

Archived version from NCDOCKS Institutional Repository <http://libres.uncg.edu/ir/asu/>



Southeastern Geology: Volume 45, No. 2 November 2007

Editor in Chief: S. Duncan Heron, Jr.

Abstract

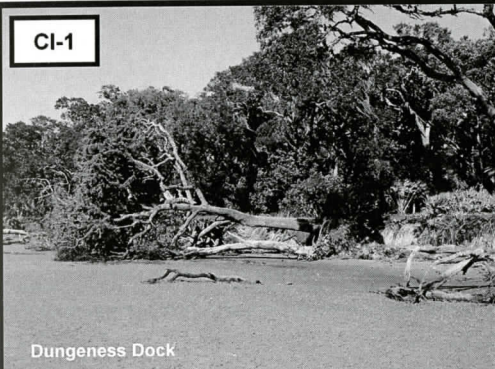
Academic journal published quarterly by the Department of Geology, Duke University.

Heron, Jr., S. (2007). Southeastern Geology, Vol. 45 No. 2, November 2007. Permission to re-print granted by Duncan Heron via Steve Hageman, Professor of Geology, Dept. of Geological & Environmental Sciences, Appalachian State University.

SOUTHEASTERN GEOLOGY



CI-1



Dungeness Dock

CI-3



Plum Orchard

CI-5



Candler Dock

CI-6



Cumberland Wharf

Vol. 45, No. 2

November 2007

SOUTHEASTERN GEOLOGY

PUBLISHED

at

DUKE UNIVERSITY

Duncan Heron

Editor in Chief

David M. Bush

Editor

This journal publishes the results of original research on all phases of geology, geophysics, geochemistry and environmental geology as related to the Southeast. Send manuscripts to **David Bush, Department of Geosciences, University of West Georgia, Carrollton, Georgia 30118, for Fed-X, etc. 1601 Maple St.,** Phone: 678-839-4057, Fax: 678-839-4071, Email: dbush@westga.edu. Please observe the following:

- 1) Type the manuscript with double space lines and submit in duplicate, or submit as an Acrobat file attached to an email.
- 2) Cite references and prepare bibliographic lists in accordance with the method found within the pages of this journal. Data citations examples can be found at <http://www.geoinfo.org/TFGeosciData.htm>
- 3) Submit line drawings and complex tables reduced to final publication size (no bigger than 8 x 5 3/8 inches).
- 4) Make certain that all photographs are sharp, clear, and of good contrast.
- 5) Stratigraphic terminology should abide by the North American Stratigraphic Code (American Association Petroleum Geologists Bulletin, v. 67, p. 841-875).
- 6) Email Acrobat (pdf) submissions are encouraged.

Subscriptions to *Southeastern Geology* for volume 45 are: individuals - \$24.00 (paid by personal check); corporations and libraries - \$36.00; foreign \$48. Inquires should be sent to: **SOUTHEASTERN GEOLOGY, DUKE UNIVERSITY, DIVISION OF EARTH & OCEAN SCIENCES, BOX 90233, DURHAM, NORTH CAROLINA 27708-0233.** Make checks payable to: *Southeastern Geology*.

Information about **SOUTHEASTERN GEOLOGY** is on the World Wide Web including a searchable author-title index 1958-2005 (Acrobat format). The URL for the Web site is: <http://www.southeasterngeology.org>

SOUTHEASTERN GEOLOGY is a peer review journal.

ISSN 0038-3678

SOUTHEASTERN GEOLOGY

Table of Contents

Volume 45, No. 2 November 2007

1. **THE IMPORTANCE OF CARBON LOSS THROUGH WETLAND
EROSION IN THE ALBEMARLE-PAMLICO-CURRITUCK SOUND
SYSTEM, NORTH CAROLINA**
 ROBERT S. YOUNG 51

2. **A LATE CAMPANIAN (CRETACEOUS) SELACHIAN ASSEMBLAGE
FROM A CLASSIC LOCALITY IN FLORENCE COUNTY, SOUTH
CAROLINA**
 DAVID J. CICIMURRI 59

3. **BACK-BARRIER SHORELINE CHANGE HISTORY: CUMBERLAND
ISLAND, GEORGIA, 1857-2002**
 CHESTER W. JACKSON, JR., CLARK ALEXANDER AND DAVID M. BUSH 73

4. **SUBAQUEOUS KARSTIFICATION OF THE TOP OF THE CLAYTON
FORMATION LIMESTONE (LOWER PALEOCENE) NEAR FT.
GAINES, GEORGIA (USA)**
 CARL R. FROEDE JR AND JOHN K. REED 87

Serials Department
Appalachian State Univ. Library
Boone, NC

THE IMPORTANCE OF CARBON LOSS THROUGH WETLAND EROSION IN THE ALBEMARLE-PAMLICO-CURRITUCK SOUND SYSTEM, NORTH CAROLINA

ROBERT S. YOUNG

*Western Carolina University
Program for the Study of Developed Shorelines
Cullowhee, North Carolina, 28723
email: ryoung@wcu.edu*

ABSTRACT

Much effort has been directed at understanding the rate of carbon accumulation, cycling, and long-term storage in wetlands. Studies have ranged from site-specific determinations of soil organic matter accumulation rates to region-wide accumulation rates, and ultimately to global assessments of the total carbon mass stored in wetland soils during the Holocene. Much recent interest has focused on changes in wetland carbon reservoirs during historical times—primarily human induced. The importance of wetland shoreline erosion and drowning as factor in the carbon budget of coastal wetlands is yet to be adequately quantified. This study incorporates new carbon accumulation data from two estuarine marsh sites with additional carbon data collected from the literature to estimate the annual, erosion-induced flux of carbon from wetlands in the Albemarle-Pamlico-Currituck Sound system in eastern North Carolina.

The annual loss of carbon through shoreline erosion (9.3×10^{10} g yr⁻¹) is roughly equal to that accumulating at the surface of estuarine wetlands in the Albemarle-Pamlico-Currituck Sound system (7.2×10^{10} g yr⁻¹). If sea-level rise rates, and thus erosion rates, increase over the next century as predicted, wetland carbon loss through erosion will overwhelm accumulation in estuarine wetlands. It is likely that estuarine wetland systems are already shrinking in response to rising sea levels.

Accounting for sources of organic carbon is crucial to the understanding of the functional aspects of an estuary. It is appar-

ent that the erosion of estuarine wetlands is a substantial source of carbon to the Albemarle-Pamlico-Currituck Sound system. As most shoreline erosion is event driven, the export of carbon from the marsh sediments to the estuary probably occurs in large pulses, most likely seasonally. Future efforts assessing the relative importance of allochthonous and autochthonous sources of carbon in estuaries with eroding wetland shorelines should consider this process in attempt to understand the fate of carbon exported in such pulses.

INTRODUCTION

Much effort has been directed at understanding carbon accumulation, cycling, and long-term storage in wetlands. Studies have ranged from site-specific determinations of soil organic matter accumulation (e.g. Craft et al., 1993) to region-wide accumulation (e.g. Botch et al., 1995), and ultimately, global assessments of the total carbon mass stored in wetland soils during the Holocene (Moore and Bellamy, 1974). Much recent interest has focused on changes in wetland carbon reservoirs during historical times — primarily human induced. Armentano and Menges (1986) estimated changes in carbon flux and loss of carbon storage capacity for temperate zone organic soils due to wetland drainage and similar disturbances. They found that the wetlands in some regions of the world (e.g. central Europe) are presently carbon sources rather than sinks due to agricultural drainage, forestry operations, and peat burning.

Similar studies have focused on changes in carbon flux and carbon reservoirs on the lower coastal plain of North Carolina. Richardson

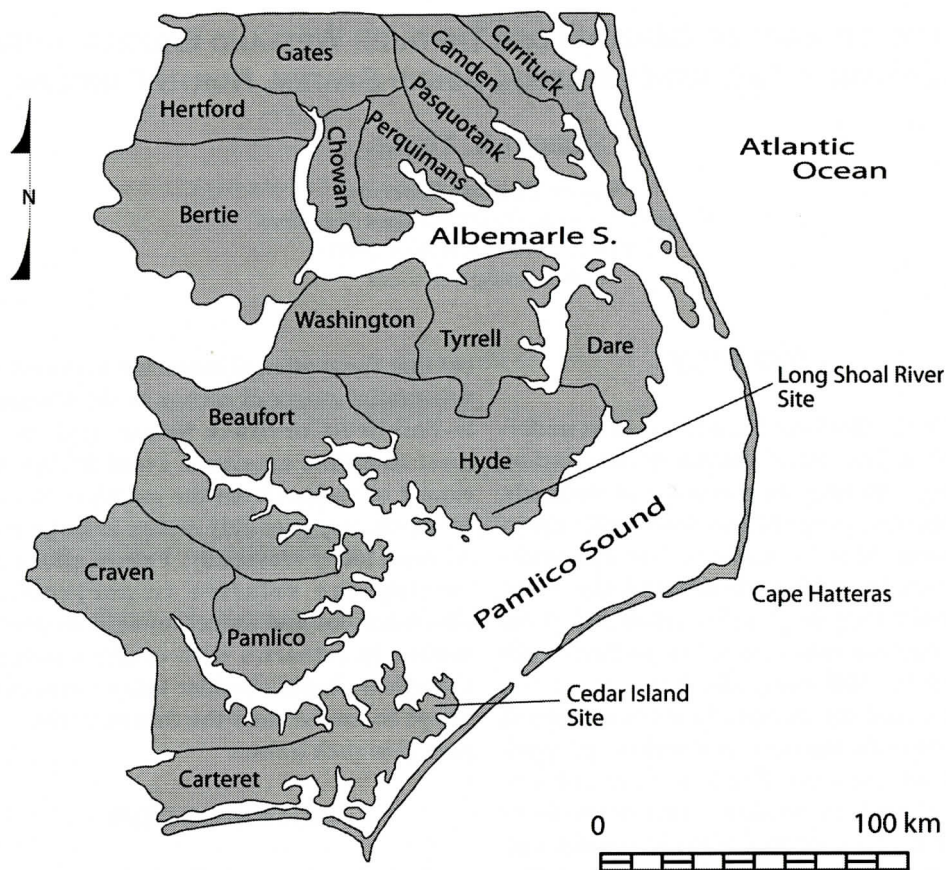


Figure 1. Counties included in the study and location of the two sites providing new carbon data.

(1981a) estimated that drainage of pocosin wetlands for forestry and agriculture, and subsequent oxidation of the organic sediment, resulted in a release of 7×10^{12} g C yr⁻¹. This is due to a loss 299,467 ha of pocosin, 33% of that originally mapped by Wilson (1962). Various impacts of wetland development and alteration on the North Carolina coastal plain have also been discussed by Stockton and Richardson (1987), Cashin et al. (1992), and Richardson and McCarthy (1994).

Yet to be adequately quantified is the importance of wetland shoreline erosion and drowning as factor in the carbon budget of coastal wetlands. This study incorporates new carbon accumulation data from two estuarine marsh sites with additional carbon data collected from the literature to estimate the annual, erosion-induced flux of carbon from wetlands in the Albe-

marle-Pamlico-Currituck Sound system in eastern North Carolina. With many investigators predicting increasing rates of coastal erosion well into the foreseeable future (e.g. Barth and Titus, 1984; Titus, 1988), it is critical that the loss of carbon through wetland shoreline retreat be factored into any consideration of the overall wetland carbon budget.

STUDY AREA

The palustrine and estuarine wetlands in 16 coastal counties bordering the North Carolina sounds were considered in this study (Fig. 1). The Albemarle-Pamlico-Currituck Sound system has negligible astronomical tides. Water-level fluctuations are a result of wind-driven circulation (Pietrafesa et al., 1986). Wells and Kim (1989) describe the sediment dynamics of

CARBON LOSS THROUGH WETLAND EROSION

Table 1. Data used to estimate annual carbon accumulation rates and carbon content of wetland soils in the study area.

Source	Bulk density (g cm ⁻³)	Organic carbon (%)	Sediment accretion (mm yr ⁻¹)	Carbon accum. rate (g ha yr ⁻¹)
Estuarine wetlands				
This study, Cedar Island site	.13 (top)	31.4 (top)	assume 1.65 from Brinson et al. (1991)	0.67 ∞ 106
	.41 (avg.)	24.2 (avg.)		
This study, Long Shoal River site	.11 (top)	32.3 (top)	assume 3.75 from Craft et al. (1993)	1.33 ∞ 106
	.32 (avg.)	25.6 (avg.)		
Brinson et al. (1991)	.12 (top)	29.71 (top)	1.3 - 2.0	0.36 ∞ 106 -
	.38 (avg.)	18.01 (avg.)		0.71 ∞ 106
Craft et al. (1993)	.13 - .16 (top)	22 - 40 (top)	2.1 - 5.4	1.06 ∞ 106 -
				1.45 ∞ 106
Benninger and Chanton (1985)	-----	-----	2.0 - 4.0	-----
Palustrine Wetlands				
Richardson (1981a)	.45	38	assume 1.0 - 1.5	1.71 ∞ 106 - 2.56 ∞ 106
Oaks and Whitehead (1979)	-----	-----	.4 (long-term average)	-----

the sounds. Marshes fringing the estuary are non-tidal and irregularly flooded. They lack tidal channels and only occasionally have a narrow apron of low marsh. A detailed discussion of the ecology and hydrology of these wetlands is found in Brinson (1991). A similar accounting for the counties' palustrine wetlands (primarily pocosin) is given in Richardson (1981b).

METHODS

This analysis includes new carbon accumulation rate and storage data for two estuarine wetland sites on Pamlico Sound (Fig. 1), as well as a survey of relevant numbers for carbon accumulation from the literature. Three vibracores each from the Cedar Island site and the Long Shoal River site were analyzed for this study. Average thickness of the organic sediments at both sites was 0.9 - 1.2 m. Bulk densities for the entire peat section were determined at 10 cm intervals using methods described by Lewis and McConchie (1994). Total organic carbon was measured at 5 cm intervals using a Carlo Erba

Strumentazione NA 1500 nitrogen/carbon/sulfur analyzer. Accretion rates were estimated using existing data from nearby marshes.

Table 1 lists the data used in estimating carbon accumulation and erosion loss for the wetlands in the North Carolina sounds. For both the new data, and the data culled from the literature, an effort was made to report organic sediment characteristics at the surface (~ 0 - 30 cm) for calculating carbon accumulation rates and average values for the entire peat layer for calculating average mass densities of carbon in the wetland sediments.

Moorhead (1992) digitized National Wetland Inventory maps to quantify the area of wetland in 20 counties in eastern North Carolina by habitat type (Cowardin et al., 1979). The 16 counties included in this study, divided into regions by Moorhead (1992), are shown in Table 2. Wetland area is reported in Table 3.

The estuarine shoreline length for Albemarle, Pamlico, and Currituck Sounds was estimated using a digital planimeter and USGS 15 minute quadrangles (Table 4). Features smaller

Table 2. Counties included in this study, by region, as divided by Moorhead (1992). Only those counties bordering Albemarle, Pamlico, and Currituck Sounds were included.

Northern counties	Central counties	Southern counties
Bertie	Dare	Beaufort
Camden	Hyde	Carteret
Chowan	Tyrrell	Craven
Currituck	Washington	Pamlico
Gates		
Hertford		
Pasquotank		
Perquimans		

Table 3. Wetland area for the sixteen counties bordering Albemarle, Pamlico, and Currituck Sounds in eastern North Carolina taken from Moorhead (1992). Totals do not include the *partly drained* or *other* categories of wetland, about 10% of the total. Counties included in the study are shown in Figure 1.

Location	Palustrine (ha)	Estuarine (ha)	Total (ha)
Northern counties	146,083	12,144	158,227
Central counties	202,214	35,505	237,719
Southern counties	168,254	41,388	209,642
Total all counties	516,551	89,037	605,588

Table 4. Estimated length of the mainland, estuarine shoreline of Albemarle, Pamlico, and Currituck Sounds: eastern North Carolina.

Trial No.	Distance (km)
1	1586.0
2	1528.2
3	1595.8
4	1735.7
5	1675.0
6	1590.0
7	1628.3
8	1586.0
9	1711.6
10	1612.3
Average	1625 ± 61

than 2-3 km were averaged over in order to keep the number reasonable. Shoreline erosion rates for the mainland shoreline of the sounds were also taken from the literature (Table 5).

RESULTS

Data used in calculating an annual flux of

Table 5. Erosion rates for the North Carolina sounds.

Source	Erosion rates
United States Soil Conservation Service (1975)	.27 - 1.37 m/yr. along the Ser-line of Albemarle and Pamlico Sounds
Phillips (1986)	.91 m/yr average for the entire shoreline
Brinson (1991)	.46 m/yr at Cedar Island, NC for year 1 .27 m/yr at Cedar Island, NC for year 2

carbon into palustrine and estuarine wetlands, average mass density of carbon in estuarine wetlands, and carbon loss through shoreline erosion are presented in Table 6. An effort was made throughout this study to produce a conservative number for wetland carbon loss through erosion. With this in mind, the following assumptions/choices have been made:

- 1) Average values for bulk density and percent carbon were used where possible.
- 2) 75% of the eroding shoreline is assumed to be wetland. Moorhead and Brinson (1995) report that 92 - 93% of the shoreline is wetland

CARBON LOSS THROUGH WETLAND EROSION

Table 6. Estimated and averaged values used for developing carbon budget.

Carbon accumulation in estuarine wetlands	Bulk density .13 g cm ⁻³	Carbon 31 %	Sediment accretion 2.0 mm yr ⁻¹	Calculated accum. rate 8.1 ∞ 105 g ha ⁻¹ yr ⁻¹
Carbon accumulation in palustrine wetlands	Bulk density .45 g cm ⁻³	Carbon 38 %	Sediment accretion 1.5 mm yr ⁻¹	Calculated accum. rate 2.6 ∞ 106 g ha ⁻¹ yr ⁻¹
Carbon density in estuarine wetland sediments	Average bulk density .37 g cm ⁻³	Average % carbon 22.6 %	Calculated average C density 8.4 ∞ 104 g m ⁻³	
Miscellaneous Values	Erosion rate .91 m yr ⁻¹	Wetland shoreline length 1219 km	Depth of eroded sediment 1 m	

Table 7. Calculated values for annual carbon storage and carbon loss through erosion in the palustrine and estuarine wetlands of Albemarle, Pamlico, and Currituck Sounds.

