the major lithofacies was determined by sieving following methods described in Folk (1980).

These vibracores were used to define the lithologic character of radar reflectors and facies identified on the processed GPR data, as well as to correlate subsurface units to produce geologic cross-sections of SCC.

RESULTS

Geomorphology

LiDAR imagery, DOQQs, and field observations were utilized to develop a geomorphic map of SCC (Figure 3). The DOQQs suggest that SCC is composed of two shore-parallel ridges that merge at Grandy Township. Further investigation with LiDAR showed that the PP Ridge truncates the LoP Ridge just north of Grandy along a north striking line (Figure 1 and Figure 4). Vegetation mapped in the low-lying areas (0 – 2 m) of SCC and Camden County using the 1998 DOQQs was identified in the field. The majority of this area is occupied by swamp forest, with marshes fringing the shorelines.

The swamp forests of SCC are dominated by numerous types of wetland trees and shrubs including bald cypress (*Taxodium distichum*), black gum (*Nyssa biflora*), wax myrtle (*Myrica cerifera*), bay (*Persea borbonia*), oak (*Quercus* sp.), and red maple (*Acer rubrum*). Needlerush (*Juncus roemerianus*), cattails (*Typha* sp.), bulrushes (*Scirpus tabernaemontani*), and reedgrass (*Phragmites australis*) dominate the marshes that fringe the shorelines.

Both ridges, LoP and PP, are linear, shore-parallel features that extend approximately 50 km and range in width from 300 m to 2 km. Elevation (based on LiDAR data) ranges from 2 to 10 m, with an average of 4 m. The highest elevations (7-10 m) are found only in a very localized area and correspond to an inactive dune field (Figure 1 and Figure 3). Slope aspect analysis of the LiDAR data reveals a portion of the PP Ridge that exhibits steep south to southeast facing linear to meandering slopes associated with ENE trending dunes, and representing the dune slip-face. The ridges are mantled with many (at least forty) Carolina Bays; very shallow (1-2 m) elliptical depressions with sand rims, with the long axis oriented NW-SE (Figure 3). The Carolina Bays range in size (long axis) from approximately 200 m to 1500 m, and typically exhibit an elevated (1-2 m) southeast rim. Much of the area has been modified by agricultural activity and development.

Lithofacies

Twenty vibracores and three sand borrow pits were examined along five shore-normal transects in order to determine stratigraphy and geologic history of SCC (Figure 2). Three dominant lithofacies and six subfacies were defined on the basis of sediment texture, color, sedimentary structures and biogenic material (Table 1).

A palynological analysis conducted by Dr. M. Farley (UNC Pembroke) revealed that only five of the eleven samples analysed contained pollen (Table 2). However, when present, the pollen included abundant *Ambrosia* (ragweed), *Gramineae* (grass), *Alnus* (alder), and *Betula* (birch), indicating climate conditions colder than present at the time of sediment deposition (M. Farley, personal communications, 2005).

Foraminifera were not found in any of the 16 samples examined and diatoms in only 2 of 9 samples. This is consistent with the findings of Johnson (1976), Peebles (1984), and Mixon (1985), who analyzed the sediments of the equivalent stratigraphic units (Poquoson and Lynnhaven Members of the Tabb Formation and the upper unit of the Wachapreague Formation) in southeast Virginia and the Delmarva Peninsula.

Diatom fragments and sponge spicules were identified in two samples from CK-1.5, within the sandy-mud (sM) lithofacies. The diatom fragments are *Cosmiodiscus sp.*, planktonic diatoms found in marine and estuarine littoral zones (Hustedt, 1955). The fragments indicate transport and reworking of the diatoms and not direct deposition. The diatom fragments and sponge spicules suggest the sM lithofacies is a back-barrier/estuarine deposit.

Geophysical Data

Six radar facies were identified based upon reflection amplitude, continuity, and geometry

Table 2. Table of pollen samples, depth sample was collected, sampled vibracores and borrow pits, associated lithofacies, and descriptions.

Core #	Depth (cm)	Associated Lithofacies	Description
CK-1	34-36	masS	Barren of palynomorphs; some general degraded cuticle
CK-1	101-103	masS	Barren
CK-1	141-143	rS	Highly productive and diverse palynoflora including alder, regweed, grass, *Betula*, other angiosperm pollen, and trilete fern spores
CK-1	201-203	masS	Barren of palynomorphs; some general degraded cuticle
CK-1	341-343	hlS	Barren of palynomorphs; some general degraded cuticle
CK-2	301-303	masS	Moderately productive with *Betula*, trilete fern spores and other angiosperm pollen, but no ragweed on initial exam
CK-4	51-53	smS	Rare fungal spores, one large trilete spore, else barren of palynomorphs; very degraded organic matter
CK-4	161-163	masS	Barren of palynomorphs; some general degraded cuticle and vascular debris
CK-4	241-243	hlS	Fairly diverse and abundant palynoflora including alder, regweed, Betula, and grass pollen
CK-7	95-97	masS	Bisaccate conifer pollen, taxodiaceous conifer pollen, grass; palynoflora not too diverse, much vascular plant debris
GA Pit	~600	N/A	Barren; degraded cuticle but very little organic matter

(Table 3). Confirmation of these interpretations is provided by correlation of GPR data to vibracores and pit exposures (Figure 5). The characteristics and interpretations of radar facies are presented in Table 3. Correlation of these facies to core data and pit exposures allowed construction of the regional depositional and chronostratigraphic framework of SCC.

Calculation of Dielectric Constant

Since GPR is a velocity-dependent technique, to find a true vertical scale it is necessary to calculate a subsurface velocity or to have extensive "ground-truth" in the form of measured core or section data (Brill, 1996). In four locations (#330, Lane Pit, CK-7, and CK-1) RF1 was identified and measured. The dielectric constant (K) can be calculated for a given geologic section with the following formula if the depth to a reflector is known:

$$K = (t/2)^2 * (c/D)^2$$

Where:

t = two-way travel time in seconds

c = speed of light in a vacuum, in meters/second ($2.998*10^8$ m/s)

D = depth to the reflector in meters

(Adapted from Davis and Annan, 1989)

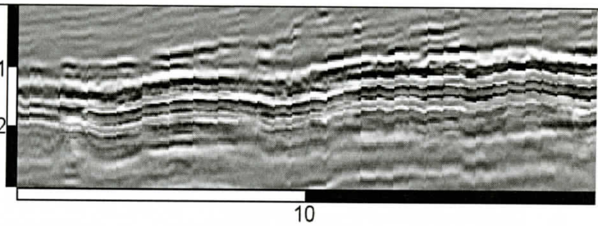
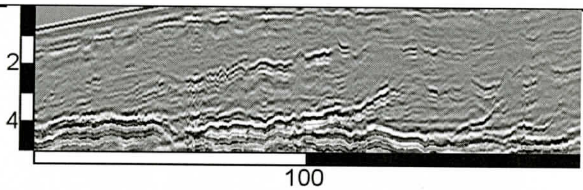
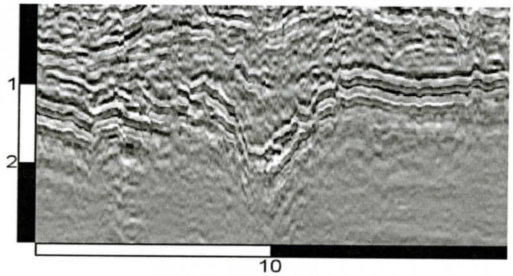
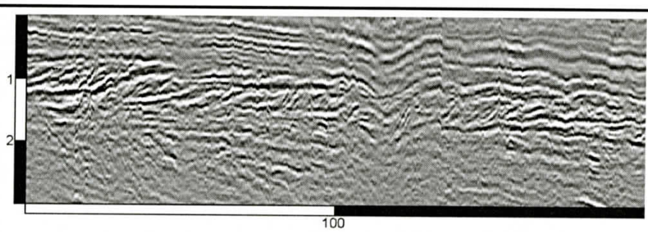
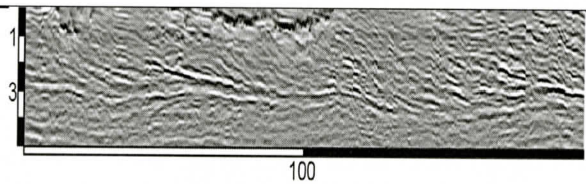
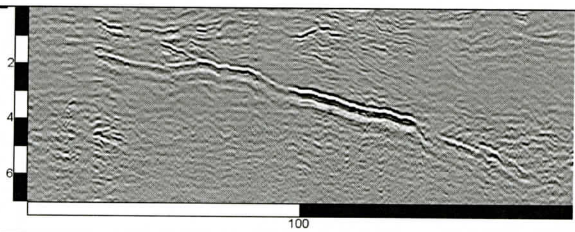
Based upon correlation between the GPR data and "ground-truth" data, the average dielectric constant was found to be 27.5, consistent with reported values for saturated sandy sediments (Davis and Annan, 1989).

DISCUSSION

Geomorphology

The ridges are the approximate height, width, and orientation of the modern Outer Banks. However, the relief is more subtle, suggesting some degradation of surface features since initial deposition, either by erosive or depositional processes. Surface smoothing may have been facilitated by general aeolian sand sheet activity during the late Pleistocene, as suggested by the upper remobilized sand unit above a buried A horizon (paleosol) at the #330 bluff site. This reactivation has been dated by OSL, suggesting sand remobilization at approximately 12.5 ± 2.7 ka (Mallinson and others, 2008A). This age agrees well with sand sheet

Table 3. Characteristics and examples of the GPR Radar Facies defined in SCC. Scales are in meters.

GPR Facies	Characteristics	Example
RF1 – Organic Rich (Peat) Layer	continuous, horizontal-subhorizontal, high amplitude reflector that may attenuate signal below	
RF2 – Roll Over	discontinuous sub-horizontal gently (1°-5°) dipping reflections	
RF3 – Channel Structure	discontinuous, medium-high amplitude, V-shaped reflector	
RF4 – Overwash Foresets	continuous, low-medium amplitude, steeply landward dipping (>20°) clinoforms	
RF5 – Foredune or Foreslope Accretion	discontinuous, low-medium amplitude, seaward dipping clinoforms	
RF6 – Diastem	continuous low-angled (<10°) high amplitude seaward dipping reflector	

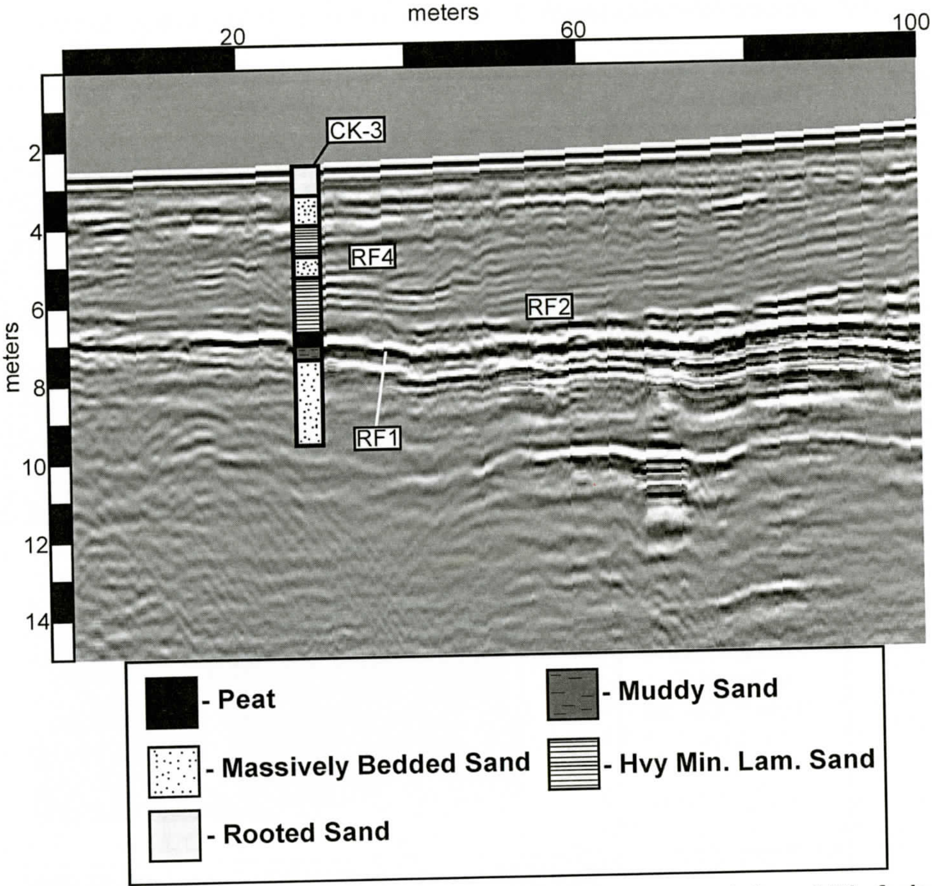


Figure 5. Section of GPR data (transect A-A'; Figure 1) showing correlation of lithofacies with reflectors and radar facies.

activity on the southeast NC coastal plain, near Morehead City, NC, where Mallinson and others (2008B) dated two episodes of sand sheet and dune activity at 13 ka to 12 ka, and again at 11 ka to 10 ka. However, these dates are slightly older than ages of aeolian reactivation found by Ivester and others (2001) on inland dunes (river-bank associated) in Georgia. Ivester and others (2001) found minor reactivation, with sand sheets (ca. 2 m thick) burying A horizons that date to approximately 9 ka.

The origin of the Carolina Bay features has been a topic of great debate, with explanations ranging from craters of a meteor shower to giant fish nests (Beyer, 1980). French and Demitroff (2001) argued the most probable explanation is that they formed in late Wisconsinan time during Marine Isotope Stage (MIS) 2 to 3 as deflation hollows, or 'blowouts', when strong katabatic winds flowed southwards from the continental ice margin across the sparsely vegetated land. Ivester and others (2004) concluded that although some Carolina Bays in the southeast US have been active since MIS (marine isotope stage) 5, the majority of them began forming in late MIS 3.

Relict aeolian landforms have been found on the Atlantic Coastal Plain from Georgia to Delaware in the form of sand sheets, crescent dunes at the rims of Carolina Bays, and riverine dunes that lie on the floodplains and adjacent terraces along the northeast sides of streams (Ivester and others, 2001). The major linear shore-parallel morphology of the SCC ridges does not resemble any of the above-mentioned aeolian deposits, but does resemble modern barrier island

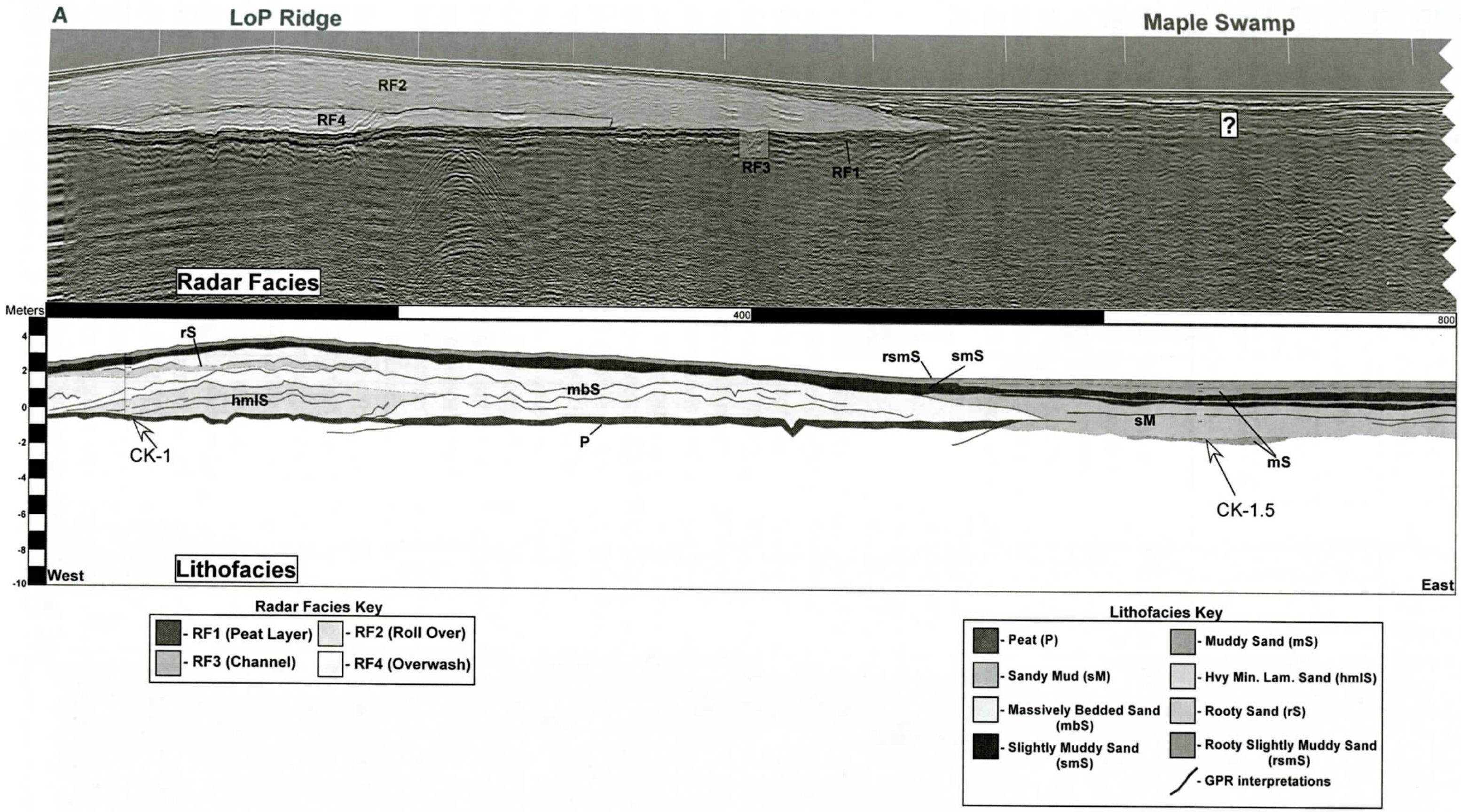


Figure 6. (Top) GPR data and radar facies, and; (bottom) lithofacies and GPR interpretations of the LoP Ridge of Transect A-A'. The GPR data suggests coastal processes including overwash, rollovers, and aeolian processes formed this sand ridge. See Figure 2 for Transect A-A' location. VE = 53X

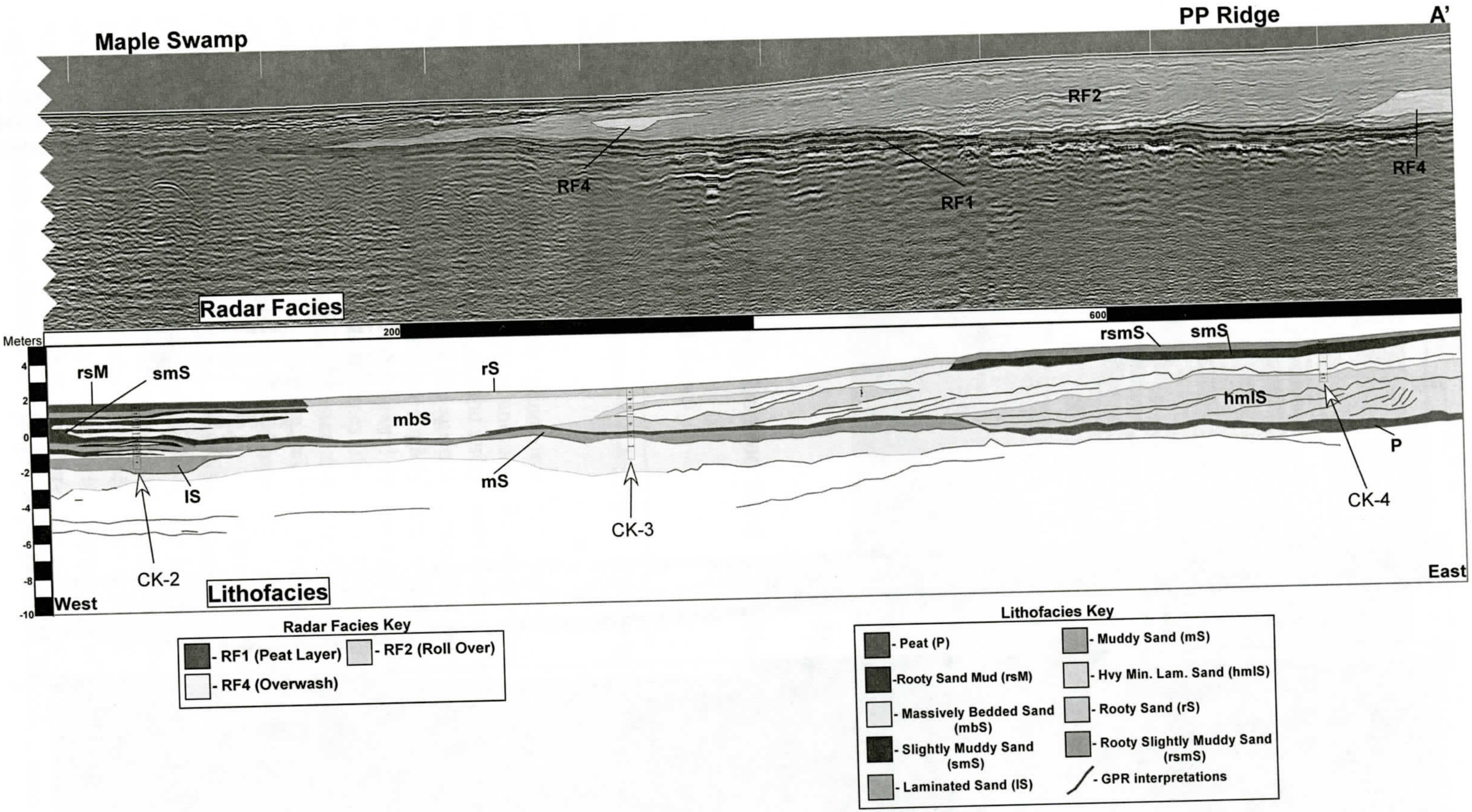


Figure 7. (Top) GPR data with radar facies, and; (bottom) lithofacies and GPR interpretations of the PP Ridge of Transect A-A'. The GPR data suggests coastal processes including overwash, rollovers, and aeolian processes formed this sand ridge. See Figure 2 for Transect A-A' location. VE = 53X

Table 4. Table of δ13C values. See Figure 1 for location of #330 site and CK-1.