Annual rate of carbon accumulation	Estuarine wetlands 7.2 ∞ 1010 g yr ⁻¹	Palustrine wetlands 1.3 ∞ 1012 g yr ⁻¹	All wetlands in study 1.4 ∞ 1012 g yr ⁻¹
Annual carbon loss through shoreline erosion	Loss of carbon per linear meter of shoreline 7.6 ∞ 104 g yr ⁻¹	Total annual loss of carbon from wetlands through erosion 9.3 ∞ 1010 g yr ⁻¹	

with the exception of the upper reaches of the sounds and tributaries where the number decreases to 51%.

3) Estuarine wetlands are being eroded, palustrine wetlands are not. While this is certainly not the case in some instances, this assumption will give a lower estimate for erosion-induced carbon loss because the mass density of carbon is much greater in palustrine wetlands (Richardson, 1981a) than estuarine.

4) An average erosion rate of 0.91 m yr⁻¹ was chosen for the study area from Table 5. While erosion rates as high as 6 m yr⁻¹ have been reported (Bellis et al., 1975), the number reported by Phillips (1986) seems reasonable as it is an averaged value for the entire shoreline.

5) In the sounds of North Carolina, estuarine, wetland margins recede primarily by erosion

rather than by drowning (Moorhead and Brinson, 1995). One meter of organic sediment is eroded as the shoreline retreats (Brinson et al., 1991).

Final results of all calculations are presented in Table 7. The annual rate of carbon loss per linear meter of shoreline was calculated by multiplying the average mass density of carbon in estuarine wetland sediments by the average erosion rate. The result was multiplied by the estimated length of wetland shoreline in the sounds to produce the number for the total annual loss of carbon from wetlands through erosion. Annual rates of total carbon accumulation were calculated by extrapolating the estimated value for carbon accumulation for each wetland type over the total area from Table 3.

DISCUSSION AND CONCLUSIONS

The annual loss of carbon through shoreline erosion is roughly equal to that accumulating at the surface of estuarine wetlands in the Albemarle-Pamlico-Currituck Sound system (Fig. 2). Carbon export due to erosion is only 7% of total annual accumulation when the inland palustrine wetlands are included. If sea-level rise rates, and thus erosion rates, increase over the next century as predicted (Pilkey and Thielker, 1992), wetland carbon loss through erosion will overwhelm accumulation in estuarine wetlands and become an even larger percentage of the total carbon accumulation in lower coastal plain wetland systems. It is likely that estuarine wetland systems are already shrinking in response to rising sea levels. Young (1995) found rates of new marsh formation on the landward boundary of two estuarine wetlands to be $0.27 - 0.32 \text{ m yr}^{-1}$ compared to the average erosion rate of 0.91 m yr^{-1} (Phillips, 1986). In addition, much of the small amount of new estuarine wetland being created on the landward margin as sea level rises is through conversion of pocosin wetland. Pocosin wetlands have an annual carbon accumulation rate that is twice that of estuarine wetlands (Table 6); thus, overall accumulation potential decreases. Finally, palustrine wetland acreage has decreased at very high rates over the last half century through human alteration (Richardson, 1981a; Cashin et al., 1992). While these trends have slowed dramatically, it is likely that palustrine wetlands will continue to shrink rather than grow as sea level rises. Human alteration continues at a slower pace and there is simply no room for the natural expansion of these systems on an increasingly developed coastal plain. All of these factors combine to suggest that wetland carbon loss through shoreline erosion will become an increasingly larger percentage of the total carbon budget for lower coastal plain wetland systems in North Carolina.

One final note, accounting for sources of organic carbon is crucial to the understanding of the functional aspects of an estuary (Copeland et al., 1984). It is apparent that the erosion of es-

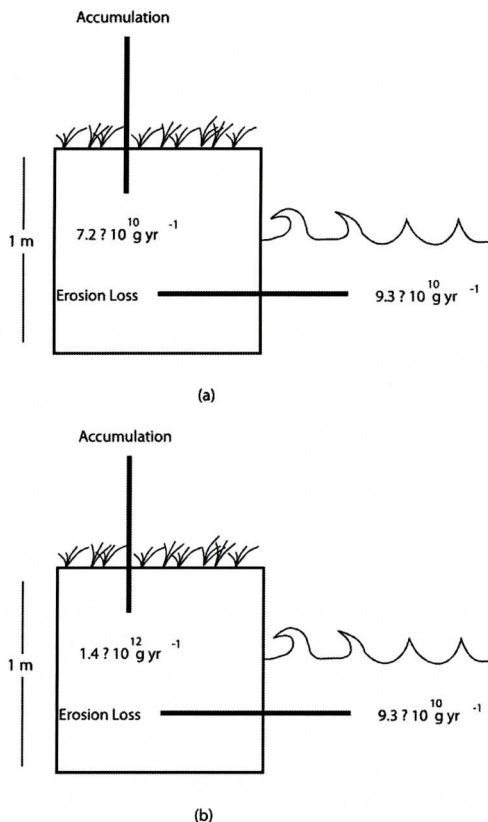


Figure 2. (a) Schematic of carbon loss through erosion compared to accumulation in estuarine wetlands in the Albemarle-Pamlico-Currituck Sound system. The two numbers are essentially in balance. (b) Schematic of carbon loss through erosion compared to accumulation in all wetlands in the 16 counties bordering the Albemarle-Pamlico-Currituck Sound system. Loss through erosion represent 7% of the total accumulation.

tuarine wetlands is a substantial source of carbon to the Albemarle-Pamlico-Currituck Sound system. As most shoreline erosion is event driven, the export of carbon from the marsh sediments to the estuary probably occurs in large pulses, most likely seasonally. Future efforts assessing the relative importance of allochthonous and autochthonous sources of carbon in estuaries with eroding wetland shorelines should consider this process in attempt to understand the fate of carbon exported in such

CARBON LOSS THROUGH WETLAND EROSION

pulses.

ACKNOWLEDGMENTS

This work was supported by the National Biological Survey cooperative agreement number 14-16-0009-91-961 and project manager Donald R. Cahoon. Leigh Anne (Milligan) Young provided help with data processing. Field assistance was provided by a large number of dedicated students in the Duke University Division of Earth and Ocean Sciences. W.H. Schlesinger provided thoughtful input.

REFERENCES

- Armentano, T. V., and Menges, E. S., 1986, Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone: *Journal of Ecology*, v. 74, p. 755-774.
- Barth, M. C., and Titus, J. G., eds., 1984, *Greenhouse Effect and Sea Level Rise*: New York, Van Nostrand Reinhold, p. 325.
- Bellis, V., O'Connor, M. P., and Riggs, S. R., 1975, Estuarine shoreline erosion in the Albemarle-Pamlico region of North Carolina: University of North Carolina Sea Grant Program, 67 p.
- Benninger, L. K., and Chanton, J. P., 1985, Fallout ²³⁹Pu and natural ²³⁸U and ²¹⁰Pb in sediments of the North River Marsh, North Carolina: *EOS*, v. 66, p. 276.
- Botch, M. S., Kobak, K. I., Vinson, T. S., and Kolchugina, T. P., 1995, Carbon pools and accumulation in peatlands of the former Soviet Union: *Global Biogeochemical Cycles*, v. 9, p. 37-46.
- Brinson, M. M., ed., 1991, *Ecology of a nontidal brackish marsh in coastal North Carolina*: U.S. Fish and Wildlife Service, National Wetlands Research Center Open-File Report 91-03, 398 p.
- Brinson, M. M., Bryant, W. L., Jones, M. N., and Benninger, L. K., 1991, Composition, distribution, and dynamics of organic sediments, in Brinson, M. M., ed., *Ecology of a nontidal brackish marsh in coastal North Carolina*: U.S. Fish and Wildlife Service, National Wetlands Research Center Open-File Report 91-03, p. 23-46.
- Cashin, G. E., Dorney, J. R., and Richardson, C. J., 1992, Wetland alteration trends on the North Carolina coastal plain: *Wetlands*, v. 12, p. 63-71.
- Copeland, B. J., Hodson, R. G., and Riggs, S. R., 1984, The ecology of the Pamlico River, North Carolina: an estuarine profile: U.S. Fish and Wildlife Service, v. 82, p. 1-83.
- Cowardin, L. M., Carter, V., Golet, F. C., and LaRoe, E. T., 1979, Classification of wetlands and deepwater habitats of the United States: U.S. Fish and Wildlife Service, Biological Services Program, 131 p.
- Craft, C. B., Seneca, E. D., and Broome, S. W., 1993, Vertical accretion in microtidal regularly and irregularly flooded estuarine marshes: *Estuarine, Coastal, and Shelf Science*, v. 37, p. 371-386.
- Lewis, D. W., and McConchie, D., 1994, *Analytical sedimentology*: New York, Chapman and Hall, 197 p.
- Moorhead, K. K., 1992, Wetland resources of coastal North Carolina: *Wetlands*, v. 12, p. 184-191.
- Moore, P. D., and Bellamy, D. J., 1974, *Peatlands*: London, Elek Science, 221p.
- Moorhead, K. K., and Brinson, M. M., 1995, Response of wetlands to rising sea level in the lower coastal plain of North Carolina: *Ecological Applications*, v. 5, p. 261-271.
- Oaks, R. Q., and Whitehead, D. R., 1979, Geologic setting and origin of the Dismal Swamp, southeastern Virginia and northeastern North Carolina, in Kirk, P. W., ed., *The Great Dismal Swamp*: Charlottesville, Virginia, University of Virginia Press, p. 1-24.
- Phillips, J. D., 1986, Coastal submergence and marsh fringe erosion: *Journal of Coastal Research*, v. 2, p. 427-436.
- Pietrafesa, L. J., Janowitz, G. S., Chao Tieh-Ying, Wiesberg, R. H., Askari, F., and Noble, E., 1986, *The physical oceanography of Pamlico Sound*: University of North Carolina Sea Grant College Publication, Working Paper 86-5, 125p.
- Pilkey, O. H., and Thieler, E. R., 1992, Erosion of the United States shoreline, in Fletcher, C. H., and Wehmler, J. F., eds., *Quaternary coasts of the United States: marine and lacustrine systems*, Special Publication No. 48: Tulsa, SEPM, p. 3-8.
- Richardson, C. J., 1981a, Pocosins: ecosystem processes and the influence of man on system response, in Richardson, C. J., ed., *Pocosin wetlands: an integrated analysis of coastal plain freshwater bogs in North Carolina*: Stroudsburg, Pennsylvania, Hutchinson Ross, p. 135-154.
- Richardson, C. J., 1981b, Pocosin wetlands: an integrated analysis of coastal plain freshwater bogs in North Carolina: Stroudsburg, Pennsylvania, Hutchinson Ross, 364 p.
- Richardson, C. J., 1991, Pocosins: an ecological perspective: *Wetlands*, v. 11, p. 335-354.
- Richardson, C. J., and McCarthy, E. J., 1994, Effect of land development and forest management on hydrologic response in southeastern coastal wetlands: a review: *Wetlands*, v. 1, p. 56-70.
- Stockton, M. B., and Richardson, C. J., 1987, Wetland development trends in coastal North Carolina, USA, from 1970 to 1984: *Environmental Management*, v. 11, p. 649-657.
- Titus, J. G., ed., 1988, *Greenhouse effect, sea level rise and coastal wetlands*: Washington, D.C., U.S. Environmental Protection Agency, 152 p.
- Wells, J. T., and Kim Seok-Yun, 1989, Sedimentation in the Albemarle-Pamlico lagoonal system: synthesis and hypotheses: *Marine Geology*, v. 88, p. 263-284.
- Wilson, K. A., 1962, North Carolina wetlands: their distribution and management: North Carolina Wildlife

ROBERT S. YOUNG

Resources Commission, 169p.

Young, R.S., 1995, Coastal wetland dynamics in response to sea-level rise: Duke University Doctoral Dissertation, 182p.

A LATE CAMPANIAN (CRETACEOUS) SELACHIAN ASSEMBLAGE FROM A CLASSIC LOCALITY IN FLORENCE COUNTY, SOUTH CAROLINA

DAVID J. CICIMURRI

*Bob Campbell Geology Museum
103 Garden Trail
Clemson University, Clemson, SC 29634
dccheech@clemson.edu*

ABSTRACT

A highly fossiliferous bed within the Campanian Donoho Creek Formation at Burches Ferry, Florence County, South Carolina, yielded a diverse vertebrate assemblage consisting predominantly of elasmobranchs. Twenty-two shark and ray species have been recovered, including *Hybodus* sp., *Lonchidion babulskii*, *Squatina hassei*, *Heterodontus* aff. *granti*, *Cantioscyllium meyeri*, *Chiloscyllium* sp., *Pararhincodon* sp., *Squalicorax kaupi*, *S. pristodontus*, *Archaeolamna kopingensis*, *Cretalamna appendiculata*, *Cretodus borodini*, *Carcharias holmdelensis*, *C. samhammeri*, *Rhinobatos casieri*, *Pseudohypolophus mcultyi*, *Rhombodus levis*, *Brachyrhizodus wichitaensis*, *Borodinopristschimmeri*, *Ischyrrhiza avoncola*, *I. mira*, and *Ptychotrygon vermiculata*. Most of these species can be considered ubiquitous in Campanian marine strata of the Atlantic and Gulf coastal plains, but *Heterodontus*, *Cantioscyllium*, *Chiloscyllium*, *Pararhincodon*, and *Borodinoprists* are poorly known from these regions. The fossils collected (i.e. types, preservation) indicate that there is a diverse mixture of animals that inhabited different parts of a delta system, including terrestrial environments.

INTRODUCTION

For nearly 100 years the exposures of Cretaceous strata along the Pee Dee River at Burches Ferry, Florence County, South Carolina (Fig. 1), have been discussed in the literature. Burches Ferry is the type section of the Peedee Formation (Stephenson, 1923), a unit originally

termed the Burches Ferry Marls by Sloan (1908). The locality is also significant because it is the origin of the Peedee Belemnite from which the carbon isotope standard is based. Previous reports on the Burches Ferry exposures have discussed the nature of the contact between the Peedee Formation and underlying Donoho Creek Formation, and it is now recognized that a significant unconformity separates the two units (Stephenson, 1912; Benson, 1969; Van Nieuwenhuise and Kanen, 1969; Woollen and Colquhoun, 1977; Parr and Lawrence, 1985; Sohl and Owens, 1991; Self-Trail et al., 2002).

Despite the numerous lithological and micro-invertebrate studies of the Donoho Creek and Peedee formations at Burches Ferry, relatively little is known regarding the vertebrate occurrences from either unit. Lawrence and Hall (1987) provided a short listing of fish and aquatic reptiles, but their sampling strategy only focused on the basal 7.5 cm of the Peedee Formation and they did not screen wash matrix. Based on the current study, Lawrence and Hall (1987) correctly concluded that the basal Peedee Formation consists of a lag deposit that includes fossils reworked from the Donoho Creek Formation, as well as material accumulated during deposition of the Peedee Formation. The purpose of the present report is to document a diverse selachian assemblage that was recovered from the Donoho Creek Formation, approximately 2.1 m below the contact with the Peedee Formation (Fig. 2). The assemblage is important because it provides a better understanding of the paleogeographic distributions of the associated taxa, some of which are only known from one or two occurrences elsewhere in the United States (see discussion below).

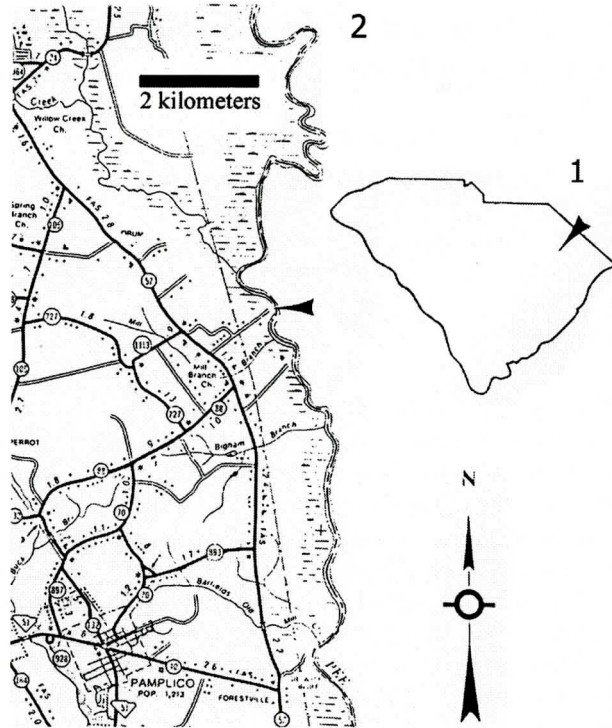


Figure 1. 1) outline of South Carolina and 2) a more detailed map showing the Pee Dee River valley near Pamplico, Florence County. Arrows in A and B indicate the Burches Ferry locality. Modified from Lawrence and Hall (1987).

DONOHO CREEK FORMATION AT BURCHES FERRY

At the Burches Ferry site, the exposed thickness of the Donoho Creek Formation varies depending on the level of the Pee Dee River, and during the 2002 field season the uppermost 3.6 m of the formation was visible. Self-Trail et al. (2002) were able to analyze 7.2 m of Donoho Creek sediments in core FLO-311 (34°03'51" N lat., 79°31'45" W long.). A major unconformity separates the Donoho Creek Formation from the overlying Peedee Formation, and only 4.9 m of the Peedee is preserved. The uppermost 1.7 m of the exposure consists of fluvial deposits from the Pee Dee River.

The Donoho Creek Formation, part of the Black Creek Group, was named by Sohl and Owens (1991) for strata along the Cape Fear River in Bladen County, North Carolina. Gohn (1992) later extended the unit into South Carolina, and the formation is now recognized (often

only in subsurface) throughout the northern

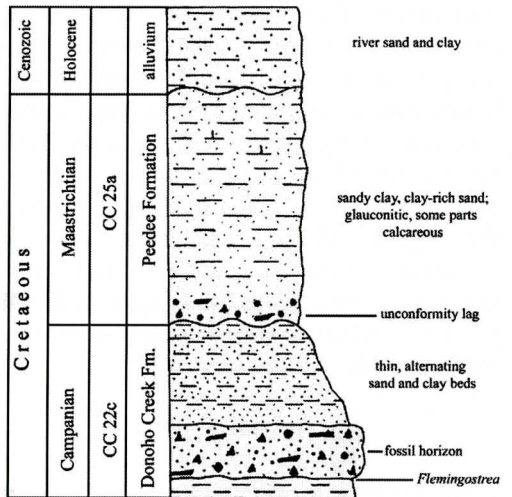


Figure 2. Stratigraphic section of Cretaceous units as exposed at Burches Ferry in August 2002. Thickness of the fossiliferous horizon as shown measures one meter. CC 22c and CC 25a are calcareous nannofossil zones.

SELACHIAN ASSEMBLAGE — FLORENCE COUNTY, SOUTH CAROLINA

Table 1. Taxonomic listing and total numbers of specimens recovered from the Donoho Creek Formation at Burches Ferry.

TAXON	# OF SPECIMENS
Chondrichthyes	
<i>Hybodus</i> sp.	37
<i>Lonchidion babulskii</i>	105
<i>Squatina hassei</i>	26
<i>Heterodontus</i> aff. <i>granti</i>	1
<i>Cantioscyllium meyeri</i>	7
<i>Chiloscyllium</i> sp.	5
<i>Pararhincodon</i> sp.	4
<i>Squalicorax kaupi</i>	389
<i>S. pristodontus</i>	6
<i>Archaeolamna kopingensis</i>	8
<i>Cretalamna appendiculata</i>	7
<i>Cretodus borodini</i>	9
<i>Carcharias holmdelensis</i>	320
<i>C. samhammeri</i>	51
<i>Rhinobatos casieri</i>	1
<i>Pseudohypolophus mcultyi</i>	326
<i>Rhombodus levis</i>	90
<i>Brachyrhizodus wichitaensis</i>	12
<i>Borodinopristsis schwimmeri</i>	1
<i>Ischyrhiza avonicola</i>	25 (+ 36 rostral spines)
<i>I. mira</i>	147 (+ 19 rostral spines)
<i>Ptychotrygon vermiculata</i>	782
Osteichthyes	
<i>Enchodus petrosus</i>	595 (+ 29 jaw fragments)
<i>Paralbula casei</i>	354
<i>Albula</i> sp.	5
<i>Anomoedus phaseolus</i>	4
" <i>Stephanodus</i> " sp.	56
cf. <i>Pachyrhizodus</i> sp.	2
Ichthyodectidae	1
Saurodontidae	7
Lepisosteidae	9 (+ 3 scales)
Reptilia	
Trionychidae indet.	2 (shell fragments)
other chelonoids	53 (shell fragments)
Crocodylia	159 (+ 12 osteoderm frags.)
Hadrosauridae	1
	Total = 3,614 teeth and rostral spines

South Carolina coastal plain. The Donoho Creek Formation generally consists of alternating beds of silty clays, fine sands, and clay-rich silts (Edwards et al., 2000), and a similar series is preserved in the uppermost 2 m of the Donoho Creek at Burches Ferry (Fig. 2). Located below this sequence is a 1 m thick bed of massive, highly fossiliferous, clay-rich, micaceous, predominantly fine-grained sand. This bed is the source of the fossils discussed in this report, and there are also occasional larger (more than 5 mm in greatest dimension) quartz and phosphatic clasts. Quartz dominates the sand fraction, but zircon and tourmaline are not uncommon. These latter two minerals, coupled with occurrences of rose quartz, support the proposal made by Sohl and Owens (1991) for an igneous/metamorphic source terrane

for Donoho Creek sediments. The fossiliferous bed is only exposed during times of drought and corresponding lowered river levels, and only the upper 1.7 m of the Donoho Creek Formation was exposed for Lawrence and Hall (1987) to examine (The present author was unable to resample the bed after 2002). Underlying the fossiliferous bed is dark gray, finely laminated clay, and these two units are separated by a layer of disarticulated, abraded *Flemingostrea* valves (see Fig. 2). Analyses of calcareous nannofossils from Burches Ferry show that the Pee Dee Formation is middle Maastrichtian in age, whereas the Donoho Creek Formation is upper Campanian and falls within calcareous nannofossil Zone CC22c (Self-Trail and Gohn, 1996; Self-Trail and Bybell, 1997; Self-Trail and others, 2002).

METHODS

Vertebrate remains are visible when the level of the Pee Dee River is low and the fossiliferous bed is exposed. During the first visit to Burches Ferry, visible macrofossils were collected before screening of bulk matrix. Screen washing at the site was performed with U.S.A. Standard Testing Sieves using 4 mm (no. 5), 2 mm (no. 10), and 1 mm (no. 18) sieves. Additionally, 25 kg of sediment was processed back at the lab. Although a distinct color difference was noted between the upper (orange) and lower (gray) parts of the bed, the unit was sampled assuming that it represented one lithologic unit. Once back at the lab, matrix was disaggregated in water and the material screen washed down to 0.25 mm (no. 60). To maximize fossil recovery, matrix that passed through the number 60 screen was retained. Each size fraction was dried and sorted under a binocular microscope. Any collecting bias affecting the faunal composition of the Donoho Creek sample occurred because of the limited amount of matrix collected rather than screening methods.

Additional matrix was recovered during a second visit to the site, and the orange and gray portions were sampled separately in the

event that they actually represented two different beds. Forty kilograms of matrix was collected, with nearly equal portions of orange and gray sediment being sampled. After screening and sorting this material, it was determined that the orange and gray portions contained the same vertebrate taxa. It is reasonable to assume that the unit represents a single lithostratigraphic bed and that the orange color is the result of meteoric weathering.

The vast majority of the vertebrate taxa recovered from the Donoho Creek Formation at Burches Ferry have been reported from many other time equivalent deposits in North America. For this reason I have chosen simply to summarize the vertebrate assemblage in Table 1. There are, however, several elasmobranch species that deserve special mention and are discussed in more detail below. The fossils outlined in Table 1 are housed at the Bob Campbell Geology Museum (BCGM), Clemson University, Clemson, South Carolina. For interested persons, the material reported by Lawrence and Hall (1987) is housed in the South Carolina State Museum in Columbia.

SYSTEMATIC PALEONTOLOGY

Class Chondrichthyes

Cohort Euselachii

Order Heterodontiformes Berg, 1940

Family Heterodontidae Gray, 1851

Heterodontus aff. *H. granti* Case and Cappetta, 1997

Material: BCGM 6200, incomplete crown (Fig. 3, 1).

Description: The crown measures just under 2 mm as preserved, and it has a sub-rectangular outline in labial view. There is a low, broadly triangular, distally directed central cusp that is flanked by three pairs of cusplets that become smaller laterally. The labial and lingual faces of the cusps are weakly convex, and a cutting edge extends along the cusps from the mesial to distal sides of the crown. There is no medial lingual crown protuberance. The lower half of the

labial face forms an obtuse angle with the upper half of the crown.

Remarks: Although the tooth is damaged, enough morphology is preserved to allow for assignment to *Heterodontus*. The preserved morphology compares closely to *Heterodontus granti* (Case and Cappetta, 1997), but additional material is needed to make a more precise taxonomic assignment.

Order Orectolobiformes Applegate, 1972

Family Ginglymostomatidae Gill, 1862

Cantioscyllium meyeri Cappetta and Case, 1999

Material: BCGM 6198, anterior tooth (Fig. 3, 2); BCGM 6199, anterolateral tooth (Fig. 3, 3); BCGM 6950, lateral tooth, BCGM 6951, anterolateral tooth (Fig. 3, 4-5), BCGM 6952, three incomplete teeth.

Description: All of the specimens are more than 2 mm in width, with the largest specimen (BCGM 6198) measuring just over 2.5 mm. Teeth are cuspidate and have a sub-triangular outline in labial view. Anterior teeth are symmetrical, but the crown becomes asymmetrical distally. A pair of very poorly developed lateral cusplets is visible on BCGM 6198, but the rest of the teeth are devoid of cusplets. In either case, there is a smooth cutting edge that extends from one side of the crown to the other. The apex of the central cusp of unworn teeth is pointed. The labial face is weakly convex, lingually inclined, and bears a series of longitudinal ridges. The ridges are rather short, weak, discontinuous, generally restricted to the lower half of the crown, and do not reach the crown base. A wide labial basal apron extends beyond the crown/root junction, and it may be uniformly convex or medially concave. The lingual face is smooth, convex, with a large medial basal protuberance. The root is triangular in basal view, concave, with a large foramen that opens into a wide labial nutritive groove. There is a pair of margino-lingual foramina and a single foramen at the lingual root margin.

Remarks: In his study of Cretaceous Missis-

SELACHIAN ASSEMBLAGE — FLORENCE COUNTY, SOUTH CAROLINA

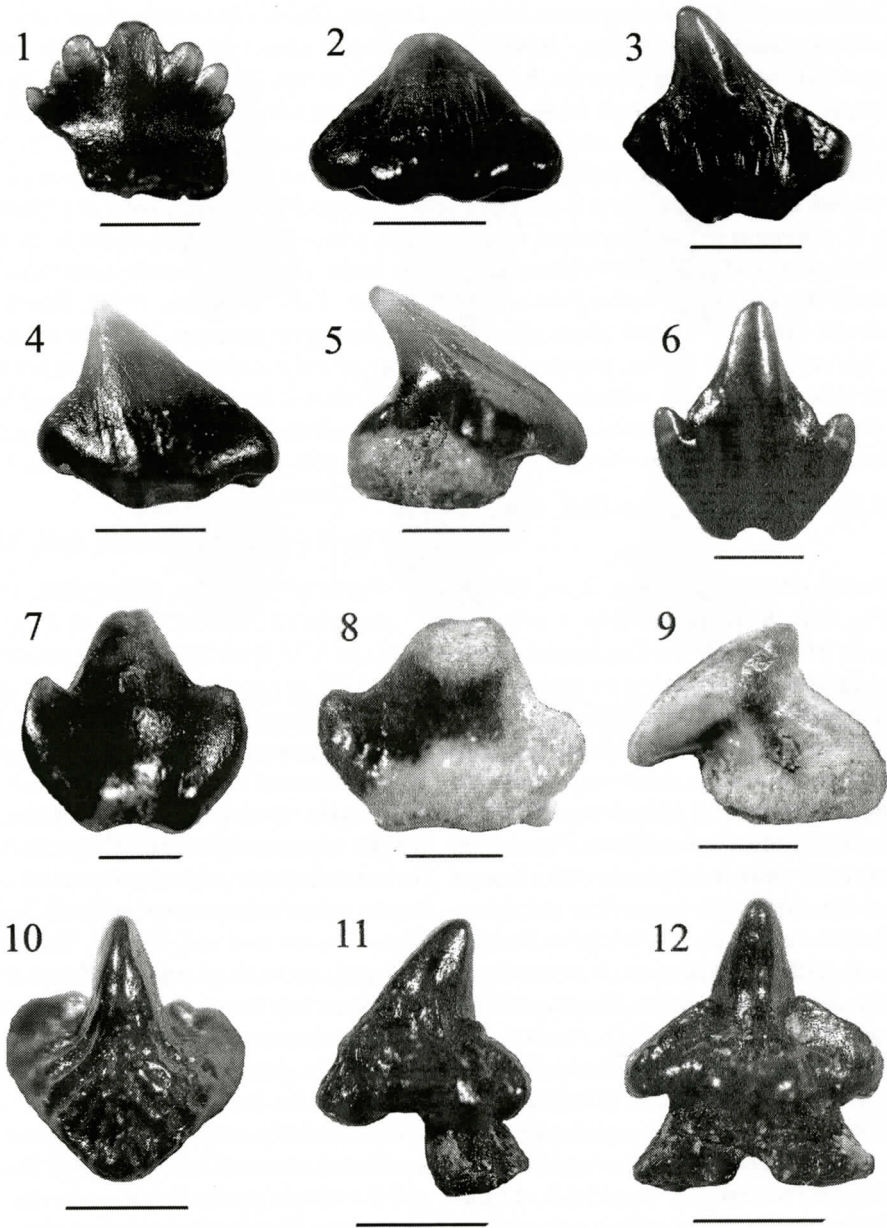


Figure 3. Donoho Creek Formation chondrichthyan taxa highlighted in the Systematic Paleontology section of this report. 1, *Heterodontus* aff. *granti*, BCGM 6200, labial view. 2-5, *Cantioscyllium meyeri*, 2, BCGM 6198, labial view; 3, BCGM 6199, labial view; 4 and 5, BCGM 6951, labial and distal views, respectively. 6-9, *Chiloscyllium* sp., 6, BCGM 6201, labial view; 7, BCGM 6202, labial view; 8 and 9, BCGM 6948, labial and distal views, respectively. 10-12, *Borodinopristsis schwimmeri*, BCGM 6242, 10, labio-occlusal; 11, mesial; 12, lingual views. Scale = 1 mm in 1-5, 0.5 mm in 6-12.

sippi Embayment elasmobranchs, Meyer (1974) differentiated a new species, *Cantioscyllium saginatus*, from *C. decipiens* on the basis of its larger size and the nature of the labial crown ornamentation. Case and Cappetta (1997) identified similar material from the Maastrichtian of Texas as *C. meyeri*, and more recently *C. saginatus* was synonymized with *C. meyeri* (Cappetta and Case, 1999). *Cantioscyllium meyeri* has been documented from several localities in the Gulf coastal plain (Meyer, 1974), but occurrences in the Atlantic coastal plain are virtually unknown, with the only other report being from the Chesapeake Bay region (see *Cantioscyllium decipiens*; Kent, 1994).

Family Hemiscylliidae Gill, 1862

Chiloscyllium sp.

Material: BCGM 6201 (Fig. 3, 6), BCGM 6202 (Fig. 3, 7), BCGM 6948 (Fig. 3, 8-9), isolated teeth; BCGM 6949, two incomplete teeth.

Description: The teeth are no greater than 1.5 mm in width, and all specimens have a cuspidate crown that is sub-triangular in labial view. The main cusp is relatively short and broad-based, flanked by a single pair of much smaller, diverging lateral cusplets. The cutting edge is smooth and continuous from the base of the mesial cusplet to the base of the distal cusplet. The labial crown face is rather flat, lingually inclined, with a bifid basal apron that extends below the crown/root junction. The lingual face is convex with a large, medially located, lingually directed protuberance. The roots of all specimens are damaged, but BCGM 6202 and BCGM 6948 show a pair of margino-lingual foramina (Fig. 3, 9), and there is a single foramen at the lingual root margin. In addition, a large basal foramen opens into a wide labial nutritive groove.

Remarks: Although the Donoho Creek *Chiloscyllium* teeth compare well with *C. greeni*, a taxon that was first reported from Turonian rocks of South Dakota, they have a bifid rather than uniformly convex labial apron (see *Brachaelurus greeni*; Cappetta, 1973). In this respect, the Donoho Creek specimens (especially BCGM 6201) are closer to *Brachaelurus* sp. 2 of Cappetta and Case (1975). The remaining

Donoho Creek *Chiloscyllium* are quite similar to *Brachaelurus* sp. 1 of Cappetta and Case (1975), except for the presence of a large pair of lateral cusplets. The *Brachaelurus* material described by Cappetta and Case (1975) is based on only three teeth, and it is possible that they are conspecific. Whereas teeth of *Chiloscyllium* have a broad labial apron, those of *Brachaelurus* have a medially constricted labial apron (Meyer, 1974; Cappetta, 1987). Based on this morphological criterion, I believe the *Brachaelurus* material reported by Cappetta and Case (1975) should be referred to *Chiloscyllium*. The taxon referred to *Chiloscyllium* cf. *greeni* by Kent (1994) compares well to the Donoho Creek *Chiloscyllium* sp.

Family Parascylliidae Gill, 1862

Pararhincodon sp. (Cappetta), 1976

Material: BCGM 6250 (Fig. 4, 1-3), BCGM 6251, BCGM 6946 (Fig. 4, 4-5), BCGM 6947 (Fig. 4, 6), isolated teeth with incomplete roots.

Description: BCGM 6250 measures just under 2 mm in crown height. The tooth has a highly asymmetrical and laterally compressed cusp. The mesial crown face is separated from the labial face by a straight cutting edge that extends from the cusp apex to the crown base. The labial face is only weakly convex, whereas the lingual face is convex and very narrow. The distal cutting edge is straight, and it extends from the cusp apex but does not reach the crown base. An inconspicuous lingual cusplet, well separated from the distal cutting edge, is located near the base of the crown. All enameloid is smooth.

BCGM 6251 and 6946 are very similar to each other, measuring 1.8 mm (as preserved) and 2.1 mm in crown height, respectively. The crowns are highly asymmetrical and laterally compressed, with a hook-like appearance in lateral view. The mesial and distal crown faces are vertical and not well differentiated from the labial face, which is highly convex. There is an indistinct mesial cutting edge that is limited to the upper half of the crown, and a second carina, located in a more lingual position, extends from the cusp apex but does not reach the crown base. There is no crown ornamentation. The roots of both specimens are incomplete, but

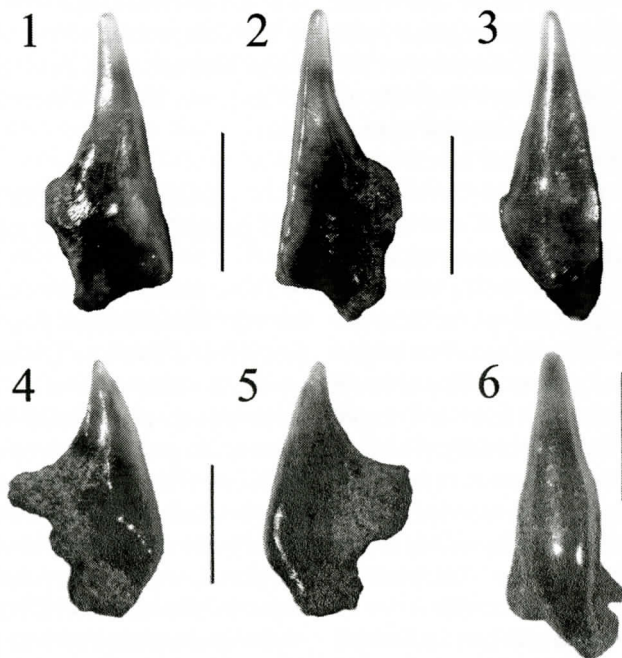


Figure 4. *Pararhincodon* sp. from the Donoho Creek Formation at Burches Ferry. 1-3, BCGM 6250, 1, distal; 2, mesial; 3, labial views. 4 and 5, BCGM 6946, distal and mesial views, respectively. 6, BCGM 6947, labial view. Scale = 1 mm in 1-5, 0.5 mm in 6.

there is evidence of a large pair of margino-lingual foramina. BCGM 6947 measures slightly over 1 mm in crown height, and it differs from BCGM 6251 and 6946 only in that the cusp is more erect.