Sample Name/ Number	Beta Analytic Sample #	Core # & Depth Relative to Ground	Location	Sediment Description	Sample Dated	$\delta^{13}C$ (0/00)
CKR-1-2	Beta-183552	grab sample from #330 bluff & 510 cm	Aydlett	top of peaty layer	bark	-24.1
CKR-2-1	Beta-183553	core ck-1-B @ 194-197 cm	Aydlett	organic rich, peat	bark	-28.4
CKR-3-1	Beta-183554	grab sample from #330 bluff & 550 cm	Aydlett	peaty layer	tree cross-section	-23.1

systems. The truncation of the LoP Ridge by the PP Ridge would not likely occur in an aeolian environment, but in an environment where water is the major eroding agent (Figure 4). Additionally, the identification of low-relief beach ridge deposits also substantiates a littoral setting.

Facies Interpretations

Ground penetrating radar and vibracores were used to define radar facies (RF) and lithofacies (LF), respectively. Using a section of GPR transect A (Figure 2) as a model that has been "ground-truthed" by vibracore lithofacies, depositional environment interpretations of the remaining transects and SCC were possible (Figures 5, 6 & Figure 7). The interpreted depositional environments for RF1 (Table 3) are well supported for transect A-A'. The P lithofacies matches the depth of the high amplitude continuous reflection of RF1. The objective then becomes to use the lithofacies that correspond to radar facies to decipher depositional environments in areas with no vibracores.

The multiple shallow-dipping subparallel reflections of RF2 and RF4 occur above the peat layer and correspond with the hlS and masS lithofacies, respectively. RF4 is interpreted as an overwash deposit based on the reflector geometry, (Table 3) and hlS and masS are interpreted as back-barrier berms and/or overwash deposits (Table 1). RF4 is interpreted as an overwash deposit in transect A-A'. RF2 corresponds with the masS and hlS lithofacies (Table 1) and is interpreted as roll over or slip face deposits (Table 3). Therefore RF2 is interpreted to represent aeolian deposits in transect A-A'.

Paleoshoreline Development

Beneath the PP Ridge, a blue-gray muddy sand (mS) to sandy mud (sM) facies (Table 1), with fossil bivalve assemblages was found, and represents the top of the underlying depositional sequence on which the PP ridge, and associated coastal lithosomes, was deposited. This underlying unit has been dated to 80 ka (MIS 5a) using OSL (Mallinson and others, 2008A) and correlates with units regionally that have been dated to ca. 70-80 ka using U-series data (Cronin and others, 1981; Mixon and others, 1982; Szabo, 1985; Wehmiller and others, 2004).

A peat layer occurs above this unit beneath the PP and LoP Ridges, and represents initial deposition of strata that is genetically linked to the PP and LoP Ridges. This peat layer returned radiocarbon ages that are essentially "dead", and $\delta^{13}C$ values of -23 to -28 per mil, typical of C3 plants (Table 4). The inclusion of tree branches and roots in the peat beneath the PP ridge (at #330 site (Figure 2)) suggest a freshwater swamp forest depositional environment. The peat beneath the LoP Ridge did not contain wood fragments and has an unclear origin. However, the $\delta^{13}C$ value of -28.3 per mil also indicates C3 vegetation, possibly Juncus sp., suggesting a fresh to low brackish water marsh depositional environment.

As sea level rose, the peat was eroded on the seaward (east) side. Once sea level peaked, the erosion of the peat ceased and overwash sediments were deposited on the peat platform. The overwash is characterized in core samples by the heavy mineral laminated sand (hlS) facies, very similar to overwash found on the modern

Outer Banks (Smith and others, 2008; Culver and others, 2006). The GPR overwash facies is found on the landward side of the LoP and PP Ridges, and exhibits westward prograding clinoforms, sometimes arranged in stacked units. These data reveal two possible overwash units above the peat unit. An aeolian sand sheet overlies the upper overwash unit. Pollen data indicate that *Ambrosia* (ragweed) and *Gramineae* (grass) colonized the dunes. A backbarrier estuarine environment is indicated beneath LoP Ridge, based on the presence of diatom fragments and sponge spicules in core CK 1.5.

As sea level receded slightly after the deposition of the LoP Ridge, a swamp forest developed along the eastern side of the ridge, as indicated by the fresh-water swamp forest peat beneath the PP ridge. As sea level rose again, the shoreline did not mimic the previous shoreline, but was positioned at an angle more like the modern shoreline. This caused the erosion of the swamp forest as well as truncation of the LoP Ridge in the southern parts of SCC (Figure 3 and Figure 4). As sea level stabilized, the PP Ridge formed as overwash deposits covered the swamp forest, and were capped by aeolian sands (Mallinson and others, 2008A). The aeolian sand deposited on the PP Ridge may also be associated with the upper masS unit of the LoP Ridge as defined in CK-1. Deposition ceased and a thin (~10 cm) paleosol formed (in late MIS 3 to MIS 2) on the PP Ridge.

A masS unit was deposited on top of the PP Ridge after the paleosol formed. OSL ages suggest that deposition of this unit occurred in two stages. Two ages, for TCK-7 and TCK-13, indicate deposition prior to the onset of the last glacial maximum (LGM) during MIS 2 (Mallinson and others, 2008A). During MIS 2, windy conditions caused blowouts or "Carolina Bays" to form in sandy areas with minimal vegetation (Ivester and others, 2004). Later reworking of the masS unit described above is evidenced by the TCK-4 age of 12.5 ± 2.7 ka.

CONCLUSIONS

Ground penetrating radar (GPR) and sedimentary patterns (defined by nine lithofacies) were utilized to determine the geologic development of the sand ridges of SCC. Nine lithofacies were described from twenty vibracores located across SCC and illustrate that the LoP Ridge and the PP Ridge are composed primarily of massively bedded sand and heavy mineral laminated sands deposited as overwash, rollovers, and aeolian sands in a coastal environment. The low-lying area between the ridges, the Maple Swamp, contains a sandy mud that is interpreted as a back-barrier/estuary deposit.

GPR defined six depositional radar facies that occur across SCC. These facies are comparable to other radar facies recognized in modern coastal systems. Although these facies, individually, may represent aeolian environments, the combination of the all the facies concludes that the PP Ridge and the LoP Ridge were deposited in close proximity to sea level. GPR also allowed the interpretation of depositional environments where no lithostratigraphic data were available. This correlation is essential when trying to determine ancient coastal environments and past sea levels.

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REFERENCES

Beyer, F., 1980. North Carolina's Bay Lakes: The "Carolina Bays", An Update on the origin and character. NCGS Special Publication 80-1.

Brill, A., 1996. The Suffolk Scarp, a Pleistocene barrier island in Beaufort and Pamlico Counties, NC. Durham, NC: Duke University, Unpublished MS Thesis, 154 p.

Cronin, T., Szabo, B., Ager, T., Hazel, J., and Owens, J., 1981. Quaternary Climates and Sea Levels of the US Atlantic Coastal Plain. Science 211, 233-240.

Culver, S., Ames, D., Corbett, D.R., Mallinson, D., Riggs, S., Smith, C., and Vance, D., 2006. Foraminiferal and Sedimentary Record of Late Holocene Barrier Island

Evolution, Pea Island, North Carolina: The role of Storm Overwash, Inlet Processes, and Anthropogenic Modification. Journal of Coastal Research 22:836-846.

Davis, J.L. and Annan, A.P., 1989. Ground Penetrating Radar for High-Resolution Mapping of Soil and Rock Stratigraphy. Geophysical Prospecting 37, 531-551.

Eames, G., 1983. The Late Quaternary Seismic Stratigraphy, Lithostratigraphy, and Geologic History of a Shelf-Barrier-Estuarine System, Dare County, North Carolina.Unpublished MS Thesis, East Carolina University.

Folk, R., 1980. Petrology of Sedimentary Rock. Hemphill Publishing Company, Austin, 182 p.

French, H.M. and Demitroff, M., 2001. Cold-climate origin of the enclosed depressions and wetlands (spungs) of the Pine Barrens, southern New Jersey, USA. Permafrost and Periglacial Processes 12, 337-350.

Hustedt, F., 1955. Marine Littoral Diatoms of Beaufort, North Carolina. North Carolina: Duke University Press, 67 p.

Ivester, A., Leigh, D., and Godfrey-Smith, D., 2001. Chronology of Inland Eolian Dunes on the Coastal Plain of Georgia, USA. Quaternary Research 55, 293-302.

Ivester, A., Godfrey-Smith, D., Brooks, M., and Taylor, B., 2004. The Timing of Carolina Bay and Inland Dune Activity on the Atlantic Coastal Plain of Georgia and South Carolina. Geological Society of America Abstracts with Programs 36(5), 69.

Johnson, G., 1976. Geology of the Mulberry Island, Newport News North, and Hampton quadrangles, Virginia. Va. Div. Min. Res./ Rept. Inv. 41, 72 p.

Mallinson, D., Burdette, K., Mahan, S., and Brook, G., 2008A. Optically stimulated luminescence age controls on late Pleistocene and Holocene coastal lithosomes, North Carolina, USA, Quaternary Research 69, 97-109.

Mallinson, D., Mahan, S., and Moore, C., 2008B. High resolution shallow geologic characterization of a late Pleistocene eolian environment using ground penetrating radar and optically stimulated luminescence techniques: North Carolina, USA. Southeastern Geology 45 (3), 161-177.

Mixon, R., Szabo, B., and Owens, J., 1982. Uranium-Series dating of mollusks and corals, and age of Pleistocene deposits, Chesapeake Bay area, Virginia and Maryland. US Geological Survey Professional Paper 1067-E, pp. E1-E18.

Mixon, R., 1985. Stratigraphic and geomorphic framework of uppermost Cenozoic Deposits in the southern Delmarva Peninsula, Virginia and Maryland. US Geological Survey Professional Paper 1067-C, 53 p.

Muhs, D., Wehmiller, J., Simmons, K., and York, L., 2004. Quaternary sea-level history of the United States. In: Gillespie, A.R., Porter, S.C. and Atwater, B.F. (Eds.), The Quaternary Period in the United States. Elsevier, Amsterdam, 147-183.

Oaks, R., 1964. Post Miocene Stratigraphy and Morphology, Outer Coastal Plain, Southeastern Virginia. Unpublished Ph.D. Dissertation, Yale University.

Peebles, P., 1984. Late Cenozoic Landforms, Stratigraphy and History of Sea Level Oscillations of Southeastern Virginia and Northeastern North Carolina. Unpublished Ph.D. Dissertation, The College of William and Mary.

Smith, C., Riggs, S., Culver, S., Ames, D., Corbett, D. R., and Mallinson, D., 2008. Geospatial Analysis of Barrier Island Width of Two Segments of the Outer Banks, North Carolina, USA: anthropogenic curtailment of natural self-sustaining processes. Journal of Coastal Research 24, 70-83.

Suarez, J., Ontiveros, C., Smith, S., and Snape, S., 2005. Use of Airborne LiDAR and Aerial Photography in the Estimation of Individual Tree Heights in Forestry. Computers & Geosciences 31, 253-262.

Szabo, B., 1985. Uranium-series dating of fossil corals from marine sediments of southeastern United States Atlantic coastal plain. Geological Society of America Bulletin 96, 398-406.

Wehmiller, J., Simmon, K., Cheng, H., Edwards, R.L., Martin-McNaughton, J., York, L., Krantz, D., and Shen, C., 2004. Uranium-series coral ages from the US Atlantic Coastal Plain- the "80-ka problem" revisited. Quaternary International 120, 3-14.

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FORAMINIFERAL ASSEMBLAGES: A TOOL FOR RECONSTRUCTING AMERICAN CIVIL WAR COASTAL LANDSCAPES

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ABSTRACT

Microfossils, especially foraminifers, are a valuable tool for interpreting paleoenvironments in marginal-marine settings. Despite their value, the use of microfossils as a geoarchaeological tool in marginal-marine environments has not been widespread. To test this utility, micropaleontological and sedimentological analysis was conducted in the back-barrier marshes of Folly Island, South Carolina, to recreate a portion of a Civil War landscape and to corroborate historical documentation of a strategically important 1863 tidal inlet.

Foraminifers and sediment were collected from the following modern environments to establish an analog for buried biofacies and lithofacies: Low marsh, high marsh, tidal inlet, washover fan, and beach and dune. Marsh subenvironments were differentiated based on agglutinated foraminiferal assemblages, while all other biofacies were distinguished based on calcareous foraminifers and other microfossils.

Civil War era maps, Union soldiers' descriptions, and global positioning satellites were used to locate the buried 19th Century tidal inlet; gouge-auger cores and foraminiferal and sedimentological analyses were used to identify the inlet deposits in the subsurface. Although lithology was useful for interpreting subenvironments, sediments, combined with microfossils, proved most useful for determining depositional environments.

INTRODUCTION

Of all Civil War battlegrounds, those located on the dynamic barrier islands of the Atlantic and Gulf Coasts are most vulnerable to both erosion and dramatic changes in geomorphology. Although several fortifications around Charleston survive today, including Forts Sumter and Moultrie, others, including Batteries Wagner and Gregg, have been lost to erosion and shoreline retreat. This study focuses on one geoarchaeological tool which has not been used to assess the location of Civil War fortifications and terrain features: foraminifers.

Foraminifers are an ideal tool for measuring environmental or ecological change as they are found in great abundance (often hundreds per cm^3) in nearly all marginal-marine environments and are sensitive to alterations in their environment. Their short generation times, often less than a year, suggest a high degree of stratigraphic resolution (Martin, 2000).

Although the Civil War history (Hagy, 1993), geology and micropaleontology (Harris and others, 1995, 1996; Hippensteel and Martin, 1999, 2000), and archaeology (Legg and Smith, 1989) of Folly Island, South Carolina, have been well documented, little interdisciplinary research has been conducted on the Civil War battlegrounds surrounding Charleston, South Carolina. The goal of this study was to demonstrate the utility of foraminifers for 1) identifying (and reconstructing) Civil War landscapes; 2) corroborating historical descriptions of these landscapes; 3) identifying the location of terrain features buried since the Civil War, thus linking 19th century and modern maps.

Two examples of previous geoarchaeological studies which used foraminifers focused on

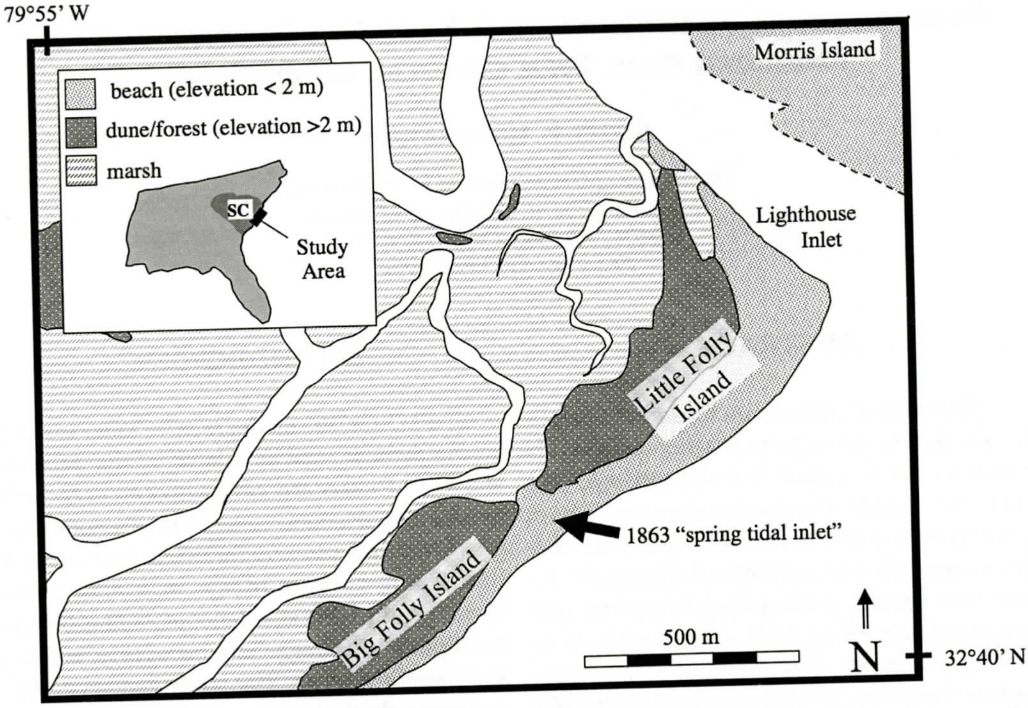

Figure 1. Folly Island in 1862-1863. This figure is a composite of several Civil War maps created by Union cartographers, including the 1863 survey map produced by the US Coastal Survey.

the determination of marginal-marine environments from much earlier than the American Civil War. Reinhardt and others (1994) used benthic foraminifers to augment earlier archaeological interpretations concerning the ancient harbor site of Caesarea Maritima, Israel. Serandrei Barbero and others (2004) used salt marsh foraminifers, similar to those found in the back-barrier marshes from Folly Island, to determine the position of lagoonal paleoenvironments in the Lagoon of Venice, Italy. Both these studies demonstrate the effectiveness of foraminiferal analysis as a tool for recreating paleoenvironments and corroborating or enhancing archaeological information.

Historical Context

In an attempt to capture Morris Island and, in turn, Charleston, South Carolina, the Union army massed troops on the next barrier island to the south: Folly Island. As a result, accurate maps from the mid 1860's exist of the island morphology and landscape (Figure 1).

In 1863 a small shallow breach periodically divided Folly Island into Little Folly and Big Folly. The landscape was described by Union Major General Quincy Gillmore (1890) as "perfectly barren, and so low that the spring tides frequently swept entirely over it". This spring tidal inlet deposited sediment on the marsh behind the island producing a flood-tidal delta similar in origin to a low energy washover fan. Historical maps were used to identify the coordinates of this inlet and global positioning satellites (GPS) were used to identify this location on the modern barrier island and in the back-barrier marshes. Foraminiferal analysis, combined with sedimentological analysis, was used to document the location and stratigraphy of this Civil War era inlet.