Remarks: Three species of *Pararhincodon* have been reported from the Cretaceous of North America: *P. crochardi* (Cenomanian; see Shimada et al., 2005), *P. groessensi* (Cenomanian to Maastrichtian; see Welton and Farrish, 1993), and *P. lehmani* (Cenomanian; see Cappetta and Case, 1999). The Donoho Creek *Pararhincodon* specimens appear to be more laterally compressed and lack the cutting edges seen on teeth of *P. crochardi* (Herman, 1977). Although the Donoho Creek specimens are similar in their overall morphology to *P. lehmani*, they lack crown ornamentation (Cappetta, 1980; Cappetta and Case, 1999). As in *Pararhincodon crochardi*, teeth of *P. groessensi* have well developed cutting edges, and lateral cusplets are also consistently present (Herman, 1977; Müller, 1989; Welton and Farish, 1993).

Until a larger sample is available to help make a specific identification (perhaps the teeth represent a new taxon), the author is content with assigning the Donoho Creek material to *Pararhincodon* sp. *Pararhincodon* is primarily known from isolated teeth, but Cappetta (1980) provided descriptions of skeletal material collected from Lebanon. The genus has a long temporal distribution and was rather widespread, with additional records from Europe and northern Africa in rocks of Cenomanian to Maastrichtian age (Cappetta, 1980; Herman, 1982; Welton and Farish, 1993).

Order Sclerorhynchiformes Kriwet, 2004

Family Sclerorhynchidae Cappetta, 1974

Borodinopristis schwimmeri Case, 1987a

Material: BCGM 6242, isolated tooth (Fig. 3, 10-12).

Description: BCGM 6242 is a very small

tooth measuring 1.1 mm in height and width, and 1 mm in length. The tooth is cuspidate, with a sub-triangular outline in occlusal view. The cusp is laterally compressed and lingually directed. The crown also has a triangular appearance in labial view, and the labial face is highly convex and heavily ornamented. Crown ornamentation consists of wide but low oblique ridges that extend from the medial part of the crown but do not reach the crown base. The ridges bifurcate distally, and the surfaces between the ridges are finely pitted. The lingual face is rather small and convex, with a series of short ridges and cavities, and there is a medial protuberance that is directed basally. The base of the crown is thick and appears to curl over the crown/root junction. The root is bilobate with a deep medial nutritive groove that is perforated by three large foramina. The basal attachment surfaces of the lobes are flat.

Remarks: This unusual and distinctive tooth represents only the third report of *Borodinopristis schwimmeri* from the Campanian of North America. Meyer (1974) was the first to describe the unique barbed rostral spines, but he tentatively referred the material to *Sclerorhynchus* (see *Sclerorhynchus* sp. 2; p.109-110 and fig. 29C). Case (1987a) later reported rostral spines from Campanian deposits of Georgia that he recognized as being identical to those of Meyer's (1974) *Sclerorhynchus* sp. 2. Case (1987a) erected a new taxon, *Borodinopristis*, because the rostral spines were significantly different from those other known sclerorhynchids, but both he and Meyer (1974) indicated affinities with *Sclerorhynchus*.

BCGM 6242 is identical to teeth that Case (1987a) referred to *B. schwimmeri*. A second species, *B. ackermanni*, was described by Case et al. (2001) from Santonian strata of Georgia. That species was differentiated from *B. schwimmeri* on the basis of tooth crown morphology, but *Borodinopristis* rostral spines are apparently specifically undiagnostic. Because of the very limited sample size available for either taxon, the morphological range within the teeth of *Borodinopristis* is unknown, and it remains to be shown that there are, in fact, two species. The temporal range of *Borodinopristis*

is now known to range from the late Santonian to late Campanian, with occurrences in Mississippi, Georgia, and South Carolina (Meyer, 1974; Case, 1987a, Case et al., 2001, this report).

COMPOSITION OF THE ELASMOBRANCH ASSEMBLAGE

The entire vertebrate assemblage collected from the Donoho Creek Fm. at Burches Ferry is presented in Table 1. The elasmobranch component is rather diverse (22 taxa), and the assemblage is practically identical to other Campanian assemblages reported from the Atlantic and Gulf coastal plains (Table 2). Assemblages from Campanian Western Interior deposits are diverse, but share few species with temporally equivalent Atlantic Coastal Plain deposits (Case 1978, 1987b).

Compositionally, 59% of the Donoho Creek Fm. elasmobranch assemblage recovered from Burches Ferry consists of taxa with presumed benthic habits (including squatiniforms, several orectolobiforms, and batoids). Taxa with presumed pelagic habits make up the remaining 41% (i.e. *Cretalamna*, *Squalicorax*, *Cretodus*). Of particular interest in the Donoho Creek assemblage is the occurrence of *Pararhincodon*, which in North America has only been reported from Texas and Kansas (Welton and Farish, 1993; Cappett and Case, 1999; Shimada et al., 2004). Although represented by a single tooth, BCGM 6242 is only the third Campanian record, as well as the easternmost occurrence, of *Borodinopristis* (see also Meyer, 1974; Case 1987a). *Squalicorax pristodontus*, *Cretalamna appendiculata*, and *Archaeolamna kopingensis* are represented by relatively few teeth, and no large *Scapanorhynchus texanus* were recovered (see below for additional comments on *Scapanorhynchus*). This is in contrast to other Campanian assemblages, where these taxa are common to abundant (Meyer, 1974; Cappetta and Case, 1975; Case, 1987b; Robb, 1989; Welton and Farish, 1993). Several rostral spines (BCGM 6237 and 6238) have been recovered that compare favorably to *Ischyrhiza monasterica* (Case and Cappetta, 1997). However, I be-

lieve these specimens (and *I. monasterica* in general) actually represent rostral spines of *I. mira* (see Kriwet [2004] for a representative growth series of *Sclerorhynchus*).

As a note of clarification in Table 2, the Donoho Creek teeth referred to *Hybodus* sp. appear to represent the same taxon reported by Cappetta and Case (see *Hybodus* sp. 1; 1975), Case and Schwimmer (1988), Kent (1994), Lauginiger and Hartstein (1983), and Robb (1989). These teeth are characterized by the development of large lateral cusplets. Teeth with poorly developed (or no) lateral cusplets, as well as longitudinally ridged fin spines, have been attributed to a second species, *H. montanensis* (Case, 1978; Robb, 1989; Kent, 1994). However, the taxonomic validity of *H. montanensis* is, in my opinion, tenuous because of the ambiguous morphological criteria developed by Case (1978, 1987), and the variations in tooth shape could simply be related to heterodonty within a single species. In addition, the fin spine morphology attributed to *H. montanensis* is quite similar to *Lonchidion* (see Estes, 1964; Duffin, 1983), a taxon consistently found with *Hybodus* in Atlantic coastal plain deposits. I found no convincing evidence for the presence of two *Hybodus* species in the Donoho Creek sample. At a locality within the city limits of Florence, South Carolina, tuberculated fin spine fragments were found in association with teeth of *Hybodus* sp., and these are considered to represent the same taxon (see also Case, 1978; Robb, 1989; Kent, 1994).

PALEOENVIRONMENTAL IMPLICATIONS

Utilizing the matrix processing methods outlined above, microscopic fossils smaller than 0.25 mm were recovered (including placoid scales, foraminifera, ostracodes). The paucity or complete lack of some elasmobranch species could be related to a collection bias in that a relatively small amount of matrix was collected. The possibility also exists that at least some of the fossils were reworked from underlying deposits that are no longer preserved (similar to the Peedee Formation unconformity lag). Self-

Trail et al. (2002) found no break in calcareous nannofossil or palynomorph assemblages, but this scenario can be tested further by sampling for vertebrate remains lower in the section.

In their report on Campanian fluvial deposits from the Western Interior basin, Blob and Fiorillo (1996) quantitatively demonstrated the effect taphonomic processes have on the accuracy of paleoecological reconstructions. They reported that current action affected not only the preservation of the fossils, but also the taxonomic composition of fossiliferous deposits. The size and shape (i.e. flat and plate-like, long and cylindrical) of vertebrate remains influenced the composition of faunas and relative abundance of each taxon. Rather than representing an *in situ* fauna, the fossiliferous deposit within the Donoho Creek Formation at Burches Ferry contains species that inhabited a variety of environments, but were mixed together through current action and deposited elsewhere. Nevertheless, it is believed that the elasmobranch fossils collected from the deposit represent a true cross section of the taxa that lived within the Pee Dee River valley during the late Campanian.

Sediments of the Black Creek Group were deposited in a prograding delta system that extended southward into the Charleston Embayment, and the Donoho Creek Formation represents delta front-prodelta facies (Sohl and Christopher, 1983; Sohl and Owens, 1991). The fossiliferous horizon within the Donoho Creek Formation at Burches Ferry is composed predominantly of marine taxa, although forms derived from terrestrial sources are represented. For example, small pieces (3 cm or less) of fossil wood have been recovered, as well as an incomplete hadrosaurian dinosaur tooth, trionychid shell fragments, and lepisosteid scales and teeth. These findings are consistent with the conclusions of Self-Trail et al. (2002) that Donoho Creek deposition was influenced by a significant amount of terrestrial input. Of the marine component, most of the vertebrate taxa can be regarded as having preferred warm, relatively shallow nearshore marine conditions. Such taxa include the hybodonts, *Squatina*, the orectolobiforms, batoids, and smaller sharks

Table 2. Comparison of the Donoho Creek elasmobranch assemblage to those reported from Campanian strata in other regions of North America. Abbreviations: SC = South Carolina, NC = North Carolina, NJ = New Jersey, DE = Delaware, CBR = Chesapeake Bay Region, GCP = Gulf Coastal Plain, WI = Western Interior. The Chesapeake Bay Region as used in this report includes Maryland and Virginia. In addition to my personal observations, species occurrences outside of South Carolina are based on Robb (1989), Lauginiger and Hartstein (1983), Cappetta and Case (1975, 1999), Meyer (1974), Case and Schwimmer (1988), Kent (1994), and Case (1978, 1987b, 1991). Note that gaps in geographic distributions, especially in Atlantic Coastal Plain deposits, could be related to a lack of data from these areas rather than actual absence of a taxon.

Locality Taxon	Atlantic Coastal Plain					GCP	WI
	SC	NC	NJ	DE	CBR		
<i>Hybodus</i> sp.	•	•	•	•	•	•	
<i>Lonchidion babulskii</i>	•	•	•	•	•	•	
<i>Squatina hassei</i>	•	•	•	•	•	•	
<i>Heterodontus</i> aff. <i>granti</i>	•					•	
<i>Cantioscyllium</i> <i>meyeri</i>	•				•	•	
<i>Chiloscyllium</i> sp.	•		•?		•?	•?	
<i>Pararhincodon</i> sp.	•					•	
<i>Squalicorax kaupi</i>	•	•	•	•	•	•	•
<i>S. pristodontus</i>	•	•	•	•	•	•	•
<i>Archaeolamna</i> <i>kopingensis</i>	•	•	•	•	•		•
<i>Cretodus borodini</i>	•		•	•	•	•	
<i>Cretalamna</i> <i>appendiculata</i>	•	•	•	•	•	•	•
<i>Carcharias</i> <i>holmdelensis</i>	•	•	•	•	•	•	
<i>Carcharias</i> <i>samhammeri</i>	•		•	•	•	•	
<i>Rhinobatos casieri</i>	•		•	•		•	•
<i>Pseudohypolophus</i> <i>mcnultyi</i>	•		•	•		•	•
<i>Rhombodus levis</i>	•	•	•	•			
<i>Brachyrhizodus</i> <i>wichitaensis</i>	•	•	•	•		•	
<i>Borodinopristsis</i> <i>schwimmeri</i>	•					•	
<i>Ischyrhiza avonicola</i>	•		•			•	•
<i>I. mira</i>	•	•	•	•	•	•	•
<i>Ptychotrygon</i> <i>vermiculata</i>	•	•	•	•		•	

like *Carcharias* and *Cretodus borodini*.

In his comprehensive study of Cretaceous elasmobranch fossils from the Gulf coastal plain, Meyer (1974) used relative abundance data to differentiate five chondrichthyan associations. Based solely on species composition, and taking into consideration the age of the deposit, the Donoho Creek assemblage from Burches Ferry is a mixture of three of Meyer's (1974) associations: *Hybodus - Parahypolophus* (= *Pseudohypolophus*), *Scapanorhynchus - Ptychotrygon*, and *Squatina*. In his *Hybodus - Pseudohypolophus* association, *Pseudohypolophus* is abundant, odontaspids are common, and *Hybodus* is present. These species were collected along with crocodylian remains and lingulid brachiopods, all of which are also found in the Donoho Creek assemblage. Meyer (1974) found the association to be typical of littoral strand line and open bay facies. In the *Scapanorhynchus - Ptychotrygon* association, *Hybodus* is present and *Ptychotrygon* is abundant, but Meyer (1974) reported *Scapanorhynchus* as common and *Pseudohypolophus* as absent. In the Donoho Creek assemblage, *Pseudohypolophus* is very common, and *Scapanorhynchus* (at least large teeth) is absent (Interestingly, Case and Schwimmer [1988] have suggested that *Carcharias holmdelensis* represents juvenile teeth of *Scapanorhynchus texanus*). The *Squatina* association, which closely overlaps the *Scapanorhynchus - Ptychotrygon* association in its taxonomic content and facies occurrences, is characterized by the presence of *Squatina*. Both of these associations were found to be typical of shallow, sublittoral facies, and additional elasmobranch taxa include *Lonchidion*, *Rhinobatos*, *Ischyrrhiza*, *Cantioscyllium*, and *Squalicorax*. A mixed elasmobranch assemblage within the Donoho Creek Formation should not be surprising given the depositional circumstances, and the fact that many sharks and rays (including fossil forms) can inhabit a wide range of environments (Compagno et al., 2005; see references cited in Table 2).

Another of Meyer's (1974) elasmobranch associations, *Pseudocorax*, was found to be typical of inner to outer sublittoral facies. The *Pseudocorax* association bears similarities to

the Donoho Creek assemblage in that *Squalicorax*, *Cretalamna*, odontaspids, and *Ischyrrhiza* are present, but *Pseudocorax* was not recovered during the current field investigations. The taxon has been reported from Campanian strata of the Western Interior and Atlantic and Gulf coastal plains (Meyer, 1974; Lauginiger and Hartstein, 1983), and the current lack of specimens from the Donoho Creek sample could simply be due to a collecting bias. Alternatively, perhaps *Pseudocorax* preferred deeper water further offshore.

Additional elasmobranch taxa that have been reported from Campanian deposits elsewhere but are absent from the Donoho Creek assemblage include *Paranomotodon*, *Sclerorhynchus*, and *Scapanorhynchus* (at least large teeth). These absences, as well as the very limited sample size of many of the Donoho Creek taxa (see Table 1), could be accounted for in several ways. In the case of *Scapanorhynchus*, the possibility has been noted that teeth referred to *Carcharias holmdelensis* are actually immature *Scapanorhynchus texanus* (Case and Schwimmer, 1988). If true, perhaps the large numbers of "*C. holmdelensis*" in the Burches Ferry sample indicates that young *Scapanorhynchus* stayed in relatively shallow water (Interestingly, *Cretalamna appendiculata* is also only represented by small teeth of younger individuals). Environmental preference could be a factor, in which case the rarity or absence of species is related to avoidance or only occasional/accidental visit into the delta front-prodelta environment. Considering the presence of terrestrially derived fossils, taphonomic processes had the biggest impact on the vertebrate composition. It is believed that the remains of animals inhabiting different parts of the delta system were mixed together through current action and deposited further offshore. This scenario would also account for the preservation of the fossils, as well as the general lack of larger material. Although this mixed assemblage represents a good cross section of the types of sharks and rays that inhabited the delta system, the small sample size for many taxa may not be an accurate indicator of species abundance (see Blob and Fiorillo, 1996). That being said, it is interesting to note

the large numbers of *Squalicorax kaupi*, *Car-charias holmdelensis*, *Pseudohypolophus*, and *Ptychotrygon* within the Donoho Creek sample (Table 1). Perhaps these taxa were very common and inhabited all parts of the delta system.

Some other fossils associated with the Donoho Creek elasmobranchs are worth discussing. One specimen, a fragment of a chelonoid plastral bone of a very young, probably neonatal individual, indicates that sea turtles came to nest on the shores to the north-northwest of the Burches Ferry locality. Many large crocodylian teeth of presumably adult individuals were collected along with teeth measuring 4 mm or less in height. These smaller teeth represent very young animals, and perhaps crocodylians nested and raised their young in more marshy areas of the upper or lower delta plain.

Associated invertebrate remains are fragmentary and include pieces of lingulid brachiopod shells. Crustaceans are represented by callianassid (*Protocallianassa* sp.), dokotican-crid (*Avitelmessus* sp.), and pagurid (hermit crab) chelae. Two ostracode taxa, *Cytherella* sp. and *Haplocytheridea* sp., were collected, as well as the benthonic foraminifera *Dentalina* sp., *Nodosaria* sp., *Robulus* sp., *Vaginulina* sp. and cf. *Planularia* sp.,

One last specimen should be mentioned. It is a rounded and highly abraded chimaeroid tritor that was recovered from within the basal lag of the Peedee Formation. Because the fossil was located right at the Donoho Creek/Peedee contact (and its poor preservation), the fossil was likely derived from the Donoho Creek formation. Although chimaeroid remains have been reported from Black Creek Group deposits of North Carolina (Robb, 1989), the Burches Ferry specimen represents the first record for South Carolina.