GEOGRAPHIC AREA AND METHODOLOGY

Folly Island, South Carolina

Folly Island, South Carolina, is located approximately 16 km S-SE from Charleston,

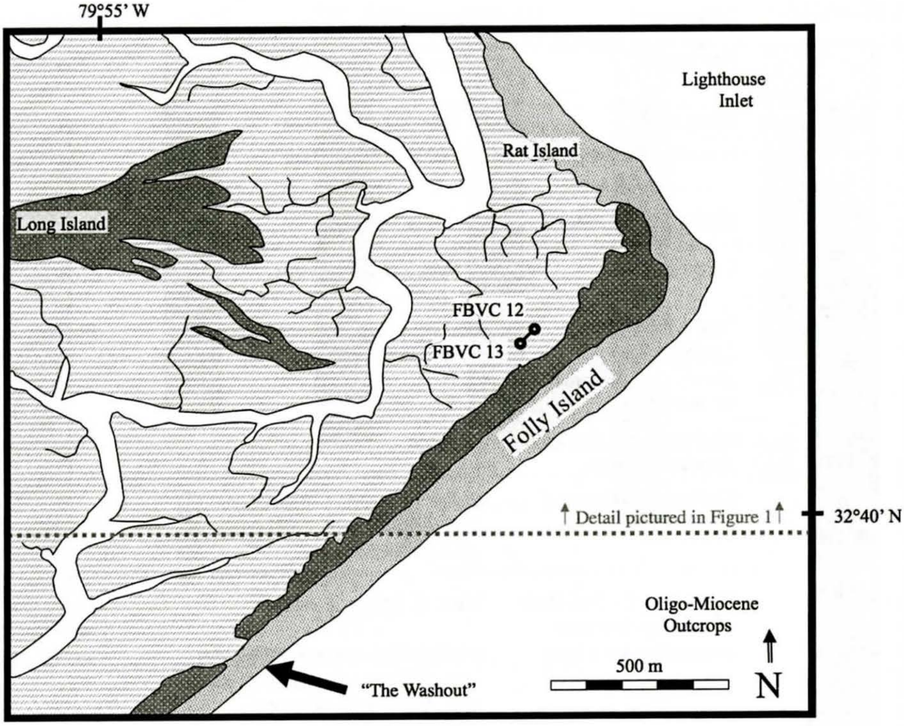

Figure 2. Folly Island in July, 2007. Location of the vibracores and gouge-auger transect is indicated, as is the location of "the washout". After the construction of the Charleston Harbor jetties in 1896 Morris Island began to retreat much more quickly than Folly Island.

South Carolina. Folly Island is separated from Morris Island, the site of intense fighting during the siege of Charleston in 1863, by Lighthouse Inlet. During the Civil War Folly Island was used as the base of operations for this siege, with camps for more than 20,000 Union troops occupying large expanses of the island. By July of 1863, there were 45 artillery pieces on Little Folly Island, including four 3-inch Ordnance rifles, six 10-pounder Parrotts, four 20-pounder Parrotts, and twelve 30-pounder Parrotts.

Field Methodology

Surface samples were collected from each of the following modern environments: Beach, dune, tidal inlet, low marsh, and high marsh. To record variation within each subenvironment, five 10-cc samples were taken from each subenvironment at five different locations on Little Folly Island. High and low marsh environments were determined based on halophyte assemblages and elevation relative to mean low tide (mlt). The low marsh subenvironment was dominated by *Spartina alterniflora* (long form) and was located between 0.92 and 1.14 m above mlt. The high marsh contained mixed *Spartina alterniflora* and *Spartina patens* and was located between 1.69 and 1.81 m above mlt. Foraminiferal content and sedimentological analysis was conducted on each sample to establish a modern analog for buried sediments. Buried storm deposits (washover fans) were identified based on the presence of offshore-indicative Oligo-Miocene and planktonic foraminifers. The Oligo-Miocene foraminifers were derived from offshore during large storms and act as a natural tracer for their original source and their mechanism of deposition (Hippensteel and Martin, 1999; 2000).

A 26 meter transect was plotted SW – NE between two vibracores which were taken in 1994 by M. Scott Harris (Coastal Carolina University). Based on the coordinates of the coring location and GPS analysis, it was determined that these vibracores penetrated the sediments de-

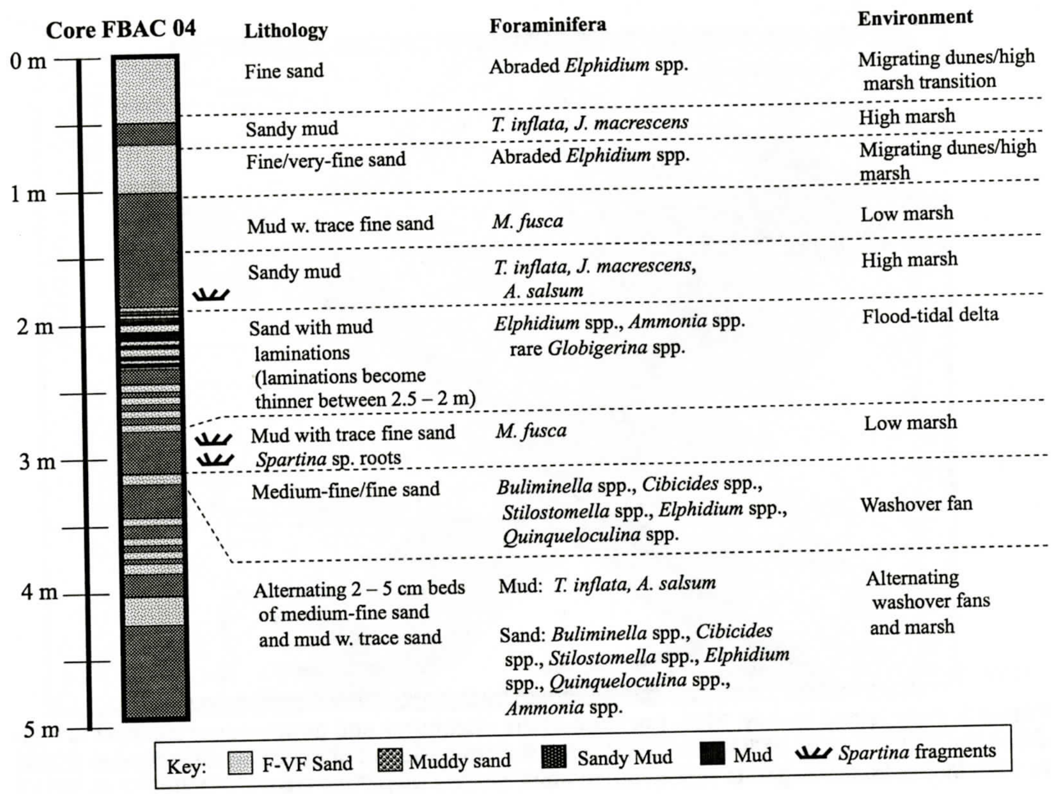

Figure 3. Core log for FBAC 04 (Folly Beach Auger Core 04). Offshore indicative Oligo-Miocene foraminifera were most common in the washover sediments found in the bottom two meters of the core while high-marsh sediments dominate the last meter of the core.

posited by the Civil War inlet that separated Little Folly from Big Folly Island (Figure 2). Five 30-mm gouge-auger cores were extracted to a maximum depth of 6 m along this transect and samples were taken at 2-cm intervals in each core. To the north of the transect three additional 5-m cores were taken (in a line from the center of the transect perpendicular to the transect). These cores were taken at 25 m, 50 m and 100 m to determine the spatio-lateral extent of the inlet and to determine the depositional subenvironments and history of accretion in the non-inlet dominated portion of the marsh. All samples were described in the field and returned to the Environmental Micropaleontology Laboratory in the Department of Geography and Earth Sciences at UNC-Charlotte for foraminiferal and sedimentological analyses.

Laboratory Methodology

Modern and downcore samples were sieved using 1-mm, 0.5-mm, and 0.074-mm screens. Grain-size distribution was measured for each sample and to facilitate comparison between modern and buried samples. The 0.5-mm and 0.074-mm screenings were analyzed for microfossil content while the samples were still wet. Three-hundred foraminifers were collected from each modern environment. A 1-cc sample was cut from the center of each gouge-auger sample and foraminifers were picked wet. As with the modern foraminiferal assemblages, 300 foraminifera were picked from the downcore samples. Only 7% of the samples did not contain at least 300 specimens; for these samples all available foraminifers were picked from the 1-cc sample.

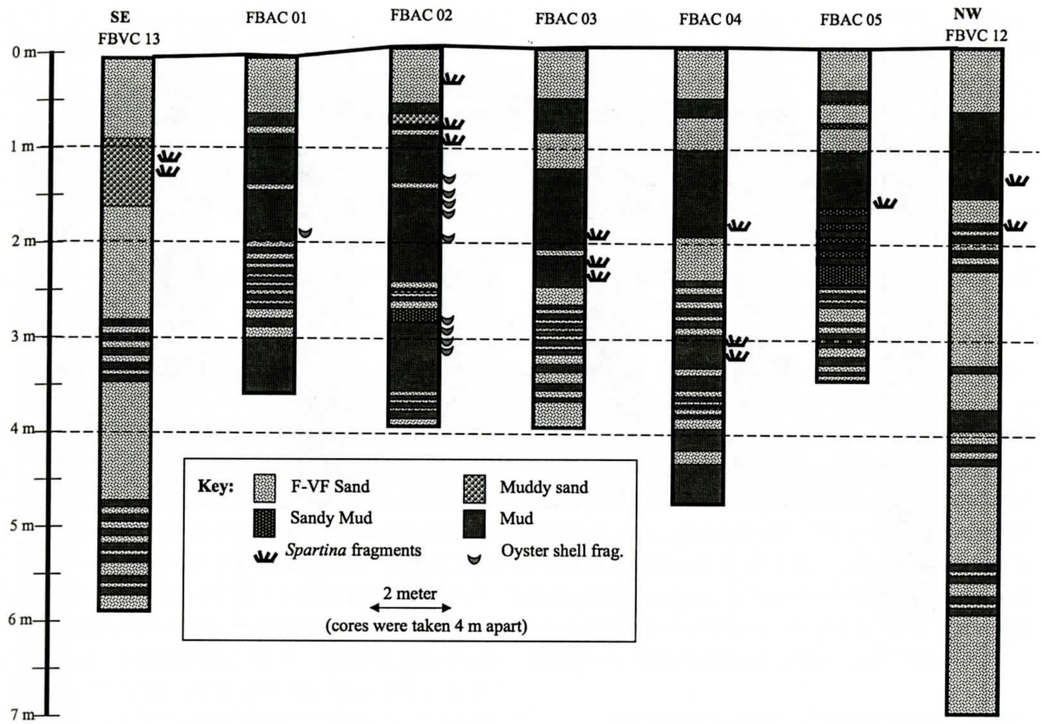

Figure 4. Lithology of the gouge-auger transect. Agglutinated foraminifera indicate a transgression in the marsh (high marsh flooded into low marsh) from approximately 2 m to 1 m.

RESULTS

Five facies were established based on microfossil content and sediment grain size:

1) Washover fans, containing medium-sand and shell fragments, were dominated by offshore-indicative *Globigerina* spp. and calcareous Oligo-Miocene foraminifers (derived from offshore during storms). These Oligo-Miocene and offshore-indicative taxa included: *Bolivina* spp., *Buccella* spp., *Bulimina* spp., *Buliminella* spp., *Cancris* spp., *Cibicides* spp., *Eponides* spp., *Fursenkoina* spp., *Hanzawaia* spp., *Nonionella* spp., *Quinqueloculina* spp., *Rosalina* spp., *Saracenaria* spp., *Siphogenerina* spp., *Stilostomella* spp., *Uvigerina* spp., and *Virgulina* spp., and planktonic spp. (primarily *Globigerina* spp.). The most abundant calcareous taxa were *Globigerina* spp., *Uvigerina* spp., and *Quinqueloculina* spp.

2) Flood-tidal delta deposits varied between fine sand and mud and contained *Elphidium* spp., *Ammonia* spp., and *Globigerina* spp., but lacked the Oligo-Miocene foraminifers present in the washovers. Apparently, the Oligo-Miocene foraminifers are only deposited in the back-barrier marshes during high-energy events (hurricanes). More than half the foraminifers present in this biofacies were *Elphidium* spp.

3) Beach and dune deposits contained well sorted fine and medium sand and abraded *Elphidium* spp. and *Ammonia* spp. Foraminifers were found in the lowest numbers in these deposits.

4) Low-marsh deposits were almost entirely mud and contained abundant agglutinated foraminifers with a high percentage of *Miliammina fusca*. Calcareous foraminifers were rare, never exceeding 2% of the assemblage.

5) High-marsh deposits contained up to 25% fine sand and exclusively agglutinated foraminifers with a high percentage of *Trochammina inflata*, *Tiphotrocha comprimata*, *Jadammina macrescens*, *Siphotrochammina lobata* and *Ammotium salsum*. There were no calcareous foraminifers in these samples.

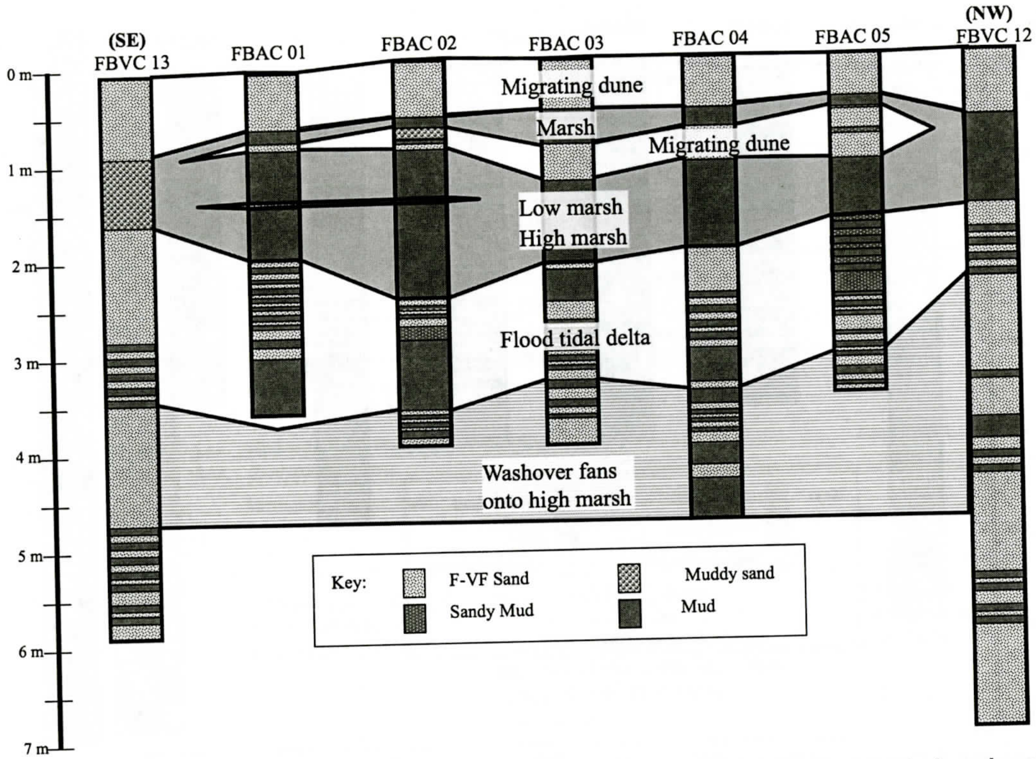

Figure 5. Stratigraphy and interpretation of the gouge-auger transect. Storm generated washover fans were replaced with the lower energy "spring" tidal inlet described by Union soldiers at approximately 3.5 m.

These facies were used to determine down-core paleoenvironments and stratigraphy along the transect and distinguish between buried marsh and inlet facies. The presence of Oligo-Miocene foraminifers was used to differentiate buried inlet and washover facies.

All five facies were present in core FBAC 04 (Figure 3)

. The interpreted environments in this core change from washover fan/low marsh from 5.0 m to 2.8 m to (Civil War) tidal delta deposits from 2.8 to 1.9 m (Figures 4 and 5). The top two meters of the core represent the modern high-marsh and encroaching dune environments.

The three cores, taken 25 m, 50 m and 100 m to the north of the transect revealed interbedded marsh and washover facies throughout the cores. In all cases where planktonic forms were identified, there was also an offshore-indicative Oligo-Miocene component of the assemblage, indicating that no "spring" tidal delta facies were present.

CONCLUSIONS

Linking Microfossil Evidence And Stratigraphy With Historical Accounts

Lennon and others (1996, p. 106) described the location of Little Folly Island: "The northern third [of Folly Island], beyond the flexure known as 'the washout' is a low-lying strip of land that formed 3,000 to 4,000 years ago. At one time, Little Folly, as this northern segment is called on old maps, could only be reached at low tide by crossing the washout (itself an old inlet). This remained the case until the 1950's…". Careful examination of Union army and Navy maps, combined with GPS and stratigraphic analyses (Figures 4 and 5), suggests the location of this spring-tidal inlet during the Civil War was approximately 1.5 km to the north of the area known today as "the washout". The area known as "the washout" represents the narrowest portion of Folly Island and was opened long before the Civil War and several times since, including during Hurricane Hugo in 1989; nevertheless, the inlet separating Little and Big Folly Islands described by Union General Gillmore was probably located farther to the north.

Little Folly Island was the most strategically important portion of the 10-km long island, and batteries were built on the northern tip of the island directly in front of the Confederate fortifications on the southern end of Morris Island. The construction of these batteries was meant to be completed covertly behind the dune field on Little Folly and the presence of a shallow inlet separating Little and Big Folly Islands doubtless complicated the logistics of the construction. The repositioning of the inlet in this study suggests that the inlet was 1.5 km closer to the Confederate batteries than previously thought, placing it within range of the largest of the Confederate artillery located on Morris Island.

Other Applications of Foraminifera for Solving Civil War Geoarchaeological Problems

Folly Island provides the ideal study area for using foraminifers to determine paleoenvironments for two reasons: 1) Offshore outcropping Oligo-Miocene foraminifers act as a natural tracer for washover sediments and differentiate washovers from flood-tidal deltas and 2) Morphologically distinct and easily identifiable agglutinated foraminifers such as *M. fusca* simplify the identification of low and high marsh deposits.

Highly detailed maps of Civil War landscapes provide further clues about the depositional environments present in the recent past. This research demonstrates the utility of foraminifers for enhancing the accuracy of both historical records and 19th century maps. With the location of Civil War terrain features identified on the surface and in the subsurface, more accurate rates of erosion can be calculated. These erosion rates could be used to determine which Civil War fortifications and batteries are most vulnerable to coastal erosion or storm damage.

Foraminiferal analysis could also be used to recreate entire battlegrounds in marginal-marine environments providing insight into the strategies chosen by opposing commanders or the routes taken by attacking and retreating forces. For example, the western salient of Fort Fisher, North Carolina, was anchored on a back-barrier marsh and this undesirable terrain slowed the Union attack on January 15, 1865. The position of these marshes has changed in the last 140 years, giving students of the second Fort Fisher campaign a misleading picture of the fighting in this area. Foraminifera could be used to map the battlefield as it appeared in 1865 (low marsh, high marsh, or barrier sand?). Geoarchaeological studies of this nature would be especially useful in regions that were not precisely mapped during the Civil War.

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REFERENCES

Hagy, J.W., 1993, To Take Charleston: The Civil War on Folly Island: Pictorial Histories Publishing Company, Inc.: Charleston, WV., 91p.

Harris, M.S., Gayes, P.T., and Krantz, D.E., 1995, Antecedent geologic controls on the modern barrier island configuration and geomorphology in the Charleston, South Carolina coastal zone: *in* Linked Earth Systems; Congress Program and Abstracts, v. 1, n. 65. 1st SEPM Congress on Sedimentary Geology; Linked Earth Systems. St. Pete Beach, FL, United States. Aug. 13-16, 1995.