CONCLUSIONS

Twenty-two shark and ray taxa have been recovered from the Campanian Donoho Creek Formation exposed at Burches Ferry, Florence County, South Carolina. Notable taxa within the Donoho Creek assemblage include *Heterodontus* aff. *granti*, *Cantioscyllium meyeri*,

Chiloscyllium sp., *Pararhincodon* sp., and *Borodinopristsis schwimmeri*, all of which are not well represented in Campanian strata elsewhere. As a whole, the Donoho Creek elasmobranch assemblage is very similar to those reported from other areas in the Atlantic and Gulf Coastal plains, but few of the species also occur in Western Interior deposits. As noted above, many shark and ray taxa are/were capable of tolerating wide salinity, temperature, and turbidity ranges. However, it is highly likely that the close similarities in species composition between the elasmobranch assemblages of Campanian Atlantic and Gulf coastal plain localities is due to the existence of similar environmental conditions (see Kauffman, 1975). Although taxonomic diversity in Campanian marine strata of the Western Interior may be comparable to the Atlantic coastal plain, relatively few species are shared by both regions. This is likely related to a difference in oceanic conditions between the two areas (Kauffman, 1975; Kauffman and Caldwell, 1993).

The vertebrate assemblage from the Donoho Creek Formation at Burches Ferry contains a mixture of animals that inhabited different environments within a delta system. This interpretation is consistent with the conclusions drawn by Robb (1989) for a temporally equivalent deposit in North Carolina. Although the Burches Ferry assemblage predominantly consists of marine taxa, several species have terrestrial origins (i.e. gar, trionychid turtle, dinosaur). Taxonomic variety, limited sample sizes (see Table 1), specimen preservation, and general lack of large remains (greater than 3 cm) are all related to the taphonomic processes that resulted in the deposition of the fossiliferous horizon. The absence of species known from Campanian strata elsewhere (i.e. *Paranomotodon*, *Sclerorhynchus*, and possibly *Scapanorhynchus*) could also be related to taphonomy, but collecting bias (relatively small amount of matrix processed) cannot be ruled out at this time. The hypotheses presented above can be tested through the collection of additional material from Burches Ferry, as well as other formations within the Black Creek Group of South Carolina.

ACKNOWLEDGEMENT

Many people helped make this report possible, and Christian Cicimurri, Mac Sprott, Richard Blob, Jason Calcagni, Paul Cicimurri, Nora Espinoza, Raymond Christopher, and Daniel George provided valuable assistance in the field. Matt Lamanna confirmed the identification of the hadrosaurian dinosaur tooth, David Parris examined the crocodylian fossils, Michael Everhart and Earl Manning provided comments on the bony fish teeth, Frederick Swain identified the ostracodes, and Gale Bishop identified the crustacean material. James Knight allowed me to study the collection reported by Lawrence and Hall (1987), and he reviewed an earlier draft. The editorial comments of Chuck Ciampaglio improved this manuscript and are greatly appreciated.

REFERENCES CITED

- Benson, P. H., Jr., 1969, Evidence against a large scale disconformity between the Upper Cretaceous Black Creek and Peedee formations in South Carolina: South Carolina Geological Survey Geologic Notes, v. 13, n. 2, p. 47-50.
- Blob, R. W., and Fiorillo, A. R., 1996, The significance of vertebrate microfossil size and shape distributions for faunal abundance reconstructions: a Late Cretaceous example: *Paleobiology*, v. 22, n. 3, p. 422-435.
- Cappetta, H., 1973, Selachians of the Carlile Shale (Turonian) of South Dakota: *Journal of Paleontology*, v. 47, n. 3, p. 504-514, 3 plates.
- Cappetta, H., 1980, Les Sélaciens du Crétacé supérieur du Liban. 1. Requins: *Palaeontographica A*, v. 168, p. 69-148, 24 plates.
- Cappetta, H., 1987, Chondrichthyes II: Mesozoic and Cenozoic Elasmobranchii: *Handbook of Paleichthyology*, v. 3B, Gustav Fischer Verlag, Stuttgart, Germany, 193 p.
- Cappetta, H., and Case, G. R., 1975, Contribution à l'étude des Sélaciens du groupe Monmouth (Campanien-Maastrichtien) du New Jersey: *Palaeontographica A*, v. 151, p. 1-46, 9 plates.
- Cappetta, H., and Case, G. R., 1999, Additions aux faunes de sélaciens du Crétacé du Texas (Albien supérieur-Campanien): *Palaeo Ichthyologica*, v. 9, p. 5-111, 30 plates.
- Case, G. R., 1978, A new selachian fauna from the Judith River Formation (Campanian) of Montana: *Palaeontographica A*, v. 160, p. 176-205, 6 plates.
- Case, G. R., 1987a, *Borodinoprists schwimmeri*, a new species of ganopristine sawfish from the Upper Blufftown Formation (Campanian) of the Upper Cretaceous of Georgia: *Bulletin of the New Jersey Academy of Science*, v. 32, n. 1, p. 25-33.
- Case, G. R., 1987b, A new selachian fauna from the Late Campanian of Wyoming (Teapot Sandstone Member, Mesaverde Formation, Bighorn Basin): *Palaeontographica A*, v. 197, p. 1-37, 15 plates.
- Case, G. R., 1991, Selachians (sharks) from the Tupelo Tongue of the Coffee sand (Campanian, Upper Cretaceous) in northern Lee County, Mississippi: *Mississippi Geology*, v. 11, n. 3, p. 1-8, 2 plates.
- Case, G. R., and Cappetta, H., 1997, A new selachian fauna from the Late Maastrichtian of Texas (Upper Cretaceous/Navarroan; Kemp Formation): *Münchner Geowissenschaften Abhandlungen*, v. 34, p. 131-189, 15 plates.
- Case, G. R., and Schwimmer, D. R., 1988, Late Cretaceous fish from the Blufftown Formation (Campanian) in western Georgia: *Journal of Paleontology*, v. 62, n. 2, p. 290-301.
- Case, G. R., Schwimmer, D. R., Borodin, P. D., and Leggett, J. J., 2001, A new selachian fauna from the Eutaw Formation (Upper Cretaceous/Early to Middle Santonian) of Chattahoochee County, Georgia: *Palaeontographica Abteilung*, v. 261, p. 83-102, 6 plates.
- Cicimurri, D. J., 2004, Late Cretaceous chondrichthyans from the Carlile Shale (Middle Turonian to Early Coniacian) of the Black Hills region, South Dakota and Wyoming: *Mountain Geologist*, v. 41, n. 1, p. 1-16.
- Compagno, L., Dando, M., and Fowler, S., 2005, *Sharks of the World*: Princeton University Press, Princeton, New Jersey, 368 p.
- Duffin, C.J., 1985, Revision of the Hybodont selachian genus *Lissodus* Brough (1935): *Palaeontographica A*, v. 188, p. 105-152.
- Edwards, L. E., Gohn, G. S., Bybell, L. M., Chirico, P. G., Christopher, R. A., Frederiksen, N. O., Prowell, D. C., Self-Trail, J. M., and Weems, R. E., 2000, Supplement to the preliminary stratigraphic database for subsurface sediments of Chester County, South Carolina: U.S. Geological Survey Open-File Report 00-049-B, 44 p.
- Gohn, G. S., 1992, Revised nomenclature, definitions, and correlations for the Cretaceous formations in the USGS-Clubhouse Crossroads #1, Dorchester, County, South Carolina: U.S. Geological Survey Professional Paper 1581, 39 p.
- Estes, R., 1964, Fossil vertebrates from the Late Cretaceous Lance Formation, eastern Wyoming: *University of California Publications in Geological Sciences*, v. 49, 180 p.
- Herman, J., 1977, Les sélaciens de terrains néocrétacés et paléocènes de Belgique et des contrées limitrophes. Elements d'une biostratigraphie intercontinentale: Mémoires pour servir à l'explication des Cartes géologiques et minières de la Belgique. Service Géologique de Belgique, v. 15, 401 p.
- Herman, J., 1982, Die Selachier-Zähne aus der Maastricht-Stufe von Hemmoor, Niederelbe (NW-Deutschland): *Geologische Jahrbuch Reihe A*, v. 61, p. 129-159.

- Kauffman, E. G., 1975, Dispersal and biostratigraphic potential of Cretaceous benthonic Bivalvia in the Western Interior. In: Caldwell, W. E. G. (ed.), *The Cretaceous System in the Western Interior of North America*. Geological Association of Canada, Special Paper 13, p. 163-194.
- Kauffman, E. G., and Caldwell, W. G. E., 1993, The Western Interior Basin in space and time. In: Kauffman, E. G., and Caldwell, W. G. E., (eds.), *Evolution of the Western Interior Basin*. Geological Association of Canada, Special Paper 39, p. 1-30.
- Kent, B. W., 1994, Fossil Sharks of the Chesapeake Bay Region, Egan, Rees and Boyer, Inc., Columbia, Maryland, 146 p.
- Kriwet, J., 2004, The systematic position of the Cretaceous sclerorhynchid sawfishes (Elasmobranchii, Pristiorestea). In: Arratia, G., and Tintori, A., (eds.), *Mesozoic Fishes, v. 3, Systematics, Paleoenvironments, and Biodiversity*. Verlag Dr. Friedrich Pfeil, Munich, p. 57-73.
- Lauginiger, E. M., and Hartstein, E. F., 1983, A Guide to the Fossil Sharks, Skates, and Rays from the Chesapeake and Delaware Canal area, Delaware: Delaware Geological Survey Open File Report 21, 64 p.
- Lawrence, D. R., and Hall, J. P., 1987, The Upper Cretaceous Peedee-Black Creek formational contact at Burches Ferry, Florence County, South Carolina: *South Carolina Geology*, v. 31, n. 2, p. 59-66.
- Meyer, R. L., 1974, Late Cretaceous elasmobranchs from the Mississippi and East Texas Embayments of the Gulf Coastal Plain: Unpublished Ph.D. dissertation, Southern Methodist University, Dallas, Texas, 419 p.
- Müller, A., 1989, Selachier (Pisces: Neoselachii) aus dem höheren Campanium (Oberkreide) Westfalens (Nordrhein-Westfalen, NW-Deutschland): *Geologie und Paläontologie in Westfalen*, v. 14, 39 p., 24 plates.
- Parr, J. E., and Lawrence, D. R., 1985, The Peedee/Black Creek contact at Burches Ferry, South Carolina; a sedimentological and paleontological study: *Bulletin of the South Carolina Academy of Science*, v. 47, 155 p.
- Self-Trail, J. M., and Bybell, L. M., 1997, Calcareous nanofossil biostratigraphy of the SCDNR testhole C-15, Jasper County, South Carolina: U.S. Geological Survey Open-File Report 97-155, 2 p. (oversized).
- Self-Trail, J. M., and Gohn, G. S., 1996, Biostratigraphic data for the Cretaceous marine sediments in the USGS St. George No. 1 core, Dorchester County, South Carolina: U.S. Geological Survey Open-File Report 96-684, 29 p.
- Self-Trail, J. M., Christopher, R. A., and Prowell, D. C., 2002, Evidence for large-scale reworking of Campanian sediments into the Upper Maastrichtian Peedee Formation at Burches Ferry, South Carolina: *Southeastern Geology*, v. 41, n. 3, p. 145-158.
- Shimada, K., Schumacher, B. A., Parkin, J. A., and Palermo, J. M., 2006, Fossil marine vertebrates from the lowermost Greenhorn Limestone (Upper Cretaceous: Middle Cenomanian) in southeastern Colorado: *Journal of Paleontology*, Memoir 63, 45 p.
- Sloan, E., 1908, Catalog of the mineral localities of South Carolina: South Carolina Geological Survey, Series IV, Bulletin 2, 505 p.
- Sohl, N. F., and Christopher, R. A., 1983, The Black Creek-Peedee formational contact (Upper Cretaceous) in the Cape Fear River region of North Carolina: U.S. Geological Survey Professional Paper 1285, 37 p.
- Sohl, N. F., and Owens, J. P., 1991, Cretaceous stratigraphy of the Carolina Coastal Plain. In: J.W. Horton, Jr., and Zullo, V.A., (eds.), *The geology of the Carolinas: 50th Anniversary Volume*, Carolina Geological Society, p. 191-220 (University of Tennessee Press, Knoxville).
- Stephenson, L. W., 1912, The Cretaceous formations. In: Clark, W. B., (ed.), *The Coastal Plain of North Carolina*. North Carolina Geological and Economic Society, v. 5, p. 73-171.
- Stephenson, L. W., 1923, The Cretaceous formations of North Carolina: *North Carolina Geological and Economic Survey*, v. 5, 604 p.
- Van Nieuwenhuise, D. S., and Kanes, W. H., 1976, Lithology and ostracode assemblages of the Peedee Formation at Burches Ferry, South Carolina: Division of Geology, South Carolina State Development Board, *Geologic Notes*, v. 20, p. 74-81.
- Welton, B. J., and Farish, R. F., 1993, *The Collector's Guide to Fossil Sharks and Rays from the Cretaceous of Texas, Before Time*, Louisville, Texas, 204 p.
- Woollen, I. D., and Colquhoun, D. J., 1977, The Black Creek-Peedee contact in Florence County, South Carolina: Division of Geology, South Carolina State Development Board, *Geologic Notes*, v. 21, p. 20-41.

BACK-BARRIER SHORELINE CHANGE HISTORY: CUMBERLAND ISLAND, GEORGIA, 1857-2002

CHESTER W. JACKSON, JR.

*Department of Geology
University of Georgia
Athens, GA 30602
cwj jr@uga.edu*

CLARK ALEXANDER

*Skidaway Institute of Oceanography
Savannah, GA 31411
clark.alexander@skio.usg.edu*

DAVID M. BUSH

*Department of Geosciences
University of West Georgia
Carrollton GA 30118
dbush@westga.edu*

ABSTRACT

Beginning in the early 1990s, an increase of coastal storm activity brought about a growing concern over the protection of cultural resources along, or within close proximity to, Cumberland Island, Georgia's back-barrier shore. Such storm activity has exacerbated the erosion problem along several segments of the shoreline already experiencing net long-term erosion. Furthermore, there is increasing concern over the possible effects of sea-level rise on the fate of these sensitive areas along the back-barrier shore. Recently, the National Park Service at Cumberland Island National Seashore began to assess impacts of erosion on several archaeological sites along the back-barrier shore of Cumberland Island. A year-long study was conducted from 2004 to 2005 that involved obtaining and analyzing digital shoreline data spanning the time period from 1857 to 2002 and making observations at various field sites within the study area. The primary objective of the study was to gain a better understanding of the spatial and temporal trends of back-barrier erosion along the back-barrier shore. Results from

the study were used to assist the National Park Service in their search for options to mitigate future shoreline erosion and potential loss of important archaeological sites. A generalization of aerial photography and historical maps suggests that greater than half of the back-barrier shoreline had a 145 year history of erosion between 1857 and 2002. Currently, methodologies developed in this study are being used to update shoreline change studies of all of Georgia's barrier islands, with the potential for global application in the future

INTRODUCTION

Situated in the southeastern U.S.A on the Atlantic Ocean, Cumberland Island is the longest and southernmost barrier island on the Georgia coast, spanning nearly 30 km in length (Figure 1). The barrier is a part of the Cumberland Island Barrier Complex which includes Little Cumberland Island as well as back-barrier marsh, stream, and inlet systems between St. Andrew Sound and St. Marys Inlet. The western side, or back-barrier, of Cumberland Island National Seashore is experiencing considerable amounts of shoreline erosion, which ultimately

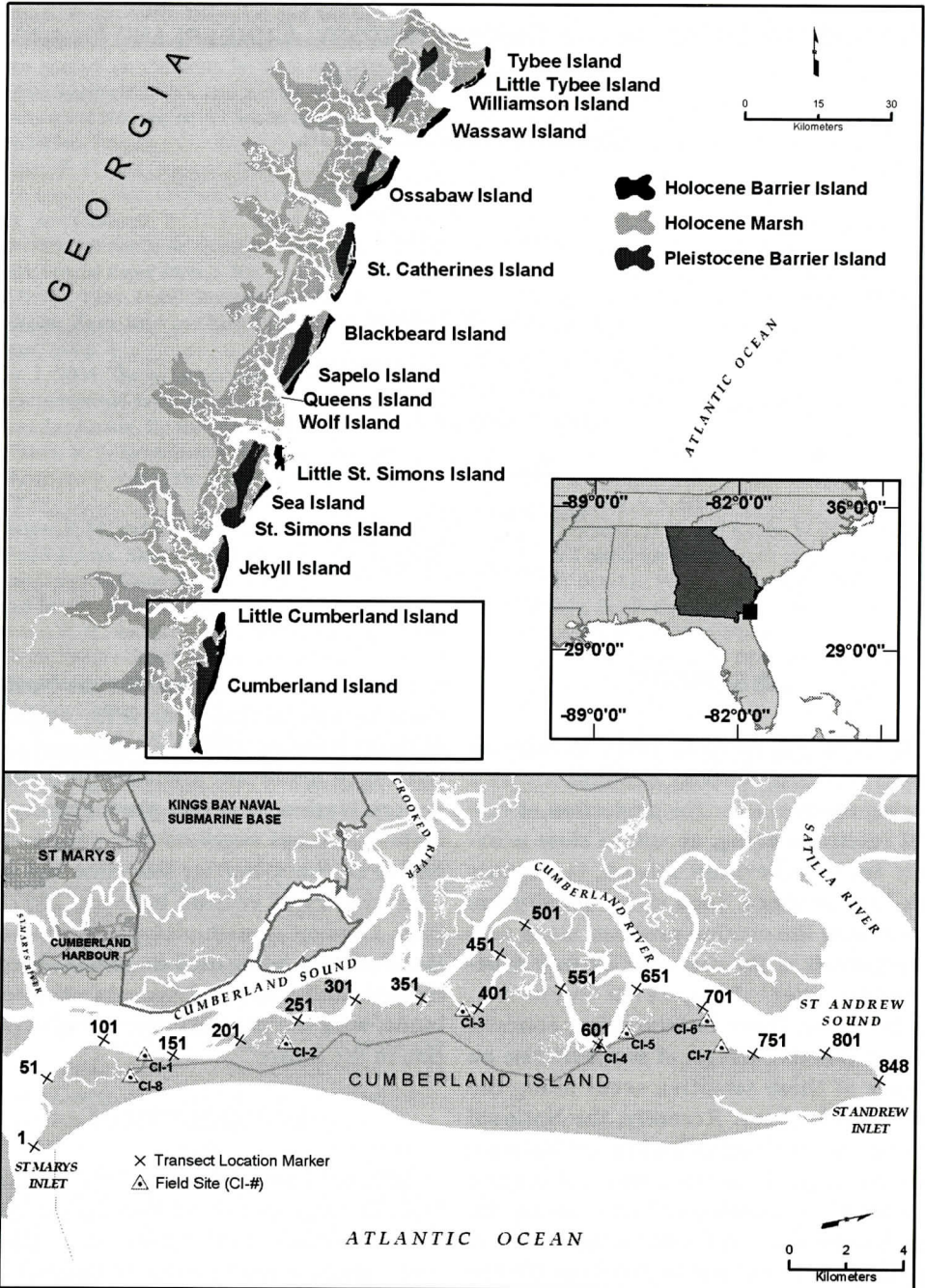


Figure 1. Location map of the Georgia coast and Cumberland Island barrier complex.

poses a threat to the natural and cultural resources found there. Prominent tidal stream cut bank erosional scarps exist along portions of the back-barrier shoreline, as the tidal streams have migrated into the tidal marsh and upland barrier.