Harris, M.S., Kindinger, J., Schwab, W.C., Gayes, P. T., 1996, Geologic and bathymetric variability, Folly Island, South Carolina; an example of a geologic framework influencing near-shore processes: *in* Geological Society of America, Southeastern Section, 45th annual meeting. Abstracts with Programs - Geological Society of America. v. 28, n. 14. Geological Society of America (GSA): Boulder, CO.

Gillmore, Q. A., 1890, Report of Major General Quincy A. Gillmore, The War of the Rebellion: The Official Records of the Union and Confederate Armies in the War of the Rebellion, 128 volumes, Washington D.C., Government Printing Office, Series 1, Part 1., p. 7.

Hippensteel, S.P. and Martin, R.E., 1999, Foraminifera as an indicator of overwash deposits, barrier island sediment supply, and barrier island evolution, Folly Island, South Carolina. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 149, p. 115 - 125.

Hippensteel, S.P. and Martin, R.E., 2000, Foraminifera as indicators of storm deposition: Implications for barrier island sediment supply and evolution: *in* Martin, R.E. ed., Environmental Micropaleontology, Kluwer Press: Dordrecht, p. 351 - 369.

Legg, J.B. and Smith, S.D., 1989, The Best Ever Occupied: Archaeological Investigations of a Civil War Encampment on Folly Island, South Carolina. Research Manuscript Series 209, South Carolina Institute of Archaeology and Anthropology, n. 32, 62p.

Lennon, G, Neal, W.J., Bush, D.M, Pilkey, O.H., Stutz, M., and Bullock, J., 1996, Living with the South Carolina Coast: Duke University Press: Durham, NC, 399p.

Martin, R.E., 2000, Introduction: Environmental Micropaleontology. *in* Martin, R.E., ed., Environmental Micropaleontology. Kluwer Press: Dordrecht, p. 1-3.

Reinhardt, E.G., Patterson, R.T., and Schroeder-Adams, C.J., 1994, Geoarchaeology of the ancient harbor site of Caesarea Maritima, Israel; evidence from sedimentology and paleoecology of benthic foraminifera: Journal of Foraminiferal Research: v. 24, p. 37-48.

Serandrei Barbero, R., Albani, A.D., and Bonardi, M., 2004, Ancient and modern salt marshes in the Lagoon of Venice: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 202, p. 229-244.

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Defining the Neareshore Marine to Fluvial Transition in the Updip Clastic Lithofacies of the Clayton Formation (Lower Paleocene) Across the West-Central Georgia Coastal Plain (USA)

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ABSTRACT

The Clayton Formation (lower Paleocene) exhibits varying marine lithofacies along strike and dip sections across the northern US Gulf Coastal Plain. In western Georgia, these lithologic variations have caused some confusion for researchers attempting to define the depositional settings. Due to the excellent exposure of the Clayton Limestone along the Chattahoochee River, geologic description for the entire Clayton Formation has traditionally emphasized the carbonate lithofacies. Only minor work has been conducted on the updip marine clastic sediments exposed across west-central Georgia. These nearshore sediments reflect early Paleogene eustatic changes across the former continental shelf and involve both sea-level rise and fall, with the latter likely enhanced by regional tectonism.

INTRODUCTION

Outcrops of the Clayton Formation (Lower Paleocene) extend across the northern US Gulf Coastal Plain from central Louisiana to central Georgia (Lindberg, 1988). From this broad exposure, the formation transitions through varying lithofacies along both strike and dip sections. In Georgia, the Clayton Formation exhibits two distinct lithofacies across the former continental shelf: 1) updip nearshore/marine clastic sediments are exposed across the west-central portion of the state, and 2) downdip middle-to-outer shelf carbonates are buried in the shallow subsurface, with isolated exposures found along the Chattahoochee and Flint River Valley corridors in southwestern Georgia.

An investigation of the updip marine clastic sediments of the Clayton Formation was undertaken across west-central Georgia to determine its lithostratigraphic history as modified by sea-level changes and probable concomitant tectonism (Figure 1).

EARLY GEOLOGIC INVESTIGATION OF THE CARBONATE AND CLASTIC LITHOFACIES

Based on their investigation of geologic outcrops along the Alabama River, Smith and Johnson (1887) established the Midway section as the lowest formal stratigraphic unit within the Eocene of Alabama. They noted that the 7.6-m exposure at Midway Landing was dominated by 5.6 m of marine limestone. From outcrops along the Chattahoochee River on the eastern side of the state, Langdon (1891) defined the Clayton Limestone synonymously with this same Midway section. In their investigation of the geology of the Georgia Coastal Plain, Veatch and Stephenson (1911, p. 220) defined the carbonates exposed along the Chattahoochee River at Fort Gaines as the "limestone of the Midway formation." Subsequent geological mapping across west-central Georgia extended the carbonate lithofacies eastward to Twiggs County (Cooke and Munyan, 1938). Cooke (1943) later assigned the Clayton limestone to the Clayton Formation, the lowest stratigraphic unit within the Paleocene. Calcar-

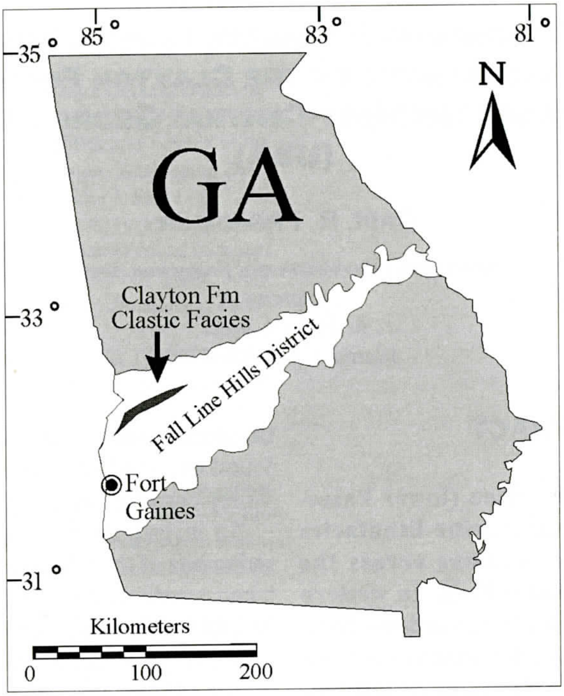

Figure 1. Generalized base map showing the approximate location of the updip marine clastic lithofacies of the Clayton Formation across west-central Georgia. The lower Paleocene sequence within this area is bounded by unconformities likely created as a result of eustatic changes and concomitant tectonism. Modified from Alhadeff and others, 2001.

eous nannofossils, collected in the late 1970s from the carbonate portion of the formation, correspond to the NP3 zone and the Danian Stage (Gibson, 1982; Gibson and others, 1982; Mancini and Tew, 1993).

While the Clayton Limestone was first identified from extensive carbonate exposures along the Chattahoochee River near Fort Gaines, Georgia (Cooke and Munyan, 1938; Langdon, 1891; Langdon 1894), Smith and others (1894) defined the entire Clayton Formation section from an exposure located approximately 47 km to the northwest along the Central Georgia Railway, 1.6 km east of the city of Clayton, Alabama. This railroad cut was later cited by both Cooke (1926, 1943) and MacNeil (1946a) as the Clayton Formation type section. Taylor (1970) subsequently defined the official Clayton Formation type section from a composite of two exposures along the same Central Georgia Railway section. However, more recent investigation of this outcrop has raised questions regarding the formal stratigraphic definition of the Clayton Formation lithostratotype and the disagreement is apparently over the thickness of the carbonate section (see Fluegeman, 1989a, 1989b; Reimers, 1986, 1989).

Working along strike across west-central Georgia, Veatch and Stephenson (1911) identified a dense sandy-clay lithofacies of the Clayton Formation while mapping the Tertiary strata. Cooke (1943) assigned these clastic sediments to the lowest of the Paleocene strata in Georgia. Subsequent investigation of the clastic lithofacies has developed from this earlier work (e.g., Kirkpatrick, 1963; Luckett, 1979; Marsalis and Friddell, 1975).

GEOMORPHOLOGY

Veatch and Stephenson (1911) placed the Clayton Formation clastic sediments within the red hills section of the Fall Line Hills physiographic division. The red color of the dense san-

Figure 2. An iron-cement mold of an echinoderm from a ferricrete in the marine clastic lithofacies of the Clayton Formation. Coin diameter 1.8 cm.

dy-clay is derived from iron minerals that also make them resistant to erosion. Within west-central Georgia, these massive, dense, sandy clays serve as a protective cap to the unlithified underlying sands of the Upper Cretaceous Providence Formation. Subsequent work by geomorphologists Clark and Zisa (1976) defined the Fall Line Hills District as highly dissected with little level land, and stream valleys 50 to 250 feet below the adjacent ridge tops. The best example of this district occurs in the area around Providence Canyon State Park (Veatch and Stephenson, 1911), where numerous large-scale, steep-sided canyons have formed in the past 150 years (see Froede and Williams, 2004). The corresponding Clayton Formation carbonate lithofacies occurs further downdip, but still within the red hills section of the Fall Line Hills District.

VARIATION IN THE CLAYTON FORMATION LITHOFACIES

A significant amount of geologic investigation has been conducted on the marine carbonate lithofacies of the Clayton Formation, especially at outcrops along the Chattahoochee River Valley corridor near Fort Gaines, Georgia (e.g., Baum and Vail, 1988; Cooke, 1926; Fluegeman, 1986, 1993; Froede and Reed, 2007; Gibson, 1989; Hastings and Toulmin, 1963; Langdon, 1891; MacNeil, 1946b; Marsalis and Friddell, 1975; Reinhardt and Gibson, 1981; Swann and Poort, 1979; Toulmin, 1955; Toulmin and LaMoreaux, 1963; Toulmin and Winters, 1954; Vail and others, 1987). Much less analysis has been devoted to the updip nearshore marine clastic sediments exposed in west-central Georgia (e.g., Cooke, 1943; Kirkpatrick, 1963; Reinhardt and others, 1994; Richards, 1955).

Across west-central Georgia, the marine clastic sediments of the Clayton Formation consist of dense, brick-red to maroon sandy clays which contrast with the underlying cross-bedded kaolin clays and quartz sands of the unconsolidated Upper Cretaceous Providence Formation (Cooke, 1943). Subsequent studies across this section of Georgia have identified some variability in the Clayton Formation sediments. Reinhardt and others (1994) included olive-brown to dark-orange-red clay along with

Figure 3. Kaolin clasts have been eroded from the top of the Upper Cretaceous Providence Formation and were incorporated within the basal transgressive sands of the Paleocene Clayton Formation. Scale in 15-cm divisions.

coarse quartz sand, ironstone, and siliceous nodules. Invertebrate molds have also been reported from the ironstone concretions (Reinhardt and Gibson, 1989) [Figure 2]. Traditionally, these clastic sediments and ferricretes have been interpreted as part of a limestone residuum (e.g., Veatch and Stephenson, 1911; Cooke, 1943; Eargle, 1955; Donovan, 1986; Reinhardt and others, 1994; Cocker, 2006). However, this perspective dramatically changed in the early 1980s when these clastic deposits were redefined in association with a rise in sea level across a lower Paleocene continental shelf setting (Gibson, 1980, 1981, 1982).

SEA LEVEL CHANGES AND TECTONIC UPLIFT

The contact between the Upper Cretaceous Providence Formation and overlying marine clastic sediments of the Paleocene Clayton Formation is marked with a disconformity. This erosional contact formed in association with a withdrawal of sea level and subaerial exposure in the late Maastrichtian (Donovan, 1986). A rise in sea level began in the latest Maastrichtian and continued through the Danian (Baum, 1989; Baum and others, 1984; Donovan, 1986; Gibson, 1980, 1982). The Clayton Formation clastic and carbonate strata were deposited during a sea-level highstand during the lower Paleocene (Gibson and others, 1982).

In his examination of the clastic lithofacies

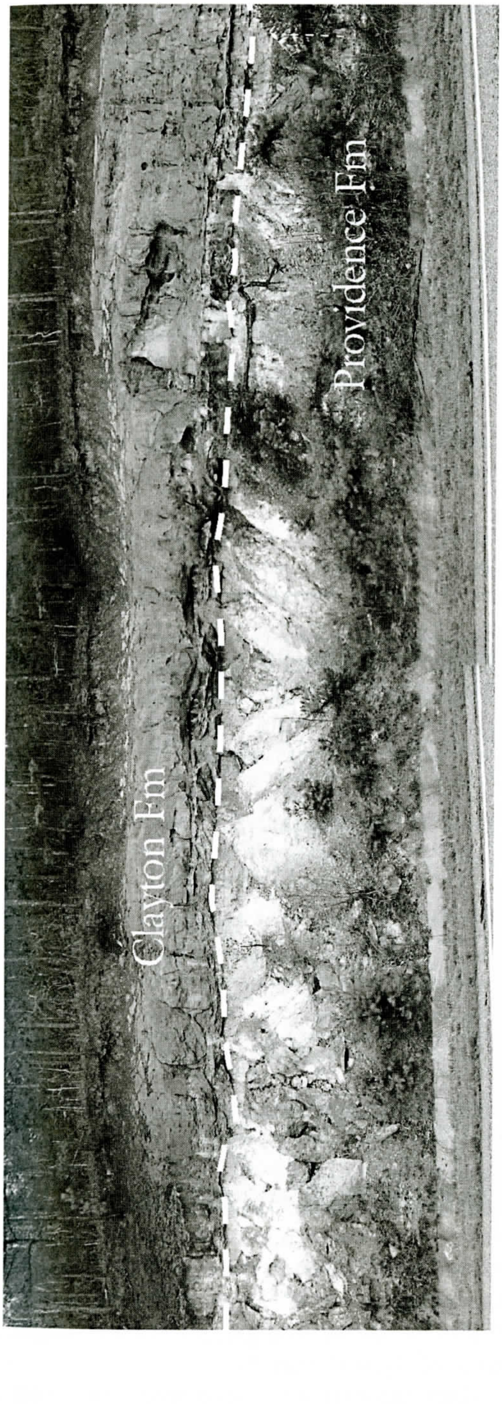

Figure 4. A major subaerially-derived disconformity marks the contact between the marine clastic sediments of the Clayton Formation and the underlying Upper Cretaceous Providence Formation. Scale on right in 15-cm divisions.

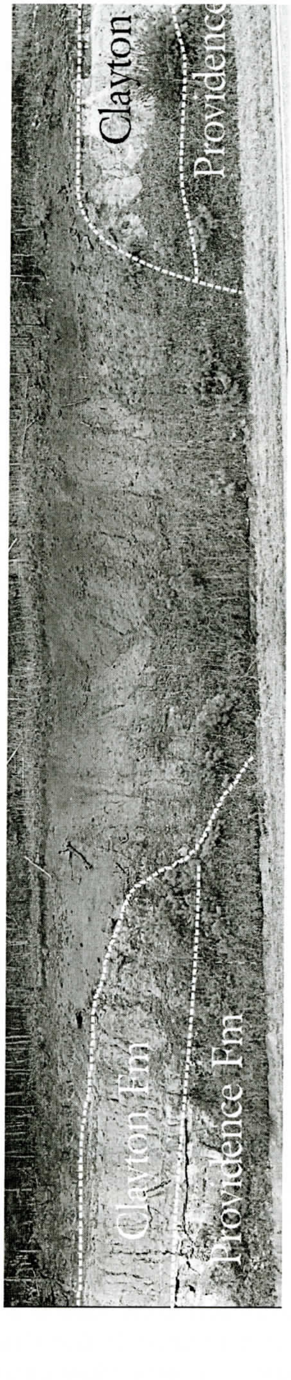

Figure 6. A deep fluvial channel, measuring approximately 9.7 m in depth and 27.5 m in width, extends through the clastic lithofacies of the Clayton Formation and down into the Upper Cretaceous Providence Formation. Scale in 15-cm divisions.

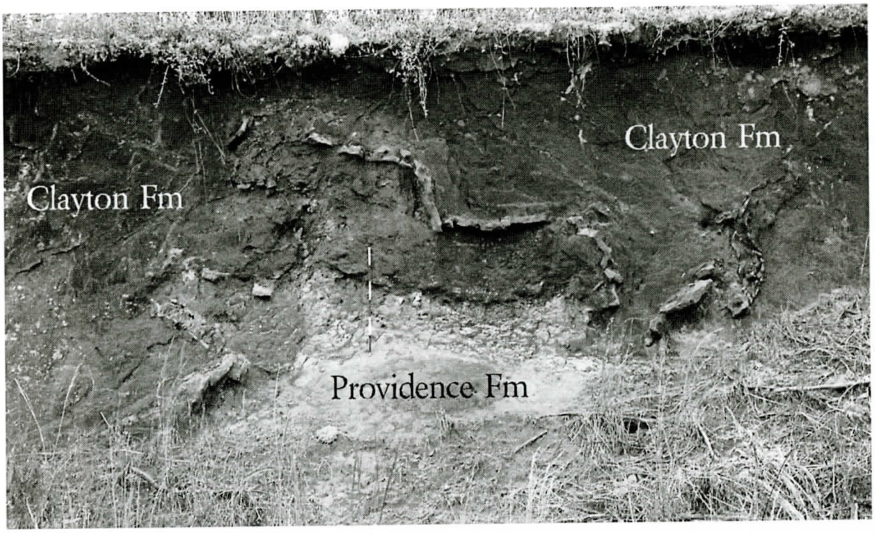

Figure 5. A groundwater-derived ferricrete in the clastic lithofacies of the Clayton Formation above deformed Upper Cretaceous Providence Formation sandy clay. Scale in 15-cm divisions.

of the Clayton Formation across west-central Georgia, Cooke (1943) noted coarse-grained, red-stained, pebbly quartz sand at many places along the base of the Clayton Formation. Consistent with earlier investigators, he believed this to be part of a limestone residuum deposit. However, a reexamination of this section in the 1980s led investigators to redefine the coarse-grained siliciclastic deposit as a transgressive lag which formed in association with a rise in sea level (Donovan, 1986; Reinhardt and Gibson, 1989) [Figure 3]. As a result of this new perspective, the interpretation of the updip marine clastic lithofacies of the Clayton Formation changed from an eroded limestone residuum to a nearshore, subtidal sand and bar sequence formed in association with a lower Paleocene transgression and highstand (Gibson, 1980, 1982, 1992; Gibson and others, 1982).

At some point during the lower Paleocene, a sea level regression followed the earlier highstand across west-central Georgia. This drop in sea-level position is manifested by a subaerial erosional surface across the top of the clastic lithofacies of the Clayton Formation (Figure 4). With the onset of subaerial conditions, groundwater flow was initiated in the shallow subsurface. Ferricretes formed in the Clayton Formation clastic sediments where anaerobic ferrous groundwater was oxidized, having likely been derived from the adjacent uplifted Piedmont (Figure 5). Precipitation initiated overland flow which developed streams across the top of the exposed Clayton Formation. Some of these channels incised deeply into the dense sandy clays (Figure 6) and subsequently filled with reworked Clayton Formation clastics and ferricrete debris (Figure 7a and 7b). The age of the channel fill materials remains an unresolved issue as some consider it a colluvium (Donovan and Reinhardt, 1986), or a part of the Nanafalia Formation (Reinhardt and others, 1994), while others consider it possibly the Miocene Altamaha Formation (Cocker and Costello, 2003; Cocker, 2006).

Problems occur in comparing the sea-level curves for the Clayton Formation in Alabama (Baum, 1989) versus the Chattahoochee River Valley (Gibson, 1981). Additionally, the updip Clayton Formation clastic lithofacies across west-central Georgia exhibits subaerial features which fail to correspond with either sea-level curve. These discrepancies suggest that the corresponding sea-level positions for the lower/middle Paleocene stratigraphic sections might be out of phase (Figure 8).

Many investigators have recognized that some form of regional uplift has occurred

Figure 7a. Channel-fill material is typically composed of reworked clastic sediments and ferricrete debris derived from upgradient source areas of the Clayton Formation. Some of the smaller ferricrete clasts are polished as a result of transport. The ferricrete fragments can be spread throughout the sandy clay matrix or they can occur as lag deposits along the base or sides of the former channels. Scale in cm.

Figure 7b. A large, highly angular ferricrete slab occurs as a lag deposit within the channel shown in Figure 6. Scale in cm and in.

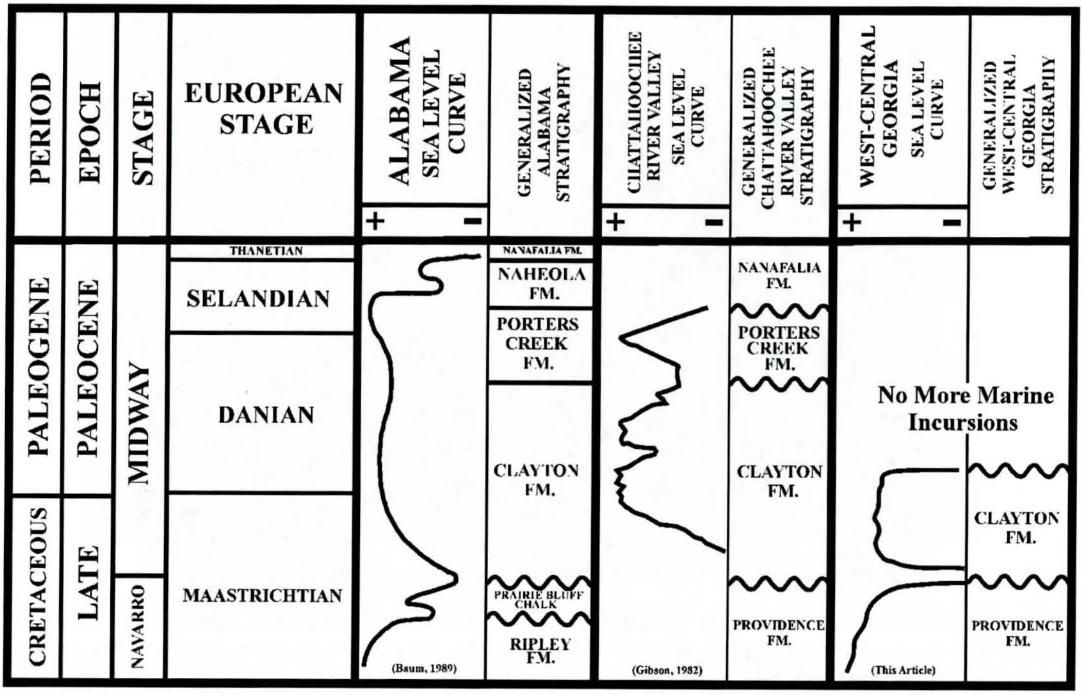

Figure 8. Sea-level curves for the Clayton Formation across the Alabama Coastal Plain, Chattahoochee River Valley, and west-central Georgia. They likely differ as a result of regional tectonism which was initiated in the lower Paleocene across the western Georgia Piedmont. The updip clastic lithofacies of the Clayton Formation across west-central Georgia exhibits a disconformable surface marked in places with incised fluvial channels. This area experienced complete withdrawal of sea level at the end of the lower Paleocene marking the end of marine conditions across west-central Georgia for the remainder of the Cenozoic. Modified from Baum (1989, Figure 1.5.5) and Gibson (1982, Figure 2).

across west-central Georgia starting at the close of the Mesozoic (e.g., Cooke, 1943; Eargle, 1955; Froede and Williams, 2004; Reinhardt and others, 1984; Riggs, 1979; Stephenson, 1928). The amount and rate of tectonism during the Paleogene has yet to be determined. Uplift of the area reduced depositional accommodation space and likely contributed to the erosion of some of the marine Paleogene strata formerly deposited across this area.

CONCLUSIONS

The Clayton Formation varies in its lithofacies across the northern US Gulf Coastal Plain. Traditionally, this has created problems especially in correlating the up- and downdip stratigraphic sections. However, defining the Clayton Formation in a marine continental shelf setting can resolve its complex lithostratigraphy. Distinct lithofacies would be expected to form across the shelf and they would be modified due to eustatic changes throughout the Paleocene. The lithology of the Clayton Formation has traditionally focused on the carbonate lithofacies, while little effort has been made to recognize and define the updip marine clastic lithofacies.

Problems occur when comparing sea-level curves for the Clayton Formation across the Alabama Coastal Plain, the Chattahoochee River Valley, and west-central Georgia. These differences could be attributed to a variation in the shelf setting or differing depositional conditions. An additional component to defining the apparent dissimilarities in sea-level position, at least across west-central Georgia, is in understanding the role played by tectonism. The thin nature of the preserved updip marine clastic lithofacies of the Clayton Formation suggests that there was little accommodation space during deposition, or possibly that the unit has experienced considerable erosion. Ferricretes within the sandy clays document the transition from marine to subaerial conditions. The disconformable surface and incised channels across the top of the Clayton Formation clastic lithofacies likely reflect continued regional uplift during the Paleogene.

Changes in sea level, likely enhanced by regional uplift across west-central/southwestern Georgia throughout the lower/middle Paleocene, have had a direct bearing on the formation and development of the updip marine clastic sediments of the Clayton Formation. This lithofacies reflects the transition from nearshore marine to subaerial conditions.

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REFERENCES CITED

Alhadeff, S.J., Musser, J.W., Sandercock, A.C., and Dyar, T.R., 2001, Digital environmental atlas of Georgia: Atlanta, Georgia, Georgia Geologic Survey CD-1.

Baum, G.R., 1989, Upper Cretaceous and Paleogene sequence stratigraphy of Alabama, *in* Mancini, E.A., Russell, E.E., Dockery, D.T., Reinhardt, J., and Smith, C.C., eds., Upper Cretaceous and Paleocene biostratigraphy and lithostratigraphy of the Eastern Gulf Coastal Plain: Washington, District of Columbia, American Geophysical Union Guidebook T372, p. 18-25.

Baum, G.R., Blechschmidt, G.L., Hardenbol, J., Loutit, T.S., Vail, P.R., and Wright, R.C., 1984, The Maastrichtian/Danian boundary in Alabama: A stratigraphically condensed section: Geological Society of America Abstracts with Programs, v. 16, p. 440.

Baum, G.R., and Vail, P.R., 1988, Sequence stratigraphic concepts applied to Paleogene outcrops, Gulf and Atlantic basins, *in* Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., eds., Sea level changes: An integrated approach: Tulsa, Oklahoma, Special Publication 42, Society of Economic Paleontologists and Mineralogists, p. 309-327.

Clark, W.Z., Jr., and Zisa, A.C., 1976, Physiographic map of Georgia: Atlanta, Georgia, Georgia Geologic Survey Map SM-4.

Cocker, M.D., 2006, Geologic atlas of the Brooksville, Cuthbert, Georgetown, and Martins Crossroads, Georgia 7.5 minute quadrangles: Atlanta, Georgia, Georgia Geologic Survey Open File Report 06-1.

Cocker, M.D., and Costello, J.O., 2003, Geology of the Americus area: Atlanta, Georgia, Georgia Geological Society field trip guidebook 23.

Cooke, C.W., 1926, The Cenozoic formations, *in* Adams, G.I., Butts, C., Stephenson, L.W., and Cooke, C.W., eds., Geology of Alabama: University, Alabama, Geological Survey of Alabama Special Report 14, p. 251-297.

Cooke, C.W., 1943, Geology of the coastal plain of Georgia: Washington, District of Columbia, US Geological Survey Bulletin 941.

Cooke, C.W., and Munyan, A.C., 1938, Stratigraphy of Coastal Plain of Georgia: American Association of Petroleum Geologists Bulletin, v. 22, p. 789-793.

Donovan, A.D., 1986, Sedimentology of the Providence Formation, *in* Reinhardt, J., ed., Stratigraphy and sedimentology of continental, nearshore, and marine Cretaceous sediments of the eastern Gulf Coastal Plain: Atlanta, Georgia, Georgia Geological Society field trip 3, p. 29-44.

Donovan, A.D., and Reinhardt, J., 1986, Providence Canyons: The Grand Canyon of southwest Georgia, *in* Neathery, T.L., ed., Southeastern Section of the Geological Society of America Centennial Field Guide Volume 6: Boulder, Colorado, Geological Society of America, p. 359-362.

Eargle, D.H., 1955, Stratigraphy of the outcropping Cretaceous rocks of Georgia: Washington, District of Columbia, US Geological Survey Bulletin 1014.

Fluegeman, R.H., Jr., 1986, Foraminifera from Paleocene Clayton Formation lithostratotype, Barbour County, Alabama: American Association of Petroleum Geologists Bulletin, v. 70, p. 591.

Fluegeman, R.H., Jr., 1989a, The Clayton Formation (Paleocene) of Alabama: I. On the Clayton Formation lithostratotype. Tulane Studies in Geology and Paleontology, v. 22, p. 27-28.

Fluegeman, R.H., Jr., 1989b, The Clayton Formation (Paleocene) of Alabama: III. The type section of the Clayton Formation of Alabama: A Reply: Tulane Studies in Geology and Paleontology, v. 22, p. 33-34.

Fluegeman, R.H., Jr., 1993, Notes on Paleocene foraminifera from the Franklin Landing section, Henry County, Alabama, *in* Kish, S.A., ed., Geologic field studies of the Coastal Plain in Alabama, Georgia, and Florida: Tallahassee, Florida, Southeastern Geological Society field trip guidebook, p. 42.

Froede, C.R., Jr., and Reed, J.K., 2007, Subaqueous karstification of the top of the Clayton Formation limestone (lower Paleocene) near Fort Gaines, Georgia (USA): Southeastern Geology, v. 45, p. 87-96.

Froede, C.R., Jr., and Williams, E.L., 2004, The origin, development, and eventual consolidation of the canyons comprising Providence Canyon State Park, Stewart County, Georgia. Southeastern Geology, v. 43, p. 39-50.

Gibson, T.G., 1980, Facies changes of lower Paleogene strata: Upper Cretaceous and lower Tertiary geology of the Chattahoochee River Valley, western Georgia and eastern Alabama, *in* Frey, R.W., ed., Excursions in Southeastern Geology, Volume II: Falls Church, Virginia, American Geological Institute field trip guidebook, p. 402-411.

Gibson, T.G., 1981, Facies changes of lower Paleogene strata, *in* Reinhardt, J., and Gibson, T.G., eds., Upper Cretaceous and lower Tertiary geology of the Chattahoochee River Valley, western Georgia and eastern Alabama: Atlanta, Georgia, Georgia Geologic Society field trip guidebook, p. 19-28.

Gibson, T.G., 1982, Paleocene to middle Eocene depositional cycles in eastern Alabama and western Georgia, *in* Arden, D.D., Beck, B.F., and Morrow, E., eds., Proceedings of the second symposium on the geology of the southeastern Coastal Plain: Atlanta, Georgia, Georgia Geologic Survey Information Circular 53, p. 53-63.

Gibson, T.G., 1989, Planktonic benthonic foraminiferal ratios: Modern patterns and Tertiary applicability: Marine micropaleontology, v. 15, p. 29-52.

Gibson, T.G., 1992, Lithologic changes in fluvial to marine depositional systems in Paleogene strata of Georgia and Alabama, *in* Gohn, G.S., ed., Proceedings of the 1988, US Geological Survey workshop on the geology and geohydrology of the Atlantic Coastal Plain: Washington, District of Columbia, US Geological Survey Circular 1059, p.109-113.

Gibson, T.G., Mancini, E.A., and Bybell, L.M., 1982, Paleocene to middle Eocene stratigraphy of Alabama: Gulf Coast Association of Geological Societies Transactions, v. 32, p. 449-458.

Hastings, E.L., and Toulmin, L.D., 1963, Summary of Paleocene and Eocene stratigraphy and economic geology of southeastern Alabama: Tallahassee, Florida, Southeastern Geological Society field trip guidebook.

Kirkpatrick, S.R., 1963, Geology of the Lumpkin SW quadrangle, Stewart County, Georgia: Compass of Sigma Gamma Epsilon, v. 41, p. 40-51.

Langdon, D.W., Jr., 1891, Variations in the Cretaceous and Tertiary strata of Alabama: Geological Society of America Bulletin, v. 2, p. 587-606.

Langdon, D.W., Jr., 1894, The Tertiary and Cretaceous formations east of the Alabama River, *in* Smith, E.A., Johnson, L.C., and Langdon, D.W., Jr., eds., Report on the geology of the Coastal Plain of Alabama: Brown Printing, Montgomery, Alabama, Geological Survey of Alabama Special Report 6, p. 368-445.

Lindberg, F.A., 1988, Gulf Coast Region: Tulsa, Oklahoma, Correlation of stratigraphic units of North America (COSUNA) project, American Association of Petroleum Geologists.

Luckett, M.A., 1979, Cretaceous and lower Tertiary stratigraphy along the Flint River, Georgia: University of Georgia, Athens, Unpublished Masters Thesis.

MacNeil, F.S., 1946a, Summary of the Midway and Wilcox stratigraphy of Alabama and Mississippi: Washington, District of Columbia, US Geological Survey Strategic Minerals Investigations Preliminary Report (3-195).

MacNeil, F.S., 1946b, The Tertiary formations of Alabama: Tallahassee, Florida, Southeastern Geological Society field trip guidebook.

Marsalis, W.E., and Friddell, M.S., 1975, A guide to selected Upper Cretaceous and lower Tertiary outcrops in the lower Chattahoochee River Valley of Georgia: Atlanta, Georgia, Georgia Geological Society Guidebook 15.

Reimers, D.D., 1986, The calcareous nanno-plankton of the Midway Group (Paleocene) of Alabama: Tulane Studies in Geology and Paleontology, v. 19, p. 1-49.

Reimers, D.D., 1989, The Clayton Formation (Paleocene) of Alabama: II. Discussion of the type section of the Clayton Formation of Alabama: Tulane Studies in Geology and Paleontology, v. 22, p. 29-33.

Reinhardt, J., and Gibson, T.G., 1981, Upper Cretaceous and lower Tertiary geology of the Chattahoochee River Valley, western Georgia and eastern Alabama, *in* Frey, R.W., ed., Excursions in southeastern geology, Volume II: Falls Church, Virginia, American Geological Institute, p. 385-463.

Reinhardt, J., and Gibson, T.G., 1989, Chattahoochee River Valley region, *in* Mancini, E.A., Russell, E.E., Dockery, D.T., Reinhardt, J., and Smith, C.C., eds., Upper Cretaceous and Paleocene biostratigraphy and lithostratigraphy of the Eastern Gulf Coastal Plain: Washington, District of Columbia, American Geophysical Union Guidebook T372, p. 97-122.

Reinhardt, J., Prowell, D.C., and Christopher, R.A., 1984, Evidence for Cenozoic tectonism in the southwest Georgia Piedmont: Geological Society of America Bulletin, v. 95, p. 1176-1187.

Reinhardt, J., Schindler, J.S., and Gibson, T.G., 1994, Geologic map of the Americus 30' X 60' quadrangle, Georgia and Alabama: Washington, District of Columbia, US Geological Survey Miscellaneous Investigations Series Map I-2174.

Richards, H.G., 1955, The Paleocene and Eocene of Georgia: Georgia Mineral Newsletter, v. 8, p. 110-116.

Riggs, S.R., 1979, Phosphorite sedimentation in Florida—a model phosphogenic system: Economic Geology, v. 74, p. 285-314.

Smith, E.A., and Johnson, L.C., 1887, Tertiary and Cretaceous strata of the Tuscaloosa, Tombigbee, and Alabama Rivers: Washington, District of Columbia, US Geological Survey Bulletin 43.

Smith, E.A., Johnson, L.C., and Langdon, D.W., Jr., 1894, Report on the geology of the Coastal Plain of Alabama: Brown Printing Company, Montgomery, Alabama, Geological Survey of Alabama Special Report 6.

Stephenson, L.W., 1928, Structural features of the Atlantic and Gulf Coastal Plain: Geological Society of America Bulletin, v. 39, p. 887-900.

Swann, C., and Poort, J.M., 1979, Early Tertiary lithostratigraphic interpretation of southwest Georgia: Gulf Coast Association of Geological Societies Transactions, v. 30, p. 386-395.

Taylor, R.S., 1970, Clayton Formation (Paleocene), type locality descriptions: Gulf Coast Association of Geological Societies Transactions, v. 20, p. 320-321.

Toulmin, L.D., 1955, Cenozoic geology of southeastern Alabama, Florida, and Georgia: American Association of Petroleum Geologists Bulletin, v. 39, p. 207-235.

Toulmin, L.D., and LaMoreaux, P.E., 1963, Stratigraphy along Chattahoochee River, connecting link between Atlantic and the Gulf Coastal Plain: American Association of Petroleum Geologists Bulletin, v. 47, p. 385-404.

Toulmin, L.D., and Winters, S.S., 1954, Pre-Eocene solution features in southeast Alabama and southwest Georgia: Florida State University Studies No. 13. Contributions to Science, v. 2, p. 72-83.

Vail, P.R., Baum, G.R., Loutit, T.S., Donovan, A.D., Mancini, E.A., and Tew, B.H., Jr., 1987, Sequence stratigraphy of the uppermost Cretaceous and Paleogene of the Alabama/western Georgia Coastal Plain: Lafayette, Louisiana, Lafayette Geological Society field trip guidebook.

Veatch, O., and Stephenson, L.W., 1911, Preliminary report on the geology of the coastal plain of Georgia: Atlanta, Georgia, Geological Survey of Georgia Bulletin 26.

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PATH OF THE NANTAHALA RIVER, WESTERN NORTH CAROLINA

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ABSTRACT

In 1907, Arthur Keith posited that the Nantahala River once flowed through the Cheoah Valley to Robbinsville, North Carolina, based on evidence of alluvium at 850 m (2,800 ft) elevation, south of Beechertown and 180 m (600 ft) above the current level of the river. The Nantahala presently flows over high grade metamorphic rocks, and Tulula Creek flows over medium grade metamorphic rocks. For this study, heavy minerals were sampled in the present-day and former floodplains of Tulula Creek, which is north of the present-day path of the Nantahala and which flows on the supposed former path of the Nanatahala River. Kyanite was found in 27,000-year-old stream sediment from Tulula Creek but not in the present-day floodplain sediments. The Nantahala likely transported the kyanite from sediments over the high grade metamorphic rock to its current location in the Cheoah Valley on medium-grade metamorphic rocks, where Tulula Creek is located, thus supporting Keith's 1907 contention.

INTRODUCTION

The Nantahala River originates on Big Butt Mountain (35.04542° N latitude, 83.47633° W longitude, 1,370 m [4,480 ft] elevation), north of the North Carolina-Georgia border, and flows northwestward at approximately 330° azimuth to Beechertown (35.27270° N latitude, 83.67811° W longitude, 600 m [2,000 ft] elevation) and then northeastward at approximately 45° azimuth to the confluence with the Little Tennessee River (35.37984° N latitude, 83.56325° W longitude, 340 m [1,120 ft] elevation) (Figs. 1,2). In 1907, Arthur Keith stated that the Nantahala River previously flowed from present-day Beechertown northwestward through the Cheoah Valley to Robbinsville, prior to diversion by stream piracy to its present course that takes a right-angle bend at Beechertown to flow northeastward through Hewitt. The previous flow path took the Nantahala through the present-day Tulula Creek stream valley. He based his assertion on "pebble deposits" found at the old Nantahala River elevation of 850 m (2,800 ft), which is 180 m (600 ft) above the current Nantahala elevation at approximately 1.7 miles southeast of Beechertown. Nearly 100 years later, we discussed with Carl Merschat (North Carolina Geological Survey) the notion that Tulula Creek may trace a former path of the Nantahala, and he indicated that the Nantahala currently flows over high grade metamorphic rocks and Tulula Creek over medium grade metamorphic rocks. Thus, we set out to sample heavy minerals in the stream gravels to confirm Keith's assertion.