Adverse conditions along a considerable length of the shoreline include exposed archaeological sites slumping into adjacent tidal channels, undermined and falling trees/vegetation, roots exposed to a depth of 1-3 m, and erosion/

retreat of marsh shoreline.

Few studies exist that quantify back-barrier shoreline erosion along the Georgia coast and little is known about the lateral movements of tidal channels (Frey, 1973). Until recently, shoreline studies have concentrated on Georgia's oceanfront shorelines (U.S. Army, 1971; Nash, 1977; Griffin and Henry, 1984; Clayton and others, 1992; Langley and others, 2003). In order to understand the erosion problem along the back-barrier shore of Cumberland Island, a GIS-based investigation was conducted to determine the extent of erosion over the length of the back-barrier and to quantify the rate of shoreline loss. Although some work has been done at a few sites established by the National Park Service, the problem has not been investigated over the length of the island. This study will allow coastal managers to further understand the potential natural and/or anthropogenic factors influencing shoreline erosion, to focus their attention on critical areas or erosion hotspots, and to develop plans to mitigate adverse erosion impacts.

METHODOLOGY

The Cumberland Island shoreline change study has two distinct phases. First, shoreline position data is extracted from a variety of sources and imported into a GIS. Second, analyses of the shoreline position changes through time are performed utilizing various GIS tools. The compilation of historical shoreline data and maps into a GIS allows for the rapid analysis and visualization of shoreline movements and delineation of erosion/accretion trends. Recently, a GIS-based program for ArcView GIS called SCARPS (Simple Change Analysis of Retreating and Prograding Systems) was developed by Jackson (2004) to provide a thorough investigation of shoreline change through computational and output features, as well as overall flexibility with shoreline data analysis. This tool has been validated in several recent shoreline studies to effectively determine shoreline change parameters (e.g., Langley et al, 2003).

Georeferenced historical aerial photographs, coastal charts, and survey maps can provide a

wealth of shoreline position and coastal geomorphologic data. During the first phase of the project, representative sets from these data sources were obtained from the USGS, National Ocean Service, and other agencies. Aerial photographs and maps were chosen to provide maximum coverage of the island's back-barrier and inlet-facing shorelines. Aerial photos and maps were scanned and georectified using ESRI's ArcGIS and ERDAS Imagine software. Because the quality and reliability of shoreline positions extracted from aerial photographs and maps hinge on the accuracy with which imagery is georectified, steps were taken to make certain these data meet or exceeded United States National Mapping Accuracy Standards (Office of Management and Budget 1947, <http://rockyweb.cr.usgs.gov/nmpstds/nmas.html>).

Following the georectification of historical imagery, the position of the shoreline was digitized on each scanned aerial photo and map within ArcGIS. During this process, the high-water (wet/dry line) line (HWL) or swash terminus, bluff toe, or marsh edge was selected as the primary indicator of shoreline position. The shoreline was digitized at a scale of 1:1,500 or larger and converted into an ESRI polyline shapefile for each image and each shapefile's GIS table was populated with attributes uniquely identifying the shoreline segment. Once the shapefile was created, a worst-case error estimate was determined for each shoreline to account for possible position errors. Clearly, a number of factors such as map or photo scale, line-width of a plotted shoreline on a map, and interpretation of the high-water line tend to limit shoreline accuracy (Anders and Byrnes, 1991, Dolan and others, 1980; Crowell and others, 1991; Moore, 2000; Thieler and Dandforth, 1994 a & b). In the current study, worst-case position error estimates ranged from 1 to 7 m for shorelines mapped from georectified aerial photography, maps and orthophotos.

After assembling the digital shorelines into a GIS database, the SCARPS ArcView GIS extension is used to calculate shoreline change and to perform statistical analyses of the dataset. SCARPS calculates shoreline change by measuring the position differences of two or

more historical shorelines within the GIS. In the current study, 848 transects were cast perpendicular to the back barrier shoreline from a baseline at a spacing interval of 50 m. Measurements of historical shoreline positions were extracted along each transect where the shoreline intersected the transect. In some cases, not all 848 transects recorded a shoreline position because of incomplete coverage of the shoreline. From these calculations, regions of shoreline exhibiting erosion, accretion, or no apparent change were identified. The "end-point rate" (EPR) shoreline change rate calculation, widely used by state and local agencies, was the primary method used to estimate both long-term and short-term shoreline change rates. The EPR method is simply the distance a shoreline has moved between two dates divided by the time elapsed between historical shorelines. The EPR method was used instead as the primary method over others, such as the Linear Regression Rate (LRR), because it is simple to calculate and doesn't require numerous historical shorelines. All shoreline change rates reported below, unless otherwise noted, are in terms of the EPR calculation method. The convention used throughout this study is that negative numbers indicate erosion and positive numbers indicate accretion.

SHORELINE CHANGES

A minimum of 10 years of relatively continuous (monthly) historical shoreline data is needed to interpret short-term trends and at least 50 years of data are needed for deciphering long-term trends (Camfield and Morang, 1996). Unfortunately, the historical shoreline record for Cumberland Island contains gaps of 5 to 10 years between aerial photos and maps from the 1980s to late 1990s, and upwards of 20 to 50 years between dates from the 1860s and early to mid-1900s. Therefore, only a handful of shoreline positions can be used to attempt to piece together the cumulative effects of all factors influencing shoreline change along the back-barrier. Unfortunately, no established methods exist that are able to statistically relate the geologic framework, thought to influence such

change, to long-term shoreline erosion (Honeycutt and others, 2002). Therefore, only apparent shoreline change trends and influences may be ascertained from statistical analyses of the dataset and visual inspections of historical aerial photographs and maps.

To determine erosion and accretion trends along the back-barrier shoreline, two spatial scales are addressed and described below: island-wide and intra-island scale. Island-wide analyses include all transects along the entire shoreline for a given time period, whereas intra-island analyses focus on transects along a segment or part of the shoreline. The results from island-wide shoreline change analyses were used to construct the shoreline erosion maps in Figure 2; the data are summarized in Table 1. Shoreline change rates listed in Tables 1 and 2 were obtained from analyses of shoreline changes from four eras of time: 1857/70 to 1933, 1933 to 1983, 1983 to 2002, and 1857/70 to 2002 (net or long-term change).

Transects were grouped qualitatively into ten intra-island zones, based on the erosion and accretion trends shown in Figure 2, to better illustrate the long-term behavior of the shore (Figure 3). For example, inspection of Figure 3 reveals that shoreline segments within Zones II, IV, VI, VIII, and X are typically dominated by erosion throughout the study period, while adjacent zones experience much less erosion or tend to accrete. Shoreline change data for Zones I-X are listed in Table 2.

Although the historical shoreline dataset contained more dates in addition to those used in the four focus eras, the shorelines used in the focus eras were primarily chosen for their spatial coverage and accuracy when used to analyze various temporal scales of change. Ultimately, a lower accuracy shoreline can be used to map changes along with another shoreline of a different date as long as the dates span a greater temporal scale. Larger temporal scales help to ensure that there is true mappable change being identified and not just error in shoreline position. Era I, spanning from 1857 to 1933, contains shoreline position data extracted from historical maps known to have spatial errors exceeding shorelines derived from modern

CUMBERLAND ISLAND BACK-BARRIER SHORELINE CHANGE

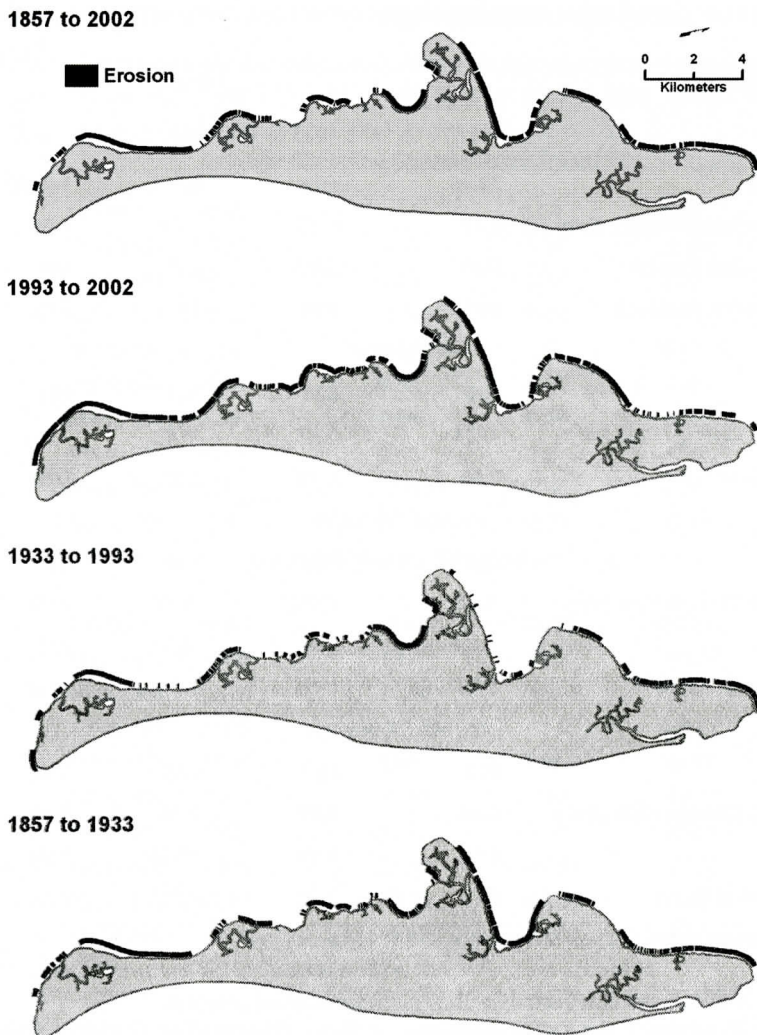


Figure 2. Shoreline change maps depicting back-barrier erosion along Cumberland Island, Georgia, for 4 eras: 1857-2002, 1983 to 2002, 1933 to 1983, 1857 to 1933. More than half of the back-barrier shoreline has experienced erosion from 1857 to 2002.

high resolution imagery. However, shoreline change trends depicted during this era are relatively reliable owing to the era's time span of ~76 years. Subsequent eras II & III, spanning 50- and 19-year periods, respectively, contain higher accuracy shorelines and represent a time of drastic/higher alteration of the back-barrier system of Cumberland Island caused by direct anthropogenic activities such as inlet/channel dredging, creation of dredge spoil islands, and emplacement of seawalls, bulkheads, and

docks. Era IV (1857 to 2002) represents the cumulative effects of all processes acting upon the shoreline throughout the entire study period of 145 years.

Era I (1857 to 1933)

The earliest series of detailed maps accurately depicting the Cumberland shoreline are U.S. Coast and Geodetic Survey (now the National Ocean Service or NOS) topographic sheets or

Table 1. Summary of back-barrier shoreline change data along Cumberland Island, Georgia, for each study era.

Statistic	Era			
	1857/70 to 1933	1933 to 1983	1983 to 2002	1857/70 to 2002
Time Span (years)	76.46	49.61	20.02	146.09
Annualized Worst-case Shoreline Error (\pm)	0.17	0.20	0.47	0.08
% Estimated Shoreline Erosion	66%	29%	85%	69%
% Estimated Shoreline Accretion	34%	71%	15%	31%
<i>All Transects</i>				
Total Transects	799	825	841	801
Average Shoreline Change Rate (m/yr)	-0.24	0.37	-0.69	-0.14
Standard Deviation of Rates	0.98	1.12	2.22	0.50
<i>Erosion Transects</i>				
Total Transects	526	238	716	553
Average Shoreline Change Rate (m/yr)	-0.66	-0.35	-1.19	-0.35
High Rate (m/yr)	-6.23	-1.91	-5.74	-2.51
Standard Deviation of Rates	0.86	0.30	1.04	0.39
<i>Accretion Transects</i>				
Total Transects	273	587	125	248
Average Shoreline Change Rate (m/yr)	0.54	0.67	2.14	0.33
High Rate (m/yr)	3.82	8.29	16.59	2.06
Standard Deviation of Rates	0.70	1.19	4.21	0.38

Note: Negative values reflect erosion and positive values are accretion.

T-sheets from field surveys conducted in 1857, 1867, and 1870. Combined, these maps provide island-wide coverage of the shoreline with the 1857 T-sheet covering the southern portion of the island, the 1867 T-sheet covering the middle portion of the island, and the 1870 T-sheet depicting the northern portion. Shoreline positions extracted from T-sheets were merged into the one island-wide shoreline representing the oldest historical shoreline in the dataset. The shoreline position is denoted “1857/70” to represent the combination of the multiple T-sheet years. Subsequently, a mixture of aerial photography and ground surveys were used to construct the NOS T-sheets starting in 1933. The noticeable difference between these maps and their older counterparts, aside from increased accuracy, is the detailed mapping of marsh channels and

other coastal features.

During the 1857 to 1933 era, which spanned ~76 years, approximately two-thirds of the back-barrier shoreline experienced net erosion (Figure 2). Although the average rate of change for all 799 transects extracted for this era was -0.24 m/yr (\pm 0.17 m/yr), the average rate among transects recording only erosion values was -0.66 m/yr (Table 1). Accretion occurring at transects recording only accretion during the era averaged approximately 0.54 m/yr.

The most notable shoreline erosion occurred primarily within Zones II, VI, VIII, and X (Figure 3). Shoreline recession was far greater along these shoreline segments and appeared to be greater at segments closest to the inlets. The shoreline eroded along Zone II, near St. Marys Inlet, an average of -66 m (-0.87 m/yr) and -46

CUMBERLAND ISLAND BACK-BARRIER SHORELINE CHANGE

Table 2. Summary of zone-wide shoreline change averages for the back-barrier of Cumberland Island, Georgia.

Zone	Transects	1857/70 to 1933	1933 to 1983	1983 to 2002	1857/70 to 2002
Average Shoreline Change Rates (m/yr)					
I	1 to 86	-0.15	1.66	0.64	0.08
II	87 to 183	-0.87	0.10	-1.90	-0.68
III	184 to 369	0.20	0.25	-0.82	0.07
IV	370 to 422	-0.14	-0.17	-0.65	-0.23
V	423 to 505	0.36	0.16	0.17	0.27
VI	506 to 643	-0.55	0.31	-0.50	-0.22
VII	644 to 667	0.03	0.90	-0.36	0.30
VIII	668 to 695	-0.32	0.43	-1.87	-0.28
IX	696 to 719	0.33	1.00	-2.48	0.16
X	720 to 848	-0.68	0.26	-0.70	-0.34
Average Shoreline Changes (m)					
I	1 to 86	-9.09	82.49	12.82	86.22
II	87 to 183	-66.06	4.75	-37.87	-99.18
III	184 to 369	13.08	12.56	-16.47	9.17
IV	370 to 422	-9.23	-8.32	-13.05	-30.61
V	423 to 505	23.96	8.09	3.48	35.53
VI	506 to 643	-33.30	15.23	-9.97	-28.04
VII	644 to 667	1.33	44.77	-7.30	38.81
VIII	668 to 695	-22.26	21.26	-37.31	-38.32
IX	696 to 719	21.57	49.70	-49.60	21.68
X	720 to 848	-46.10	12.97	-14.04	-47.17

Note: Negative values reflect erosion and positive values are accretion.

m (-0.68 m/yr) within Zone X near St. Andrew Inlet along the Little Cumberland Island portion of the barrier complex.

Within Zone II, maximum shoreline recession reached ~190 m at Transect #103 and tended to decrease at transects immediately north and south of this point. Inspection of the NOS T-sheets revealed that this portion of the island is essentially a protrusion in the shoreline apparently eroding through the time period of record (Figure 2). The protrusion is comprised of a mixture of morphologic features including vegetated dredge spoil islands, upland, and tidal marsh. Zone I flanks the southern border of the protrusion but tends to experience less erosion as the southern end of the island elongated or accreted during this era.

Within Zone X, substantial erosion occurred

between Transect #729 to #739 and ranged from approximately -100 to -400 m. This region represents the northernmost extent of the upland portion of Cumberland Island and includes Little Cumberland Island. Inspection of the 1933 survey maps reveals that shoreline retreat along this segment was likely attributed to the formation and/or widening of a shore-normal tidal creek adjacent to the upland shoreline. Based on examinations of the 1983 aerial photographs, the shoreline subsequently attained a position similar to that existing in 1870, as the tidal creek became infilled with sediment.