From its origin near the Georgia border, the Nantahala flows over kyanite-sillimanite grade metamorphic rocks, crossing a kyanite-stauro-

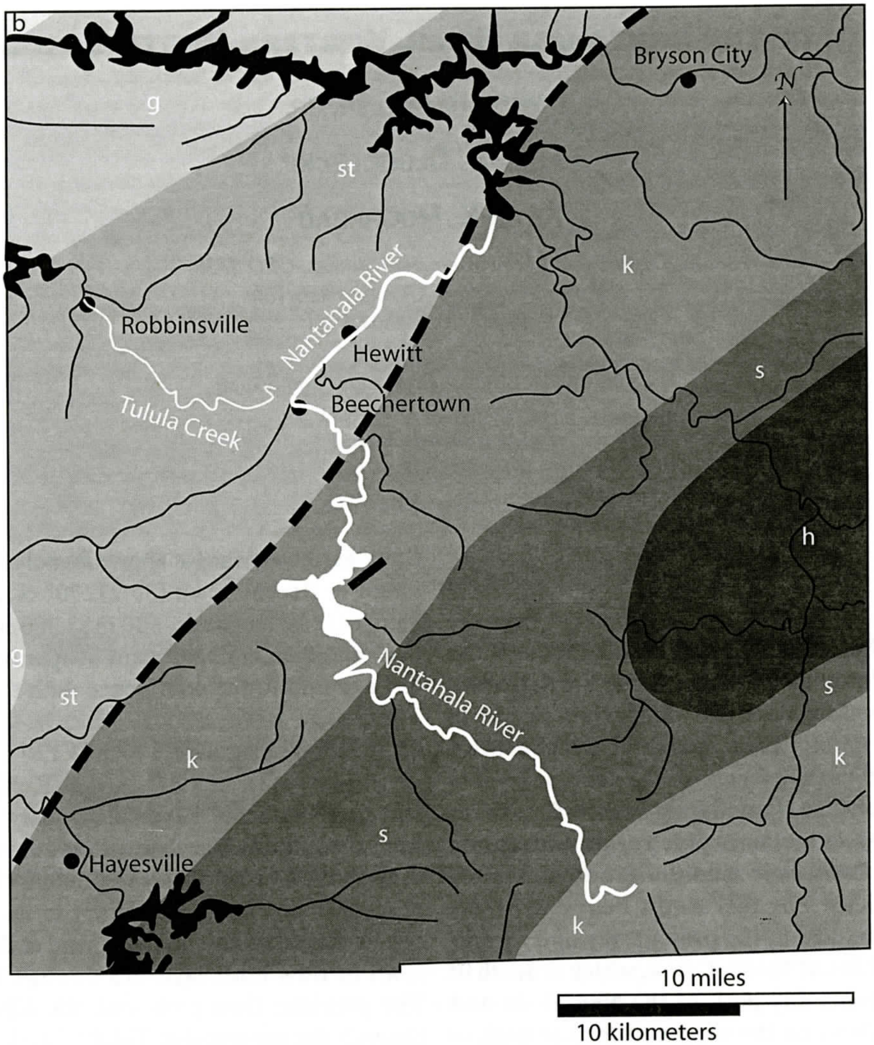

Figure 1. Metamorphic isograds in the Tulula Creek and Nantahala River drainages, shown in white. Isograd between medium- (staurolite) and high- (kyanite) grade metamorphism is indicated by the black dashed line. Metamorphic zones are abbreviated as b=biotite, g=garnet, st=staurolite, k=kyanite, s=sillimanite, h=hypersthene. Single black line on east side of lake along Nantahala River is staurolite (NW side)/kyanite (SE side) isograd according to Aylor (1994). Metamorphic map from Butler (1984) compilation on North Carolina Geologic Map (North Carolina Geological Survey, 1985).

lite isograd southeast of Beechertown, within the Blue Ridge physiographic province. The isograd shown by the dashed line on Figure 1 from is from Butler's (1985) compilation on the North Carolina Geologic Map (North Carolina Geological Survey, 1985), and a more recent location of the same isograd (Aylor, 1994) is shown as a single dark line on the east side of the lake on the Nantahala River. Aylor (1994) indicates the rocks southeast of the dashed isograd in Figure 1 to be that of the Dean Formation, which is composed of metapelites. Rocks to the northwest of that isograd are siltstones of the Nantahala Formation and mostly biotite schist and slate of the Brasstown Formation. The Nantahala River currently runs northwestward over the Nanatahala Formation for at least two kilometers before turning northeast-

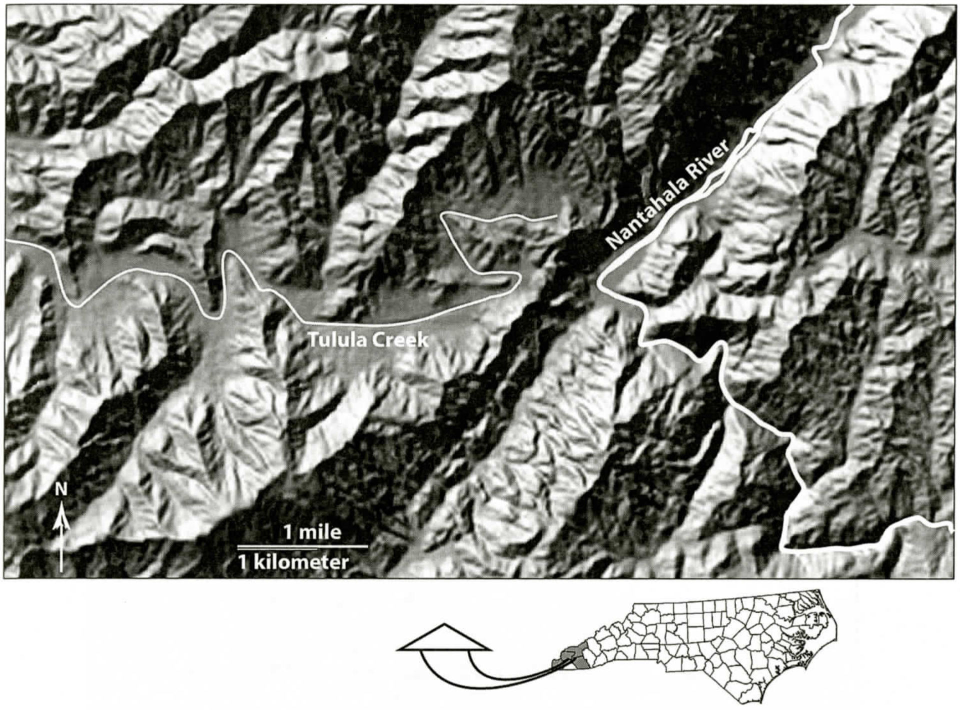

Figure 2. Digital elevation model of Beechertown area, with Tulula Creek and Nantahala River outlined in white lines. From the headwaters of Tulula Creek, the Cheoah Valley runs W and NW to Robbinsville, continuing NW along the Cheoah River to the Tennessee River, near the North Carolina-Tennessee border.

ward at Beechertown and away from the headwaters of Tulula Creek, which also flows over the Nantahala Formation. Thus, little difference was expected or seen in the mineral composition of the heavy mineral fraction, except for the presence/absence of some metamorphic indicator minerals.

METHODS

Old floodplain deposits were sampled with a 7-cm-diameter auger in four places to a depth of 2.5 meters, which is far below the contemporary floodplain bottom at approximately 15 cm (38 in) depth. Contemporary stream sediments in Tulula Creek and the Nantahala River were sampled to the bottom of the floodplain with a shovel (Fig. 3). Samples were concentrated by panning with a 61-cm (24-inch) plastic pan and concentrated further using sodium polytungstate ($3Na_2WO_4 \cdot 9WO_3 \cdot H_2O$; specific gravity 2.84). Sediments with organic matter, including stems and leaves, from kyanite-bearing sample T3 were sent in 2005 to a commercial lab (Geo-Cron Laboratories) for a ^{14}C age date.

RESULTS AND CONCLUSIONS

A topographic barrier of approximately 250 m (820 ft) relief exists today between the Nantahala River and Tulula Creek (Fig. 3). As implied by Keith (1907), the Nantahala flowed at that elevation or above the barrier until captured by stream piracy of the "branch of the Little Tennessee" River, which rejuvenated flow by increasing the gradient along the present course of the Nantahala River. We have no evidence for the cause of the piracy, but given the significantly higher elevation (180 m) of the stream pebble deposits indicated by Keith, a reasonable cause could be simple headward erosion of the pre-Nantahala River section, which flows northeastward from Beechertown. Once the Nantahala River stopped flowing northwest-

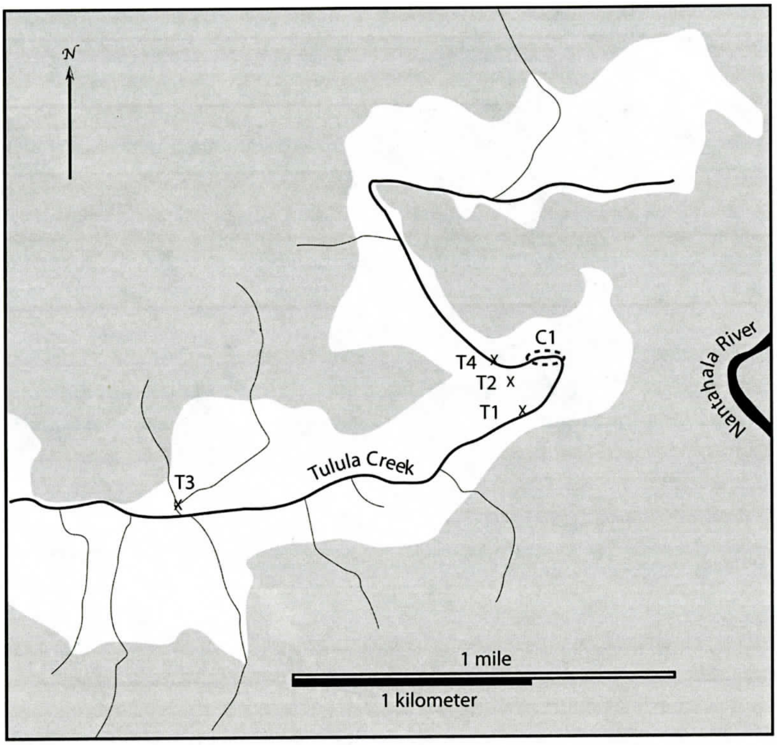

Figure 3. Locations of floodplain samples in Tulula Creek floodplain (white). C1 is a composite sample from the current floodplain within the dashed ellipse, and T1-T4 were taken from 1 to 3 meters depth below the current floodplain.

ward from Beechertown and instead began flowing northeastward, downcutting diminished the elevation of the Nantahala River while leaving the abandoned section of it, the headwaters of (new) Tulula Creek, with little capacity, high and relatively dry.

Tulula Creek flows over bedrock that suffered medium grade metamorphism (Aylor, 1994), which was confirmed with contemporary stream sediments that contain medium-grade metamorphic minerals, such as garnet and staurolite but no high-grade minerals, such as kyanite, sillimanite, or hypersthene. However, kyanite was found in gravels from the Tulula floodplain at 1.7-1.9 m (5.6-6.2 ft) depth in heavy-mineral sample T3 and at 2.1-2.3 m (6.9-7.5 ft) depth in sample T1. This kyanite likely was transported from the present location of the Nantahala River to the south, confirming Keith's (1907) supposition. Organic material from the kyanite-bearing horizon in sample T3 was dated at 27,000 years BP, which indicates that the Nantahala River flowed through the Tulula Creek valley at least 27,000 years ago and possibly earlier.

ACKNOWLEDGEMENTS

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REFERENCES CITED

Aylor, Joseph Garnett, Jr. 1994, Paleozoic History of the Nantahala and Brasstown Formations of the Basal Murphy Belt, Southwesternmost North Carolina and North-

ernmost Georgia: unpublished Ph.D. dissertation, Florida State University, Tallahassee, 421 p.
Keith, A., 1907, Description of the Nantahala Quadrangle, North Carolina-Tennessee: *in* Geologic and Topographic Atlas of the United States, Nantahala Folio, No. 143, G.W. Stose (Ed.), U.S. Geological Survey, 12 p.
North Carolina Geological Survey, 1985, Geologic Map of North Carolina: North Carolina Department of Natural Resources and Community Development, Geological Survey Section, scale 1:500,000.

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A New Species of *Faujasiid cassiduloid* (Echinoidea: Irregularia) from the Santonian-Campanian Boundary (Upper Cretaceous) in the Eastern Gulf States

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ABSTRACT

In central Alabama, the upper part of the Tombigbee Sand Member, Eutaw Formation (Upper Cretaceous: Gulfian: Santonian), contains the locally common faujasiid cassiduloid *Hardouinia bassleri* (Twitchell). A closely related, unpublished *Hardouinia* species occurs at a slightly younger interval in the Tombigbee Sand in northeast Mississippi and in the middle Blufftown Formation of eastern Alabama. Although very similar to *H. bassleri* with respect to general test morphology, phyllodes, and apical system, *Hardouinia saucierae* sp. nov. is distinguished by its larger size, more anterior peristome, depressed buccal pores, stouter bourrelets, lower periproct, and more acute ambitus. In Mississippi and eastern Alabama, *Hardouinia saucierae* occurs at or very near the Santonian-Campanian boundary. The great anatomical similarity between the new species and *H. bassleri*, coupled with its immediately superjacent stratigraphic occurrence and geographic proximity, suggests the slightly younger *H. saucierae* may be a contiguous descendant of *H. bassleri*. These two closely related non-co-occurring species are each accompanied by a second co-occurring species of *Hardouinia*, the additional species being different in each case depending on certain combinations of unit, age, and location.

INTRODUCTION

In an unpublished Masters thesis, the third author described eighteen "new" macroinvertebrate species from Upper Cretaceous sediments in the vicinity of Starkville, Mississippi (Hayes 1951). One of the confirmed new species was a cassiduloid echinoid of the Family Faujasiidae—a relatively common and diverse irregular echinoid group in Gulfian age deposits of southeastern North America.

This is the first time any portion of the late Mr. Hayes' thesis has ever been published. Given the inaccessible nature of the unpublished manuscript, which provides only a superficial illustrated description of the new species, as

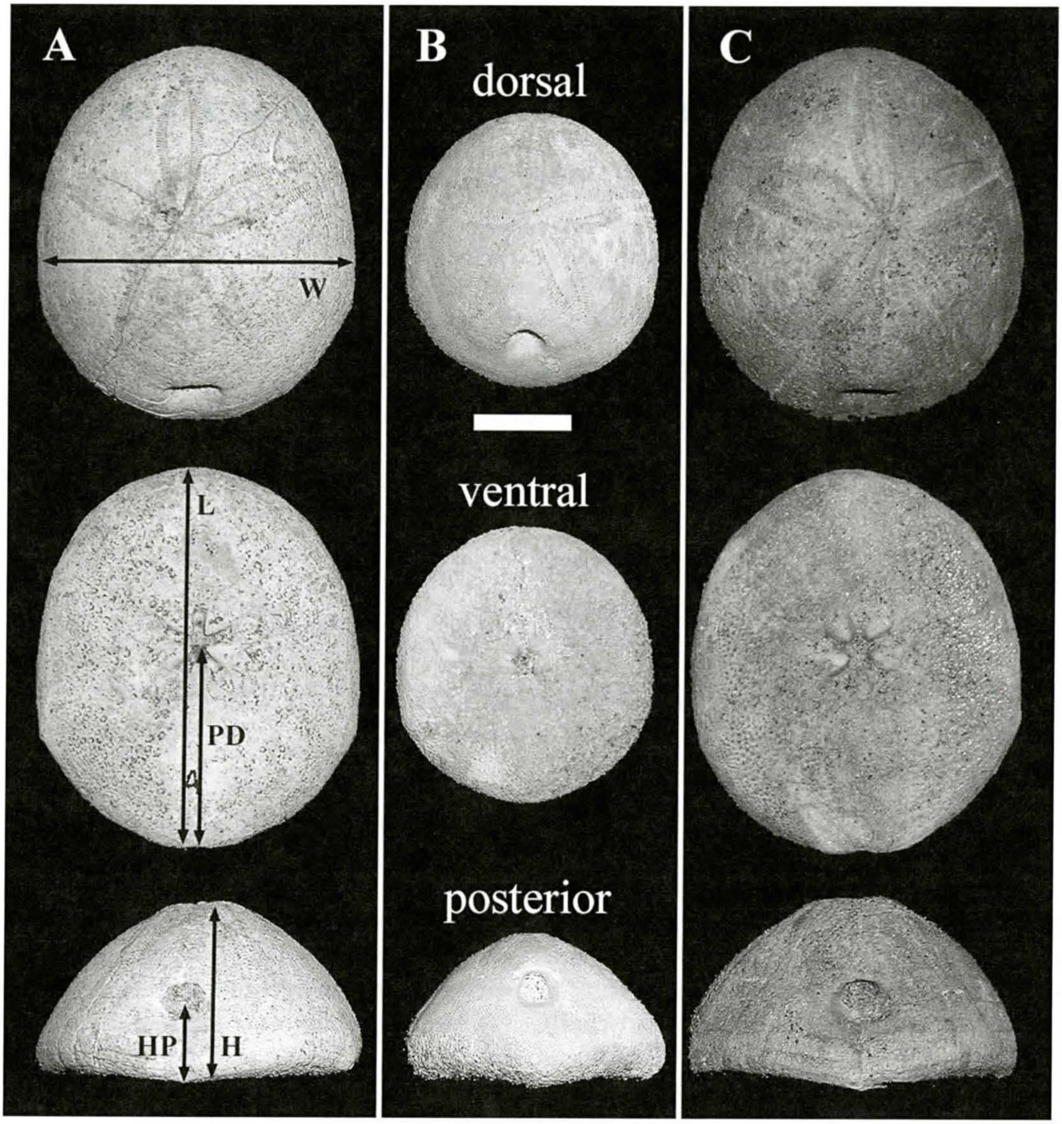

Figure 1. Tests of two closely related *Hardouinia* species from the Tombigbee Sand Member of the Eutaw Formation, Central Gulf States. A, C, *Hardouinia saucierae* sp. nov. from the latest Santonian/earliest Campanian levels of the Tombigbee Sand in northeast Mississippi; B, *Hardouinia bassleri* (Twitchell 1915) from the Late Santonian Tombigbee Sand of central Alabama. A, MMNS IP-811.A, paratype, from south of Aberdeen, Miss.; B, MMNS IP-729.1 from Montgomery, Ala.; C, MMNS IP-575.13 from west of Aberdeen, Miss. Test length (L), width (W), height (H), peristome distance (PD), and periproct height (HP) are measurements used in comparing the two species (see text and Table 1). Note the larger size, greater length/width ratio, slightly anterior peristome, more acute ambitus, and lower periproct in *H. saucierae* compared to *H. bassleri*. White bar = 1 cm.

well as the unknown location of the original type material, there is reasonable justification to publish a formal description of this echinoid.

All type and referred material resides in the Invertebrate Paleontology (IP) collection at the Mississippi Museum of Natural Science (MMNS). Hayes' (1951) types, officially classified as lost, were at one time deposited at the Dunn-Seiler Museum, Department of Geosciences, Mississippi State University (MSU).

Specific locality information for all sites discussed in this paper is recorded in the Conservation Biology Section at the MMNS and is available upon request to the research community.

The systematic nomenclature employed herein follows that of Smith and Jeffery (2000).

SYSTEMATIC PALEONTOLOGY

Class Echinoidea Leske, 1778
Order Cassiduloida L. Agassiz and Desor, 1847
Family Faujasiidae Lambert *in* Doncieux, 1905
Subfamily Stigmatopyginae Smith and Wright, 2000
Genus *Hardouinia* Haime *in* d'Archiac and Haime, 1853
Hardouinia saucierae sp. nov.
(Figures 1-5, Table 1)

MMNS IP-37 from Kennedy Lake (MS.13.006) in Clay County, Mississippi, is the designated holotype. MMNS IP-1619 (partial test) from Plymouth Bluff (MS.44.012) on the Tombigbee River, Lowndes County, Mississippi, and MMNS IP-811 (three complete tests) from the Fowlkes bentonite mine (MS.48.005) near Aberdeen in nearby Monroe County are the designated paratypes (Figure 1, A). All material in the type series is from the uppermost portion of the Tombigbee Sand Member, Eutaw Formation. Hayes' (1951) lost holotype, MSU 2007, was also from the Tombigbee Sand at Plymouth Bluff, and his paratype, MSU 2007A, was collected from the same unit just upstream on the Tombigbee River at Barton's Bluff (MS.13.015), Clay County. The unavailability of the chirotypes necessitated the naming of new type material.

Additional material examined — The hypodigm consists of the type series plus MMNS IP-789 and IP-1249 from the middle Blufftown Formation near Hatchechubbee, Alabama (AL.57.001), and MMNS IP-575 (66 tests) from the Tombigbee Sand (upper Eutaw Formation) near Aberdeen, Mississippi (MS.48.004) (Figure 1, C). In addition, a large sample of the closely related *Hardouinia bassleri* (Twitchell) was used for comparison, as were examples of other congenerics. The *H. bassleri* tests consisted of MMNS IP-729 (33 tests) (Figure 1, B) and IP-790 (44 tests) from the Tombigbee Sand at Montgomery, Alabama (AL.51.001), and MMNS IP-1030 (2 tests) from the same level in the Tombigbee Sand at Selma, Alabama (AL.24.002).

Etymology — The late W. E. Hayes requested this new echinoid species bear his wife's maiden name of Saucier (Hayes 1951).

Description — Hayes (1951, p. 72-73) provided a very general description of *Hardouinia saucierae*, but only two specimens were available to the author at the time, one of which was incomplete. In addition, the original, unpublished description was insufficient in terms of distinguishing the new species from similar species of *Hardouinia*. The current samples are also larger and from different locations, thus we now have a better idea of variation within the species.

As is typical of most cassiduloids, *Hardouinia saucierae* sp. nov. is flattened ventrally with adoral phyllodes about a subcentral peristome and is strongly convex dorsally where a petalloid ambulacral system is flush with the surface of the test's dome. As in the described species of faujasiids, the new species has a relatively large genital plate 2 (madreporite), strongly developed bourrelets, phyllodes with biserial pores, equal petaloid ambulacra, and interambulacrum 5 ventrally pronounced and forming a low ridge with a bare granular zone. The new species is a member of the Subfamily Stigmatopyginae, which is characterized by having an invaginated, fully dorsal periproct, in contrast to the marginal/inframarginal, surficial periproct of the Faujasiinae (Smith and Wright, 2000). *Hardouinia* is distinguished from other faujasiid genera by a unique combination of the aforementioned family characters, particularly the shared possession of tooth-like bourrelets about a subcentral peristome, a tetrabasal apical system with four gonopores, a low median ridge on interambulacrum 5 ventrally, and the position and morphology of the periproct.

More specifically, *Hardouinia saucierae* is a small, elongate, subconical faujasiid, oval to subpentagonal in apical/oral outline, with a relatively acute ambitus. The new species is fur-

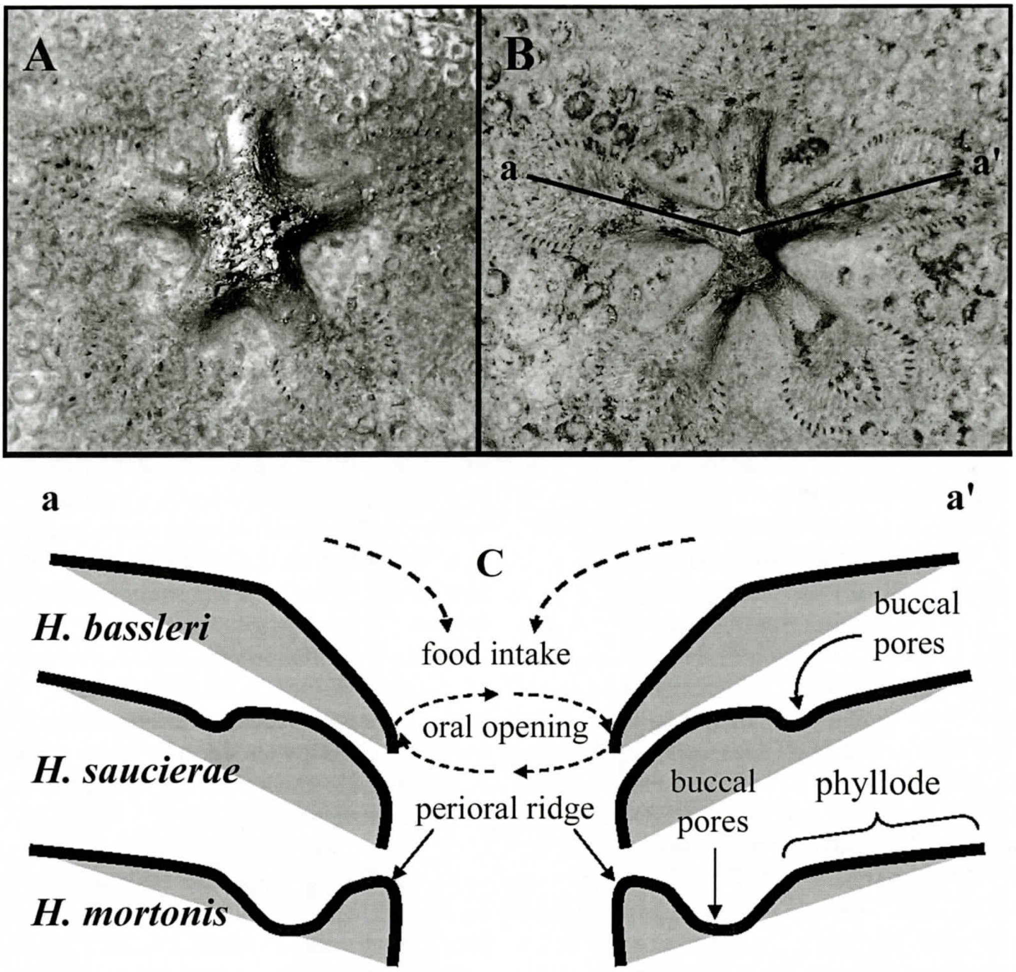

Figure 2. Peristome differences among species of *Hardouinia*. The bourrelets of *Hardouinia bassleri* (A) are blunt and subdued compared to the sharper, more projecting bourrelets of *H. saucierae* (B). Longitudinal cross-sections of the phyllodes are also species diagnostic (C). Following an a-a' transect (B), the perioral region slopes inward more steeply in *H. bassleri* than other species of *Hardouinia*, including *H. saucierae* and *H. mortonis* (C). A perioral ridge results from a depression at the base of each phyllode in *H. mortonis*. A similar, less developed depression occurs in *H. saucierae*, which lacks the sharp perioral ridge of *H. mortonis*. A pair of buccal pores is located in each perioral depression.

ther distinguished by a round, recessed, supramarginal periproct, situated below mid-height, as well as a slightly anterior peristome. Of the existing described species of *Hardouinia*, the new species is most similar to *Hardouinia bassleri* (Twitchell) (Figure 1, B) from the Late Santonian of central Alabama. The new species is also similar, but less so, to *H. stantoni* (Clark) from the Middle Turonian of Colorado, *H. taylori* (Warren) from the Middle Campanian of Colorado and Alberta, and *H. mortonis* (Michelin) and *H. aequorea* (Morton) from the Maastrichtian of the Southeast (see review of Cooke, 1953). All possess a subpentagonal dorsoventral outline and a rounded, recessed periproct. The apical system of *H. saucierae* is much like that of other species of *Hardouinia* and essentially indistinguishable from *H.*

bassleri, both possessing a relatively small G2 compared to that in *H. mortonis*. The length/width ratio of the petals is like that of *H. bassleri* and *H. aequorea*. Additionally, the phyllodes of *H. saucierae* are essentially the same as those in *H. bassleri* and *H. stantoni* with 11 to 13 pores in each outer series of phyllode V and four to seven pores in each inner series. Compared to the older species, *Hardouinia mortonis* has four to six fewer pores in each outer series of phyllode V and only one to two pores in the inner series, whereas *H. aequorea* has an essentially intermediate condition (e.g. Kier 1962, p. 145-146). In addition, *H. aequorea* has a higher, more vertically elongate perianal recession than *H. saucierae*.

Hardouinia saucierae is different from *Hardouinia bassleri* in several qualitative respects, particularly in terms of ambital curvature and morphology of the peristome and periproct. First, the new species has a more acute test margin than *H. bassleri*, which possesses a more rounded ambitus. Second, the bourrelets of *H. bassleri* are not as developed as in *H. saucierae*, *H. mortonis*, and most of the remaining Campanian and Maastrichtian species of *Hardouinia* (Figure 2, A & B). *Hardouinia aequorea* (Morton), which differs from *H. bassleri* in the shape of its periproct, is the only other congeneric exhibiting weak bourrelet development like that of *H. bassleri*. Smith and Jeffery (2000) subsumed *Hardouinia micrococcus* (Gabb), a gigantic species, and *H. porrecta* (Clark), a large species, under *H. aequorea* (Morton), a small to very small faujasiid. Their synonymy was largely based on attributing the much weaker bourrelet development in H. *aequorea*, versus the more pronounced, pointed bourrelets of H. *porrecta* and H. *micrococcus*, to allometric differences associated with either ontogeny or body size differences among populations. If this is the case, then populations of very small *H. mortonis* might also have comparably reduced bourrelets relative to much larger conspecifics. We have not observed this to be the case. Even in the range of size overlap, *H. saucierae* has distinctly better developed bourrelets than *H. bassleri*, suggesting this character is species diagnostic and may operate independently of size.

Third, the buccal pores are located in a depression at the base of each phyllode in certain North American faujasiids. This depression is relatively small and shallow in *H. saucierae* but profound in *H. mortonis*, in which its inner margin (bordering the oral opening) forms a "perioral ridge" (Smith and Jeffery, 2000). In others, like *Hardouinia kellumi* (Stephenson), *H. aequorea* (sensu lato), and *H. bassleri*, the perioral region lacks a depression and slopes steeply into the oral opening (Figure 2, C). Lastly, the perianal recession, very round in *H. saucierae* and *H. mortonis*, is vertically elongate in *H. bassleri* (although not particularly evident in Figure 1), in which it is somewhat comparable to that of *H. aequorea*.

Hardouinia saucierae also exhibits several distinguishing statistical morphometries, particularly those relating to test size and position of the peristome and periproct. Maximum length (Length, L), maximum transverse width (Width), maximum height (Height), relative position of peristome (PPs), and relative height of periproct (HPp) were measured for 68 tests of *H. saucierae* and 74 tests of *H. bassleri*. Length was measured along the longitudinal axis passing through the centers of petal III, the peristome, and the periproct (Figure 1). Width was measured normal to Length and at the greatest transverse breadth of the test. Height was measured transversely across the test at the highest elevation of the apical system from the base. PPs is the relative distance, positive or negative, from the exact center of the test (as measured from the posterior margin). Thus, PPs = PD – Length/2, where PD is the distance of the center of the peristome from the posterior edge of the ambitus, measured along the Length. Similarly, HPp is the relative vertical position of the periproct with respect to center-height (i.e. half the Height). Thus, HPp = HP – Height/2, where HP is the height of the periproct as measured from the base of the test just below the periproct. All measurements were taken with a stainless Helios dial caliper and reported in millimeters. The most relevant morphometric data—namely Length, PPs, and HPp—are presented in Table 1 and Figure 3.

Measurements of the two species' popula-

	Hardouinia saucierae, n=68 Northeast Mississippi				*Hardouinia bassleri*, n=74 Central Alabama			
	Length	L/W	PPs	HPp	Length	L/W	PPs	HPp
Maximum	40.9	1.28	2.2	0.8	32.8	1.15	0.9	3.6
Mean	36.2	1.16	1.1	-0.9	24.7	1.08	-0.1	1.9
Minimum	31.7	1.08	0.1	-2.5	17.4	1.02	-1.1	-1.2
Stand. Dev.	2.08	0.04	0.45	0.76	3.25	0.03	0.45	0.74

Table 1. Morphometric statistics for the faujasiid cassiduloids *Hardouinia saucierae* sp. nov. and *Hardouinia bassleri* (Twitchell) from the Tombigbee Sand of Mississippi and Alabama, respectively (The few available Alabama specimens of *H. saucierae* were not in sufficient condition to allow for complete measurements of any tests). This table provides maximum length (Length), length/width ratio (L/W), relative position of peristome (PPs), and relative height of periproct (HPp) as distinguishing test metrics (illustrated in Figures 1, 3). Positive values represent millimeters anterior to (PPs) or above (HPp) center (i.e. midway); negative values are posterior to (PPs) or below (HPp) center. "Center" is defined as Length/2 for PPs and Height/2 for HPp. PPs = PD – Length/2, where PD is the distance of peristome from posterior margin of test, measured along the Length. HPp = HP – Height/2, where HP is the height of periproct measured from base of test.

tions reveals the larger size of the new species, averaging 47% longer than *H. bassleri* (~2.6 times larger volumetrically). The length:width ratio is greater in *H. saucierae*, although not profoundly. More importantly, Table 1 reveals the more anterior position of the peristome and the lower elevation of the periproct in the new species (see also Figure 1). Five each of the smallest *H. saucierae*, the larger species, and the largest *H. bassleri*, the smaller species, were compared for similarity in peristome and periproct positions in order to detect the morphological overlap within the range of size overlap (Figure 3). Regardless of Length, the posterior-most peristome positions (lowest PPs's) observed in *H. saucierae* do not overlap with the anterior-most peristome positions (highest PPs's) observed in *H. bassleri*. Likewise, the highest periprocts (HPp's) observed in *H. saucierae* do not overlap with the lowest periprocts (HPp's) observed in *H. bassleri* (HPp's). In sum, there is no overlap in position of the peristome or periproct where there is overlap in size (Length), making the two species distinct with respect to the position of these two structures.

Although geographically disjunct by an along-strike distance of approximately 235 miles, the known populations of *Hardouinia saucierae* in northeast Mississippi and east-central Alabama seem to be different only in relative height of test, the former somewhat taller than the latter. However, this is based on a handful of incomplete tests collected thus far from the easternmost point of the species' known range in the Blufftown Formation.

Occurrence & Age

Occurrence — *Hardouinia saucierae* sp. nov. has been recovered from contemporaneous levels in two different, geographically disjunct lithologic units. The new species occurs high in the Tombigbee Sand Member of the Eutaw Formation in Mississippi and in the middle part of the Blufftown Formation in eastern Alabama (Figures 4, 5). All localities date to the Santonian/Campanian boundary, and the exact age of these stratigraphic positions will be discussed in detail further below.

In general, the Tombigbee Sand consists of very fine- to fine-grained, glauconitic, clayey and silty quartz sands that are massively bedded, commonly macrofossiliferous, and represent mostly inner shelf, nearshore environments (Russell and Keady, 1983). The insoluble component of the zone containing *Hardouinia saucierae* tests is fine quartz sand. In the study area,

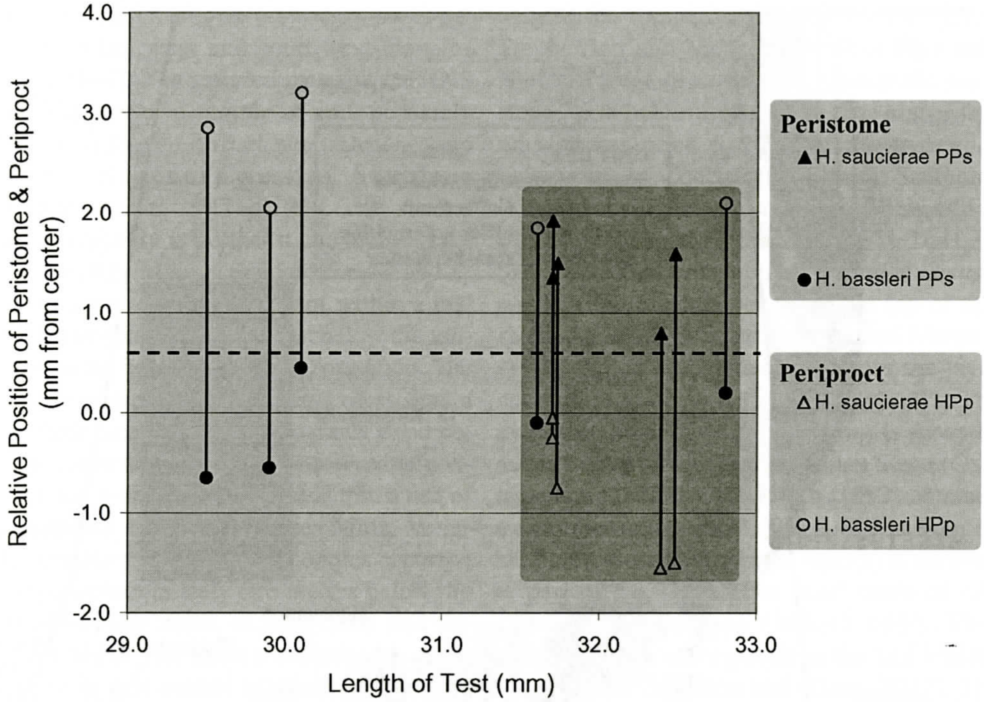

Figure 3. The affect of size overlap on the relative position of the peristome (PPs, black data points) and relative height of the periproct (HPp, clear data points) using the five smallest *Hardouinia saucierae* (triangles) and five largest *Hardouinia bassleri* (circles)—the former averaging larger in test size than the latter. Note the absence of interspecific overlap in the relative position of the peristome and periproct (y-axis, dashed line) regardless of the presence of interspecific overlap in test size (x-axis, gray box). Solid vertical lines represent the peristome and periproct pair for each of the ten tests. See Table 1 (and text) for sample size and detailed definitions of PPs and HPp.

the Tombigbee Sand lies conformably on the lower unnamed member of the Eutaw Formation and is in turn conformably overlain by the finer-grained, deeper water marls of the Mooreville Formation. Plymouth Bluff, which has yielded specimens of the new echinoid (including the chirotypes), is the type locality for the Tombigbee Sand (Stephenson and Monroe, 1940).

The Blufftown Formation south of Hatchechubbee, Alabama, generally consists of poorly sorted, macrofossiliferous, sandy, calcareous silts also representing inner shelf environments (Skotnicki and King, 1986). However, there are thin intervals in the Blufftown composed of medium to coarse quartz sand, such as the echinoid-bearing layer in the middle part of the formation. The Blufftown sand yielding the new echinoid averages notably coarser and less glauconitic than the contemporaneous echinoid-bearing sand in the Tombigbee Sand of Mississippi. The Blufftown Formation is typically perceived as lying unconformably upon the Eutaw Formation and is in turn unconformably overlain by the Cusseta Formation (review of Skotnicki and King 1986). It is considered the eastern lithostratigraphic equivalent of the Mooreville Formation, with which it intertongues to the west (Figure 4).