Era II (1933 to 1983)

Unlike the Era I, where net erosion characterized the back-barrier, accretion dominated

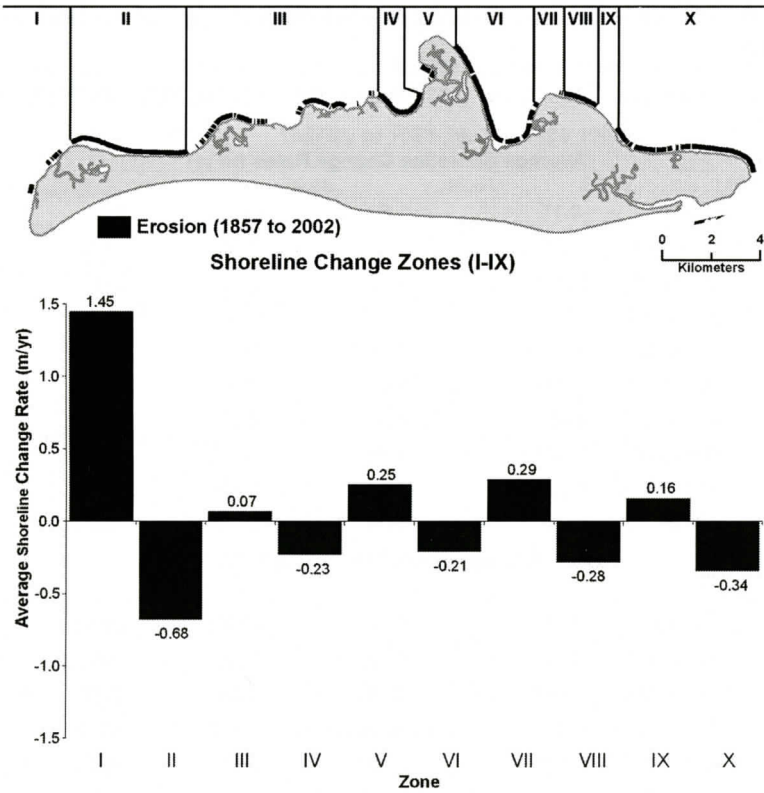


Figure 3. Back-barrier shoreline change zones and their average shoreline change rates from 1857 to 2002 for Cumberland Island, Georgia. Each zone tends to be dominated by accretion or erosion, however, Zone III is a mixture of both processes. Higher shoreline accretion rates along Zone I are due to the elongation of the southern spit.

during Era II (between 1933 and 1983) (Figure 2). Spanning a nearly 50-year time period, the average shoreline change rate for the back-barrier was 0.37 m/yr (± 0.20 m/yr). Nevertheless, almost one-third of the back-barrier shoreline continued to experience erosion at an average rate of 0.35 m/yr, especially along Zones II, III, and IV. Interestingly, shoreline accretion along Zone I increased ten-fold from the previous era with rates averaging nearly 1.66 m/yr as the island continued its southerly elongation (Table 2).

Still, what is puzzling about net back-barrier change during Era II is the overall increase in accretion on an island-wide scale. It may be attributable to the accuracy of the shoreline position data from the 1933 survey maps and the 1983 aerial photographs. However, analyses of static features such as seawalls and historical

landmarks, reveal horizontal displacements below the projected worst-case error estimates for the era. Similar results were obtained from analyses of the 1933 and 1974 shoreline position, where net accretion occurred along most of the island. If shoreline position inaccuracies are partially ruled out, the mechanism for accretion along most of the island is uncertain. Because increased sedimentation is essential for the progradation of shorelines and the establishment of new marsh, it is reasonable to assume that sediment supply during this period increased. As pointed out by Griffin and Henry, 1984, such an increase might be attributed to increased logging and development in Georgia's piedmont and coastal plain provinces in the early 1900s, thus increasing the sediment loads of coastal rivers/streams. It also could be attributed to development activities taking place within close

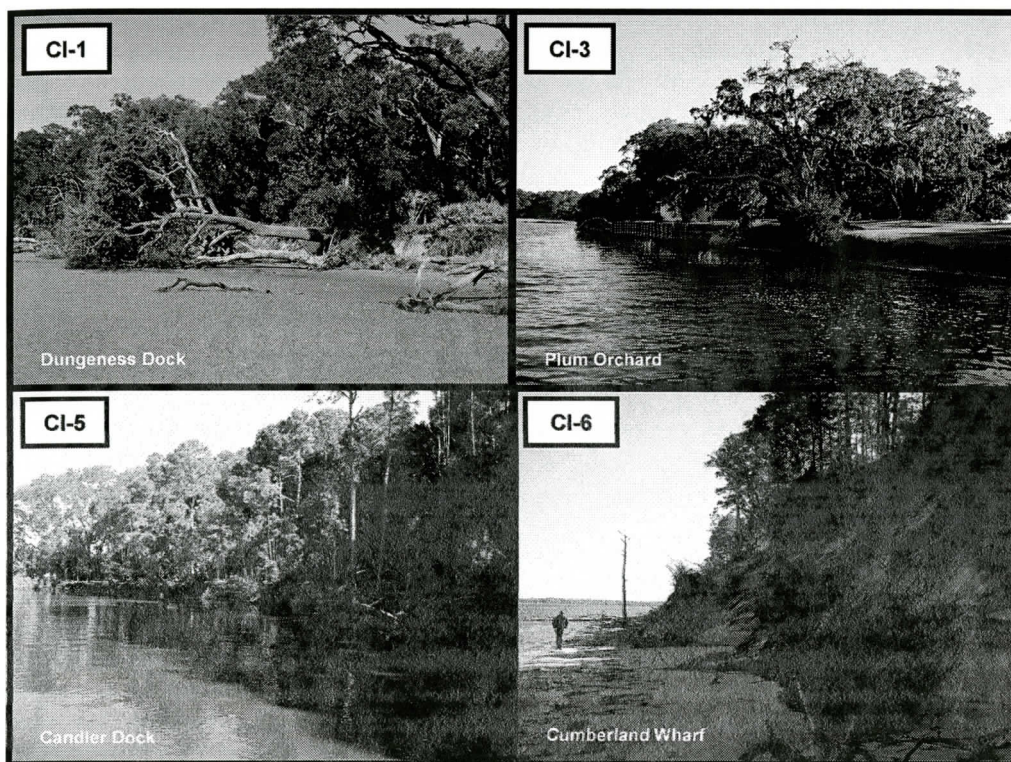


Figure 4. Ground photographs of features along select erosional shorelines at field sites located on Cumberland Island, Georgia: (CI-1) low sediment bank 2 to 3 meters high, (CI-3) wooden bulkhead, (CI-5) heavily vegetated bank, and (CI-6) high sandy bluff.

proximity to the back-barrier, such as dredging and new development, which have the potential to alter the sedimentary system. However, the actual mechanism(s) remain(s) unclear.

Era III (1983 to 2002)

Erosion appeared to dominate the back-barrier shoreline during Era III (1983 to 2002), the shortest time period of the study (Figure 2). Only about 15% of the back-barrier shore experienced accretion. Although the island's net shoreline change rate averaged -0.69 m/yr (± 0.47 m/yr), areas suffering exclusively from erosion had average rates exceeding 1 m/yr (Table 1). In general, the trend of erosion increases away from Zone V toward the inlets (Table 2). More importantly, average shoreline change rates along Zones II, VIII, and IX approached, or exceed -2 m/yr. Conversely, the only shoreline segment with substantial accretion oc-

curred along Zone I at 0.64 m/yr.

Apart from potential error(s) of the shoreline positions, the record of such wide-spread erosion over a short period of time is alarming and suggests factors other than long-term sea-level rise may be influencing change. Shoreline erosion might be associated with climate events such as periods of droughts experienced in Georgia during the 1980s and 1990s. Furthermore, changes in the hydrodynamic properties in adjacent tidal inlets might have played a major role. Such changes could have been brought on by human activities such as dredging of inlet/back-barrier channels. An increase in tidal prism, a potential consequence of dredging, can cause back-barrier channels to dilate and encroach on adjacent barrier shore. As stated above, the actual mechanism(s) driving shoreline erosion remain unclear. What is known is that artificially stabilized shoreline segments, as identified on aerial photographs, have little or

no beach/marsh fronting them and have shifted the erosion problem to areas immediately adjacent to the structure. Evidence of this can be found along the Dungeness dock (field site CI-1) area along the seawall and along Plum Orchard's bulkhead at site CI-3 (Figures 4 & 5). Shorelines adjacent to the seawall at Dungeness dock are offset landward 5 to 10 m from shifting of erosion hot spots produced by tidal processes and wave action.

Era IV (1857 to 2002)

Era IV encompasses the entire record of historical shoreline data and reveals the long-term shoreline change trends. Throughout the entire study period spanning 1857 to 2002, shoreline change has varied both in magnitude and spatial extent along the back-barrier (Figures 2 & 3). A graph of average annual shoreline change rates in Figure 3 best illustrates the long-term behavior of the back-barrier shore for each zone. Although the island-wide average shoreline erosion rate was -0.14 m/yr (± 0.08 m/yr) for all calculated transects, over two-thirds of the island had an average shoreline recession rate of -0.35 m/yr for transects with only net erosion (Table 1). Furthermore, Figure 3 reveals that Zones II, IV, VI, VIII, and X have experienced long-term erosion. When viewed from a coastal management standpoint, these Zones could be considered erosion hotspots or areas of concern, especially the shoreline along Zone II, given the frequency and magnitude of erosion suffered in that area.

Although Zone I has experienced long-term accretion, it also should be considered an area of concern because it is highly likely that the elongation of the southerly spit region will undergo physical alteration. In other words, shoreline morphology within the zone is affected by inlet processes and sensitive to changes in sedimentation rates and inlet channel hydraulics. Because the St. Marys Inlet is artificially stabilized and maintained, elongation of the spit is restricted to the inlet flood channel's present position between the jetties. This confinement places the shore immediately adjacent to the active channel which can lead to dramatic shifts of

shoreline positions. These shifts in shoreline position appear to be caused by the attachment and subsequent erosion of flood delta shoals along the back-barrier shoreline adjacent to the inlet. Since the emplacement of the north and south jetties during the late 1800s, the shoreline position along Zone I has been in a state of fluctuation far greater than any other zone as evidenced in Figures 2 and 3.

The Zone II Erosion Hotspot (Dungeness Docks)

The Dungeness docks (Site CI-1) are located within Zone II and is an area of concern (Figure 5). The shoreline at this site is mainly a low bluff (2-3 m). The dock platform extends nearly 20 meters from a seawall over 260 m long, that armors the shoreline. Construction of the seawall took place in the early 1900s and has undergone modifications since then to extend and reinforce the structure. Since 1857, the shoreline has retreated approximately 50 m immediately adjacent to the dock (Figure 5). However, rapid shoreline erosion at points 300 m south and north of the dock has resulted in a loss of almost -132 m and -67 m respectively (Figure 5).

Erosion along this region is likely enhanced by end-around effects that occur at the ends of the seawall. The end-around effect is an increase in erosion due to scour caused by the displacement of wave/current energy from the seawall onto the adjacent natural shoreline. Typically, shoreline erosion rates are higher immediately adjacent to hard structures such as seawalls. Furthermore, Pleistocene semiconsolidated humate sands and muds outcrop along portions humate sandstones and muds of the shoreline also appears to be enhancing erosion rates (Figure 5). Field investigations of zones where these strata outcrop the outcrops of the semiconsolidated sands and muds revealed headlands where erosion was greater on either side of the headland. The effect of these headlands illustrate the importance of existing geologic framework in shoreline change (Riggs and others, 1995).

Given the rapid rates of erosion, as evidenced in both GIS analyses and field observations, it is highly likely that archaeological sites

CUMBERLAND ISLAND BACK-BARRIER SHORELINE CHANGE

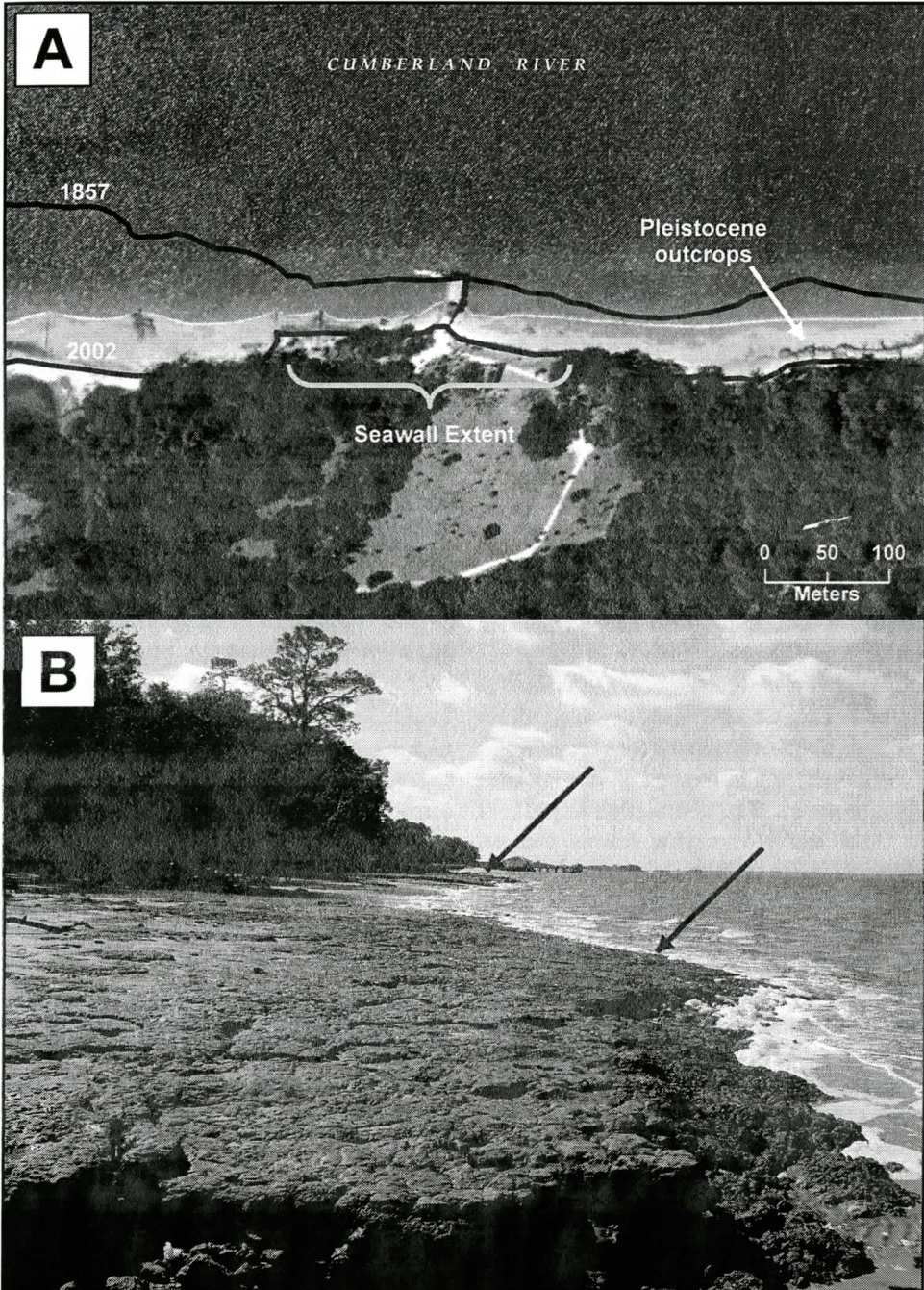


Figure 5. Shoreline erosion along field site CI-1 (Dungeness Docks) located on Cumberland Island, Georgia. A 2002 vertical aerial photograph (a) depicts the Dungeness docks, seawall, and historical shorelines from 1857 and 2002 and a 2005 ground photograph (b) depicts Pleistocene mini-headlands flanking a sandy pocket beach. The seawall is holding the shoreline in place around the docks and causing an erosional offset of 50+ m to the adjacent natural shoreline immediately south (left in photo) of the structure.

located within less than 3 m of the shoreline will become endangered within the next 2 to 5 years. Furthermore, it is reasonable to assume that these areas are especially sensitive to boat-wake and wind-generated wave activity (storms) as short-term shoreline erosion factors. Combined with inlet dynamics, the above-mentioned factors likely exacerbate erosion along a shoreline whose erosion patterns appear to be dictated by the complex interplay between long-term sea-level rise and the geological framework. Therefore, it becomes imperative that short-term erosion processes that are caused by anthropogenic activities are effectively managed for the protection of sensitive natural and cultural resources within this area.

DISCUSSION

The Cumberland Island back-barrier shore, though not as dramatically dynamic a feature as the oceanfront shoreline, remains in a constant state of relatively slow change. When viewed in terms of decades and/or century-long timeframes, it is ultimately shaped by a complex set of factors operating in concert at varying time and length scales. The cumulative impacts of factors such as sea-level rise, storms, channel movements, inlets, human activity, and the existing geologic framework appear to have led to shoreline erosion along most of the back-barrier length. For that reason, from a management perspective, it is important to have adequate historical shoreline data to investigate trends of back-barrier changes and to eventually relate the changes to the dominant factors influencing the observed trends. Although the present database is limited to 10 historical shoreline positions, noticeable shoreline change trends emerged and are reasonably linked to various factors such as inlet dynamics, geologic framework, and human activity. However, a more detailed shoreline dataset is needed to more precisely link shoreline behavior to long- and short-term factors.

Based on the trends found in the GIS analysis, coupled with field observations, five primary shorelines segments are subject to chronic erosion: Zones II, IV, VI, VIII, and X. These

erosion zones, though not equal in length, are distributed along various reaches that punctuate the length of the island. Although storms have had an obvious impact on the entirety of the island's shoreline, the development and persistence of these erosion zones along Cumberland Island are most certainly related to complex processes associated with adjacent inlets, sea-level rise, tidal channel dynamics, boat wakes, and even biological activity (grazing by horses, deer, and other livestock). Understanding the nature and principle causes of the shoreline losses in these areas, which are zones of higher erosion rate as compared to those of adjacent shoreline reaches, is critical to developing a sound back-barrier management and preservation plan.

Finally, using methods developed in this study, the authors are currently involved with projects to conduct new, improved shoreline change studies of the Georgia coast. The aim of these studies is to improve upon previous shoreline investigations by developing new GIS-based tools for analyzing shorelines, extracting high resolution shoreline data from aerial photography and coastal survey maps, and performing field observations along the Georgia coast. More importantly, these studies will address the entire barrier island's shoreline, not just the oceanfront. Ultimately, techniques used in this and future studies will be applicable on a global scale.

ACKNOWLEDGEMENTS

The authors would like to thank Joan Rikon of the National Geodetic Survey for her help with providing access to various imagery datasets. Brad Sprinkle and Donnie Richardson provided access to the Georgia Department of Transportation air photo library. Dr. Rebecca Dodge of GAView and the University of West Georgia (UWG) provided some imagery and computing resources to aid with the GIS analysis. Special thanks to John Fry (NPS, Cumberland Island National Seashore) for providing funding and numerous resources throughout the course of the project. UWG Faculty Research Grants to DMB are also gratefully acknowledged.