Although collected loose in scree at Plymouth Bluff, MMNS IP-1619 is believed to be from the uppermost portion of the Tombigbee Sand, or "layer 5" of Stephenson and Monroe (1940, p. 73). This layer is also, presumably, the origin of MSU 2007 and 2007A (the missing original chirotypes), the latter specimen from just up river at Barton's Bluff (MS.13.015). The

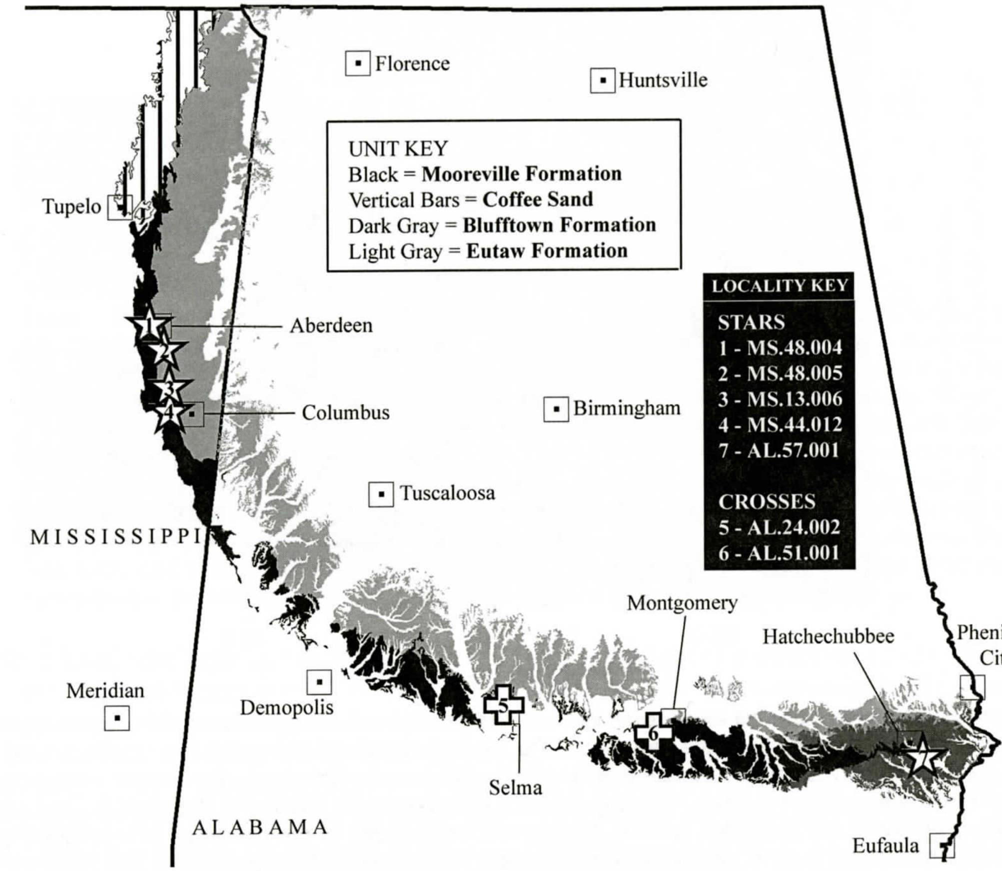

Figure 4. Geologic map of localities mentioned in text. The Eutaw Formation (Light Gray) and the younger Mooreville Marl (Black) extend for nearly the entire length of the Gulfian outcrop present in the Central Gulf. However, the Coffee Sand (Vertical Bars) extends no further south than northeastern Mississippi and the Blufftown Formation (Dark Gray) no further west than eastern Alabama. Due to the nature of the ArcMap (GIS) layers, geologic units in Mississippi are represented as essentially continuous outcrop, whereas those in Alabama are interrupted by modern floodplains. Localities yielding *Hardouinia saucierae* sp. nov. [stars: 1, 2, 3, 4 & 7] are located in the upper Tombigbee Sand (Eutaw Fm) and middle Blufftown Fm, whereas localities yielding *H. bassleri* (Twitchell) [crosses: 5 & 6] are located in the Tombigbee Sand (Eutaw Fm) of central Alabama. Locality MS.13.015 (mentioned in text), which has also yielded material of the new species, is not plotted but is essentially equivalent to MS.13.006 [star 3].

Kennedy Lake specimen (MMNS IP-37) was found in a relatively limited and transient exposure of the Tombigbee Sand. Although no local stratigraphic reference points were ascertainable, the position of this specimen was suspected to be within the uppermost portion of the member—again "layer 5." The three paratypes (MMNS IP-811) from the Fowlkes Mine (MS.48.005) have the best stratigraphic provenance (all other material having been collected by other parties). They were collected by the primary author within 5 to 8 meters below the contact of the Tombigbee Sand with the Mooreville Formation, as defined by Stephenson and Monroe (1940), in a calcareous sandstone containing common *Exogyra ponderosa* Roemer and *Neithea quinquecostata* (Sowerby). Although not observed within the active mine pit where the echinoids were collected, the contact between the Tombigbee Sand and overlying

Mooreville marl lies at (or very near) the pit perimeter on the west and southwest margins (Torries 1964). The referred material (MMNS IP-575) is part of a sample of approximately 1,000 tests recovered from two transient sand pits (now lagoons) west of Aberdeen (MS.48.004) from 1997 to 1998. This second Aberdeen locality is northeast and along strike of the Fowlkes Mine. Cassiduloid tests and *E. ponderosa* valves were abundant within a bed of the Tombigbee Sand lying just below the sandy marl of the basal Mooreville Formation. The echinoids occupied a distinct layer less than a meter thick located more than a meter or so below the estimated Tombigbee-Mooreville contact and immediately below and within a bed of *E. ponderosa*, as at the Fowlkes Mine. Vertebrate remains and phosphatic nodules occurred in a layer approximately two meters below the echinoid-oyster zone, at Aberdeen and the Fowlkes Mine. The known occurrences of *H. saucierae* in east-central Mississippi therefore indicate that the new echinoid is confined to the uppermost part of the Tombigbee Sand Member of the Eutaw Formation.

Age — Plymouth Bluff near Columbus, Mississippi, has been the subject of much stratigraphic and paleontologic research. It is the type locality for the Tombigbee Sand (Stephenson and Monroe, 1940) and is the primary local reference section for the current study. Ammonites, crinoids, microfossils, and nannofossils have all been used to correlate the strata at Plymouth Bluff to the European and the Western Interior standard sections. Regrettably, due to construction of the Tenn-Tom Waterway bypass channel around the old river bend containing Plymouth Bluff, erosion no longer occurs along this once scenic vista, resulting in very little observable stratigraphic resolution.

A Late Santonian *Boehmoceras* ammonite assemblage described by Kennedy and Cobban (1991) from the lower part of the Tombigbee Sand near Plymouth Bluff is located 16.0 m below the local top of the member (as defined by Stephenson and Monroe, 1940) and ~9 m below "layer 5," the presumed origin of *H. saucierae* at this location. Kennedy and others (1997) described the highest occurring ammonite assemblage in the Tombigbee Sand in "layer 4" (sensu Stephenson and Monroe, 1940) at Plymouth Bluff—a ledge of calcareous, glauconitic sandstone 7.0 m below the local top. The higher fauna was assigned to the *Submortoniceras tequesquitense* Zone, which is latest Santonian to earliest Campanian in ammonite composition (review of Kennedy and others, 1997). The Late Santonian marker crinoid *Marsupites testudinarius* (Schlotheim) occurs in the top of this sandstone layer (e.g. Stephenson and Monroe, 1940), which is situated just below the layer containing the new echinoid ("layer 5"). The extinction point of *M. testudinarius* is accepted as the beginning of the Campanian Stage (Gale and others, 1995). Obradovich (1993) obtained a radiometric age of 84.09 ± 0.40 Ma from an ammonite-bearing bentonite layer(s) in the lower part of the Tombigbee Sand south of Aberdeen, Mississippi (MS.48.005). This numerical date corresponds to the late Middle Santonian of Gradstein and others (2005). The senior author has collected the ammonites *Boehmoceras arculus* (Morton), *Placenticeras syrtale* (Morton), and *Scaphites leei* Reeside, form I, from these same bentonite layers, ~30 m below the occurrence of *Hardouinia saucierae* in the upper part of the Tombigbee Sand. This ammonite assemblage is compositionally consistent with the Late Santonian *Boehmoceras* fauna of Kennedy and Cobban (1991) mentioned above. The subjacent occurrence of the *Boehmoceras* fauna and previously mentioned *Marsupites testudinarius* provide a maximum local age for *H. saucierae*. In sum, available macrofossil indices suggest that *Hardouinia saucierae* is confined to a zone at or near the Santonian/Campanian boundary in Mississippi.

Planktonic foraminiferal and calcareous nannofossil zonation—as defined by Caron (1985) and Sissingh (1977) respectively—suggest that "layer 5," the uppermost bed in the Tombigbee Sand at Plymouth Bluff, dates entirely to the Late Santonian, at least according to the sampling and interpretation of Dowsett (1989) and Mancini and Soens (1994). Planktonic foram analysis performed by Puckett (2005) suggests the Santonian-Campanian boundary, based on the highest observed occurrence of *Dicarinella*

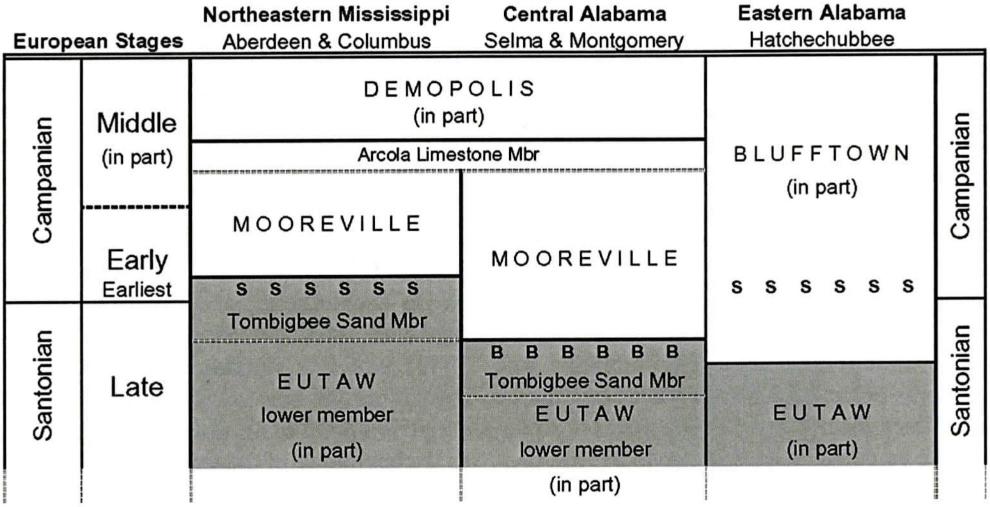

Figure 5. Generalized Central Gulf correlation chart for the Late Santonian through early Middle Campanian depicting the stratigraphic occurrence of *Hardouinia bassleri* (Twitchell) [B] and *Hardouinia saucierae* sp. nov. [S]. Note that *H. saucierae* is currently known to occur in the vicinity of the boundary, not necessarily above it. Co-occurring minority *Hardouinia* species [H, C, M] comprise between ~0.3% [H] and ~7% [M] of the total *Hardouinia* tests collected for each *Hardouinia* species pair within each region (see text for names of the co-occurring species). Formational units are given in capital letters and member level units separated by dotted lines. The Eutaw Fm is represented in gray. Chart based on biostratrigraphic information from Puckett (1996, 2005, pers. com. 2007). No relative thickness relationships implied.

asymetrica, falls stratigraphically lower at this locality than estimated by others, below the Tombigbee/Mooreville contact (Figure 5). A foram analysis (graciously provided by T. M. Puckett) was performed on a single sediment sample from one of the echinoid sites (MS.48.005), and a lone test of *D. asymetrica* was recovered from two kilograms of matrix submitted. This weak result, coupled with the potential for contamination at all sample sites, warrants more controlled sampling at a later date. Until then, and according to published microfossil interpretations, *Hardouinia saucierae* occurs either comfortably below the Santonian/Campanian boundary, which is placed in the lowest meter of the Mooreville by Dowsett (1989) and Mancini and Soens (1994), or very near the boundary, which is placed in the uppermost meter of the Tombigbee Sand by Puckett (2005). In contrast, the related *Hardouinia bassleri* occurs well below the Santonian/Campanian boundary (~36 m) in eastern Alabama, based on the stratigraphic work of Dowsett (1989) and Puckett (2005).

In eastern Alabama, *Hardouinia saucierae* sp. nov. occurs in the middle of the Blufftown Formation. As is the case with the Tombigbee Sand in Mississippi, *Exogyra ponderosa* Roemer and *Neithea quinquecostata* (Sowerby) were the only identifiable macroinvertebrate guide fossils found in direct association with the new echinoid in the Blufftown. Sohl and Smith (1980) placed the entire Blufftown Formation within the Early (Lower) Campanian based on a combination of several biostratigraphic indices, including macroinvertebates. Based on a thorough analysis of foram assemblages throughout the Blufftown, Rosen (1985) placed the lower 90+ m of the unit within the Santonian and the upper 90+ m within the Campanian. Using the first appearance of *Dicarinella asymetrica*, T. M. Puckett (pers. com.) has dated points in the Blufftown approximately 24 meters down-section from the *H. saucierae* layer as Late Santonian and points 24-30 meters up-section as Early (but not earliest) Campanian. Therefore, in the easternmost part of its known distribution, *H. saucierae* also occurs in the vicinity of the Santonian/Campanian boundary.

DISCUSSION

Hardouinia saucierae sp. nov. is a faujasiid cassiduloid closest morphologically to *Hardouinia bassleri* but differs in its larger test with a more acute ambitus, lower periproct, a more anterior peristome, stouter bourrelets, and location of the buccal pores in a depression at the base of each phyllode. The new species occurs in the massive fine sands of the Tombigbee Sand Member of the Eutaw Formation of northeastern Mississippi and in medium to coarse sand lenses of the middle Blufftown Formation of east-central Alabama. Based on a close consensus of mostly biostratigraphic data, *H. saucierae* occurs near or at the Santonian/ Campanian boundary at both locations. The related *Hardouinia bassleri* (Twitchell) occurs in fine sands within the Tombigbee Member but substantially below the boundary and is known only from central Alabama, situated geographically between the disjunct Tombigbee Sand and Blufftown populations of *H. saucierae*. Given the great similarity between these two species and their relative stratigraphic and geographic proximity, *H. saucierae* may be perceived as an immediate descendant of the older *H. bassleri*.

The genus *Hardouinia* is frequently encountered as multiple species wherever it occurs in the Central Gulf. A second species of *Hardouinia* co-occurs with *H. saucierae* and *H. bassleri* at most locations, but the additional species is different depending on geographic location and age (Figure 5). *Hardouinia clypeus* Cooke co-occurs with *H. bassleri* in central Alabama (Cooke 1955) and is considerably less abundant than the commoner *H. bassleri* at 2.5% of total echinoids collected (n = 448) in Montgomery (AL.51.001). Likewise, another new and very rare species of *Hardouinia* was collected with *H. saucierae* at Aberdeen (MS.48.004). The yet to be described species constitutes ~0.3% of total tests collected (n ≈ 1,000), which were otherwise composed entirely of *H. saucierae*. In the middle Blufftown Formation at Hatchechubbee (AL.57.001), *H. saucierae* is the rarer echinoid, constituting only ~7% of echinoids recovered (n ≈ 40). *Hardouinia micrococcus* (Gabb, sensu stricto), previously unreported outside of the Middle to Late Campanian Cussetta Sand (Cooke, 1953, "Ripley formation"), is the commoner species at this location and other Blufftown sites in the Hatchechubbee area. It would seem that wherever two species of *Hardouinia* co-occur in the Late Santonian-Early Campanian sands of the Central Gulf, one is by far the dominant species in terms of relative abundance.

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REFERENCES

Caron, M., 1985, Cretaceous planktic foraminifera, p. 17-86, *in* Bolli, H. M., Saunders, J. B., and Perch-Nielsen, K. (eds.): Plankton stratigraphy, New York, Cambridge University Press.

Cooke, C. W., 1953, American Upper Cretaceous Echinoidea: U. S. Geological Survey Professional Paper, v. 254, p. 1-44.

Cooke, C. W., 1955, Some Cretaceous echinoids from the Americas: U. S. Geological Survey Professional Paper, v. 264, p. 87-112.

Dowsett, H. J., 1989, Documentation of the Santonian-Campanian and Austinian-Tayloran stage boundaries in Mississippi and Alabama using calcareous microfossils: U. S. Geological Survey Bulletin, v. 1884, p. 1-20.

Gale, A. S., Montgomery, P., Kennedy, W. J., Hancock, J. M., Burnett, J. A., and McArthur, J. M., 1995, Definition of the global correlation of the Santonian-Campanian boundary: Terra Nova, v. 7, p. 611-622.

Gradstein, F.M., Ogg, J.G., Smith, A.G., Agterberg, F. P., Bleeker, W., Cooper, R.A., Davydov, V., Gibbard, P., Hinnov, L., House, M.R., Lourens, L., Luterbacher, H.-P., McArthur, J.M., Melchin, M.J., Robb, L.J., Shergold, J., Villeneuve, M., Wardlaw, B.R., Ali, J., Brinkhuis, H., Hilgen, F.J., Hooker, J., Howarth, R. J., Knoll, A.H., Laskar, J., Monechi, S., Powell, J., Plumb, K.A., Raffi, I., Röhl, U., Sanfilippo, A., Schmitz, B., Shackleton, N.J., Shields, G.A., Strauss, H., Van Dam, J., Veizer, J., van Kolfschoten, T., and Wilson, D., 2005, A Geologic Time Scale 2004, Cambridge University Press, New York, 589 p.

Hayes, W. E., 1951 [unpublished], The smaller fossils from the Upper Cretaceous of the Starkville area: Master's Thesis, Mississippi State University, Mississippi State, 147 p.

Kennedy, W.J., and Cobban, W.A., 1991, Upper Cretaceous (upper Santonian) *Boehmoceras* fauna from the Gulf Coast region of the United States: Geological Magazine, v. 128, p. 167-189.

Kennedy, W.J., Cobban, W.A., and Landman, N.H., 1997, Campanian ammonites from the Tombigbee Sand Member of the Eutaw Formation, the Mooreville Formation, and the basal part of the Demopolis Formation in Mississippi and Alabama: American Museum Novitates, v. 3201, p. 1-44.

Kier, P. M., 1962, Revision of the cassiduloid echinoids: Smithsonian Miscellaneous Collections, v. 144, p. 1-262.

King, D. T., Jr., and Skotnicki, M. C., 1994, Upper Cretaceous stratigraphy and sea-level history, Gulf Coastal Plain of central and eastern Alabama: Geological Society of America Special Paper, v. 287, p. 27-42.

Mancini, E. A., and Soens, D. D., 1994, Paleoenvironments of the Tombigbee Sand Member of the Eutaw Formation (Upper Cretaceous) of eastern Mississippi and western Alabama: Gulf Coast Association of Geological Societies Transactions, v. 44, p. 421-430.

Obradovich, J. D., 1993. A Cretaceous time scale, p. 379-396, *in* Caldwell, G. E., and Kauffman, E. G. (eds.): Evolution of the Western Interior Basin, Geological Association of Canada, St. John's, Newfoundland.

Puckett, T. M., 1996, Ecologic atlas of Upper Cretaceous ostracodes of Alabama: Geological Survey of Alabama Monograph, v. 14, p. 1-176.

Puckett, T. M., 2005, Santonian-Maastrichtian planktonic foraminiferal and ostracode biostratigraphy of the northern Gulf Coastal Plain, USA: Stratigraphy, v. 2, p. 117-146.

Rosen, R.N., 1985, Foraminiferal stratigraphy and paleoecology of the Blufftown Formation (Santonian-Campanian) of Georgia and eastern Alabama: Gulf Coast Association of Geological Societies Transactions, v. 35, p. 485-492.

Russell, E. E., and Keady, D. M., 1983, Notes on Upper Cretaceous lithostratigraphy of the Eastern Mississippi Embayment, p. 1-15, *in* Russell, E. E., Keady, D. M., Mancini, E. A., and Smith, C. C. (eds.): Upper Cretaceous lithostratigraphy and biostratigraphy in northeast Mississippi, southwest Tennessee and northwest Alabama, shelf calks and coastal clastics: Tuscaloosa, Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists.

Sissingh, W., 1977, Biostratigraphy of Cretaceous calcareous nannoplankton: Geologie en Mijnbouw, v. 56, p. 37-65.

Skotnicki, M. C., and King, D. T., Jr., 1986, Depositional facies and sea-level dynamics of the Blufftown Formation, lower Campanian of east Alabama: Southeastern Geology, v. 27, p. 53-67.

Smith, A. B., and Jeffery, C. H., 2000, Maastrichtian and Palaeocene echinoids: A key to world faunas: Special Papers in Palaeontology, v. 63, p. 1-406.

Smith, A. B., and Wright, C. W., 2000, Neognathostomata (cassiduloids), p. 391-439 (and pls. 130-138), *in* Rushton, A. W. A., and Thomas, A. T. (eds.): British Cretaceous echinoids, Part 6, Palaeontographical Society, London.

Sohl, N. F., and Smith, C. C., 1980, Upper Cretaceous and lower Tertiary geology of the Chattahoochee River Valley, western Georgia and eastern Alabama—Notes on Cretaceous biostratigraphy, p. 392-402, *in* Frey, R. W., and Neathery, T. L. (eds.): Excursions in southeastern geology, American Geological Institute, Falls Church, Virginia.

Stephenson, L. W., and Monroe, W. H., 1940, The Upper Cretaceous deposits: Mississippi Geological Survey Bulletin, v. 40, p. 1-296.

Torries, T. F., 1964, Geology of the northeast quarter of the West Point, Mississippi quadrangle, and related bentonites: Mississippi Geological Survey Bulletin, v. 102, p. 62-98.