LITERATURE CITED

- Anders, F.J. and Byrnes, M.R., 1991. Accuracy of shoreline change rates as determined from maps and aerial photographs. *Shore and Beach*, 59(1), 17-26.
- Camfield, F.E., and Morang, A., 1996. Defining and interpreting shoreline change. *Ocean and Coastal Management*, Vol. 32, No. 3, pp. 129-151.
- Clayton, T.D., Taylor, L.A., Cleary, W.J., Hosier, P.E., Graber, P., Neal, W.J. and Pilkey, O.H., 1992. *Living with the Georgia Shore*. Duke University Press, Durham, North Carolina, 145p.
- Crowell, M., Leatherman, S.P. and Buckley, M.K., 1991. Historical Shoreline Change: Error Analysis and Mapping Accuracy. *Journal of Coastal Research*, 7(3), 839-853.
- Dolan, R., Hayden, B.P., May, P. and May, S., 1980. The reliability of shoreline change measurements from aerial photographs. *Shore and Beach* 48(4), 22-29.
- Frey, R.W., 1973. The Neogene of the Georgia Coast. 8th Annual Field Trip of the Georgia Geological Society. The Department of Geology, University of Georgia, 102p.
- Griffin, M.M., and Henry, V.J., 1984. Historical changes in mean high water shoreline of Georgia, 1857-1982. *Georgia Department of Natural Resources Bulletin* 98, 96 p.
- Honeycutt, M.G., Krantz, D.E., and Crowell, M., 2002. Role of nearshore geology and rate calculation methods in assessing coastal erosion hazards, *Proceedings of Solutions to Coastal Disasters'02* (San Diego, California), pp.582-595.
- Jackson, C.W., 2004. *Quantitative Shoreline Change Analysis of an Inlet-Influenced Transgressive Barrier System: Figure Eight Island, North Carolina*. MS Thesis, University of North Carolina at Wilmington.
- Langley, S.K., C.R. Alexander, D.M. Bush, and C.W. Jackson, 2003. Modernizing Shoreline Change Analysis in Georgia Using Topographic Survey Sheets in a GIS Environment. In Byrnes, Mark R., Crowell, Mark, and Fowler, Cindy, (eds.), *Shoreline Mapping and Change Analysis: Technical Considerations and Management Implications*, *Journal of Coastal Research Special Issue* 38, p. 168-177.
- Moore, L. J., 2000. Shoreline mapping techniques. *Journal of Coastal Research*, 16(1), 111-124.
- Nash, J.G., 1977. Historical changes in the mean high water shoreline and nearshore bathymetry of south Georgia and north Florida. Athens, Georgia: University of Georgia, Master's thesis, 148 p.
- Riggs, Stanley R., William J. Cleary, and Stephen W. Snyder, 1995. Influence of inherited geologic framework on barrier shoreface morphology and dynamics, *Marine Geology*, Vol. 126, Issue 1-4, pp.213-234
- Thieler, R.E. and Danforth, W.W., 1994a. Historical shoreline mapping (I): improving techniques and reducing position errors. *Journal of Coastal Research*, 10(3), 549-563.
- Thieler, E. Robert, and William W. Danforth, 1994b. Historical shoreline mapping; (II), Application of the Digital Shoreline Mapping and Analysis Systems (DSMS/DSAS) to shoreline change mapping in Puerto Rico, *Journal of Coastal Research*, 10(3), 600-620.
- Thieler, E. R., Martin, D., and Ergul, A., 2003. The Digital Shoreline Analysis System, version 2.0: Shoreline change measurement software extension for ArcView. USGS Open-File Report 03-076.
- U.S. Army. 1971. *National Shoreline Study, Regional Inventory Report: South Atlantic-Gulf Region, Puerto Rico, and Virgin Islands*. U.S. Army Engineering Division, South Atlantic, Atlanta, GA, 388 p.

SUBAQUEOUS KARSTIFICATION OF THE TOP OF THE CLAYTON FORMATION LIMESTONE (LOWER PALEOCENE) NEAR FT. GAINES, GEORGIA (USA)

CARL R. FROEDE JR.

*U.S. Environmental Protection Agency
Region 4
Atlanta, Georgia 30303-8960*

JOHN K. REED

*915 Hunting Horn Way
Evans, Georgia 30809*

ABSTRACT

A karst surface containing numerous solution pits occurs on the top of the Clayton Formation limestone (lower Paleocene) in the proximity of Fort Gaines, Georgia (USA). Previous workers have interpreted this karst surface as having developed in a subaerial paleosetting which was subsequently buried by transgressive deposits. However, our examination of numerous carbonate outcrops along the Chattahoochee River and Town Creek suggests an alternative explanation. Apparently, the karstic surface and its associated pits and cavities resulted from the decomposition of overlying organic-rich sediments (i.e., the Gravel Creek Sand Member of the Nanafalia Formation - middle Paleocene) coupled with the downward expulsion of acidic connate fluids. Deepest dissolution appears to occur preferentially as pits and cavities within the limestone along joints likely developed in association with the regional uplift of southwestern Georgia during the Lower Paleogene. Subaqueous karst development ended with the cessation of acid production from the decomposing organics within the compacting Gravel Creek Sand Member.

INTRODUCTION

Karst development is typically associated with subaerial settings and is thought to occur predominately as a function of precipitation-driven chemical dissolution. A karst surface on

top of the Clayton Formation limestone is exposed along portions of the Chattahoochee River south of the Walter F. George Lock and Dam and along the sidewalls of Town Creek adjacent to Fort Gaines, Georgia (USA) [Figures 1 and 2]. We investigated this area in an effort to understand the geological history and geochemical processes responsible for the development of the karst surface on the Clayton Formation limestone and its possible relationship to the overlying Gravel Creek Sand Member infill.

STRATIGRAPHIC AND PALEONTOLOGICAL DESCRIPTION

Many geologic investigations were conducted along this portion of the Chattahoochee River before the construction of the Walter F. George Lock and Dam in 1962 (e.g., Langdon, 1891; Smith and others, 1894; Veatch and Stephenson, 1911; Cooke, 1943; Toulmin and Winters, 1954; Toulmin and LaMoreaux, 1963; Toulmin and others, 1964). Additional studies occurred following the creation of Lake Eufaula (e.g., Marsalis and Friddell, 1975; Swann and Poort, 1979; Reinhardt and Gibson, 1980; Gibson, 1982). Investigation of the various exposures and outcrops within this area of southeastern Alabama and southwestern Georgia has resulted in the development of a stratigraphic column which is unique to this part of the southeast. Strata exposed along the Chattahoochee River do not, in many instances, directly correspond lithologically to the type localities on the Gulf Coastal Plain. The local stratigraphic section is presented as Figure 3.

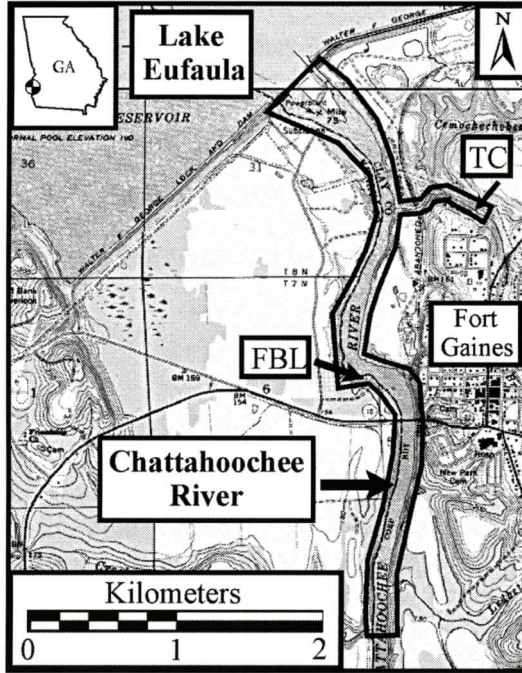


Figure 1. Base map of the area of study. Due to the sedimentary cover above the Clayton Formation limestone, the best exposures of the carbonate occur along the sidewalls of the local creeks and along the banks of the Chattahoochee River south of the Walter F. George Lock and Dam. The black line encloses the area of study for this investigation. The Franklin Boat Landing (FBL) provides an excellent land-based locale from which to examine the contact between the Clayton Formation and overlying Nanafalia Formation. Town Creek (TC) also provides excellent sidewall exposures of the dissolutional contact. Map constructed from the United States Geological Survey 7.5 minute quadrangle for Fort Gaines, ALA.-GA., 1969. The contour interval is 10 feet.



Figure 2. Photograph of the top of the Clayton Formation limestone exposed along the Chattahoochee River just south of the Franklin Boat Landing. The lighter limestone surface contains numerous solution pits filled with Gravel Creek Sand Member sediments (white outlined darker areas).

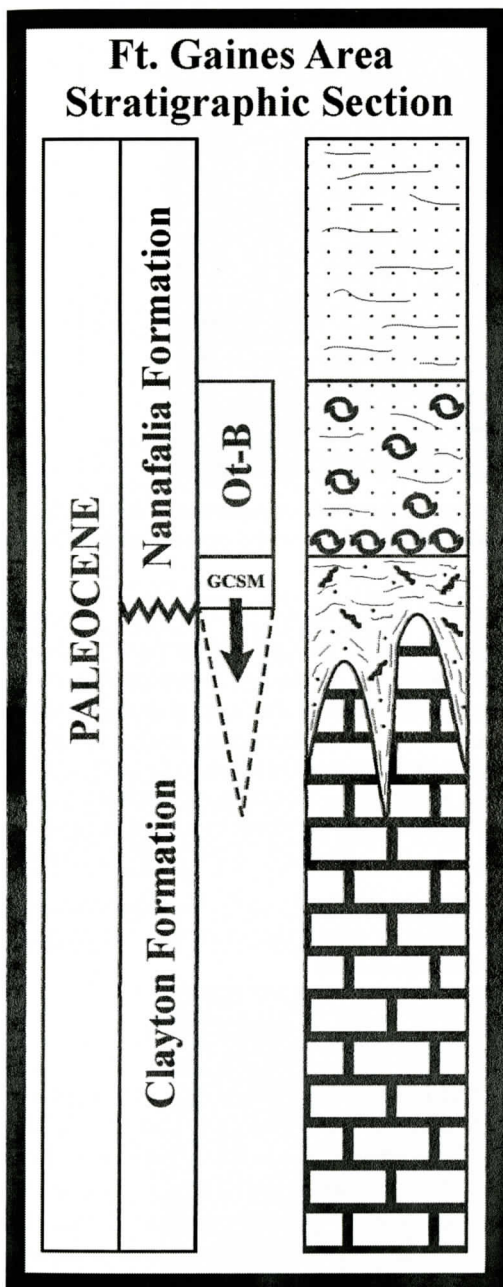


Figure 3. Generalized stratigraphic section of the study area around Fort Gaines, Georgia. A significant unconformity occurs between the Clayton Formation and the overlying Nanafalia Formation. The Gravel Creek Sand Member (GCSM) contains macro-paleontologic remains (e.g., petrified wood, lignite, marine fish fossils) suggestive of an estuarine to lagoonal paleo-setting. Sedimentation of the GCSM occurred as the top of the Clayton Formation limestone was dissolved (as indicated by the downward pointing arrow). Soft-sediment plastic flow features within the GCSM abound in and around the solution pits. The smooth sidewalls and floors of the cavities are not reflective of abrasion, but rather dissolution. In some instances, iron minerals (i.e., ferrihydrite and goethite) have precipitated along the solution pit sidewalls. The *Odontogryphaea thirsae* shell beds (Ot-B - hollow circles) cap the GCSM. See text for a description of the lithology. Modified from cross-sections in Marsalis and Friddell (1975), and Reinhardt and Gibson (1980).

From exposures along the Chattahoochee River, the Clayton limestone (lower Paleocene) is described as soft, creamy-yellow limestone containing echinoid spines and other obscure organisms (Cooke, 1943). Toulmin and LaMoreaux (1963) described the unit as an algal microcoquina composed largely of calcareous organic remains, calcareous algae, foramin-

ifera, shell fragments, bryozoans, and other small fossils. Due to its high calcareous algal content, Bryan (1993) defined the carbonate unit as a rhodolithic limestone.

A significant unconformity of uncertain duration separates the Clayton Formation from the overlying Nanafalia Formation (middle Paleocene). Cooke (1943) described the Nanafalia

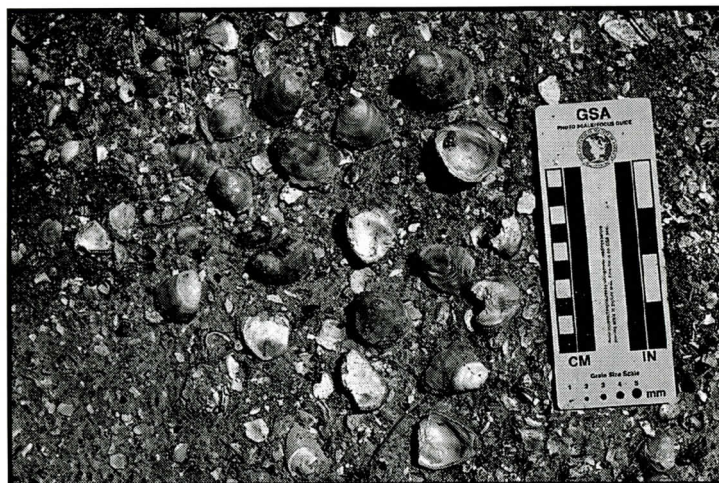


Figure 4. Relatively flat lying *Odontogryphaea thirsae* beds occur directly above the Gravel Creek Sand Member sediments. These shells have weathered from a clayey sand outcrop at the Franklin Boat Landing. Scale in inches and centimeters.

clastic sediments as fine, white, micaceous sand. Marsalis and Friddell (1975) identified the Nanafalia sediments as medium-gray, highly micaceous, carbonaceous, lignitic, fossiliferous silt and fine sand with some calcareous siltstone nodules that are septarian in character. They correlated the karst cavity fill material to the Gravel Creek Sand Member of the Nanafalia Formation and described it as a medium- to coarse-grained sand with clay and lignite (Marsalis and Friddell, 1975). Swan and Poort (1979) defined the Gravel Creek Sand fill as cross-bedded, kaolinitic, and highly micaceous, with medium to coarse-grained sands. The unit is covered by additional clastic sediments containing *Ostraea thirsae* (now identified as *Odontogryphaea thirsae*). The fossil invertebrates occur in a relatively flat-lying layer readily discernible at the Franklin Boat Landing (Figure 4).

Langdon (1891; Smith and others, 1894) first identified the massive carbonate unit exposed along the Chattahoochee River near Fort Gaines as the "Clayton Limestone." Cooke (1943) later incorporated the limestone into the Clayton Formation. Only recently has some effort been made to subdivide the massive carbonate unit into possible stratigraphic members. Fluegeman (1986, 1993) collected foraminifera from near the top of the carbonate unit exposed at the

Franklin Boat Landing. His analysis indicated that the microfossils are not necessarily age restricted to the Clayton Formation-McBryde Limestone Member. The microfossils could extend the age of the carbonate to the top of the Porters Creek Formation-Matthews Landing Marl Member (middle Paleocene) [Figure 5]. No further paleontological work has been conducted on the limestone (Fluegeman, 2005) and its age and position within the Chattahoochee River Valley stratigraphic section is subject to further refinement.

PALEOSETTING

The Clayton Formation carbonate is postulated to have formed on the northern side of the Gulf Trough during the lower Paleocene (Bryan, 1993). Unfortunately, the exact position of the limestone on the submerged shelf cannot be deduced from either its lithologic or paleontologic content. However, rhodoliths within the carbonate unit (Figure 6) suggest strong currents associated with the Suwannee Strait (see Huddleston, 1993, Figure 49, p. 108). Rhodoliths are essentially red algal concentric encrusted concretions often formed by rolling in turbulent water currents (Neuendorf and others, 2005). Based on the size and flattened nature of these concretions, Carter and others (1995) pro-

SUBAQUEOUS KARSTIFICATION

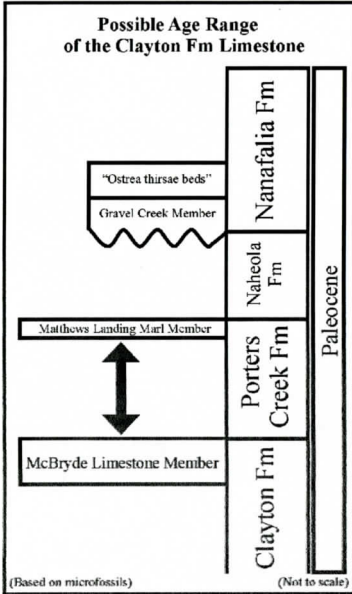


Figure 5. Generalized stratigraphic column showing the possible age range of the top of the carbonate unit exposed at the Franklin Boat Landing, based on foraminifera. To alleviate confusion, we identify the carbonate unit as the Clayton Formation limestone recognizing the possibility that additional study may yield a different age assignment and correlate to a different formation/member.

posed that they reflect the close proximity of the limestone unit to the former Gulf Trough shelf

edge [Note: The Gulf Trough and Suwannee Strait occur within the subsurface along the same axis from Apalachicola, Florida across the southern Georgia coastal plain. The Gulf Trough was an embayment which terminated in central Georgia, near McRae, while the Suwannee Strait extended to the Atlantic Ocean at Charleston, South Carolina]. The karst surface on the top of the Clayton Formation carbonate is suggested to have developed in a subaerial setting (Bryan, 1993; Carter and Manker, 1995), possibly in association with a sea level lowstand (Baum and Vail, 1987).

The Nanafalia Formation section exposed along the Chattahoochee River has been interpreted as representing an ascending transition from restricted-marine to more shallow marine conditions (Reinhardt and Gibson, 1980). Swan and Poort (1979) defined the Gravel Creek Sand Member of the Nanafalia Formation as fluvial to marginal marine. Baum and Vail (1987) interpreted these clastic sediments as incised valley fill deposits. Similarly, Bryan (1993) proposed that the Gravel Creek Sand sediments were transgressive, channel-fill sands.

KARSTIC SOLUTION PITS

Originally, Langdon (1891) and Smith and

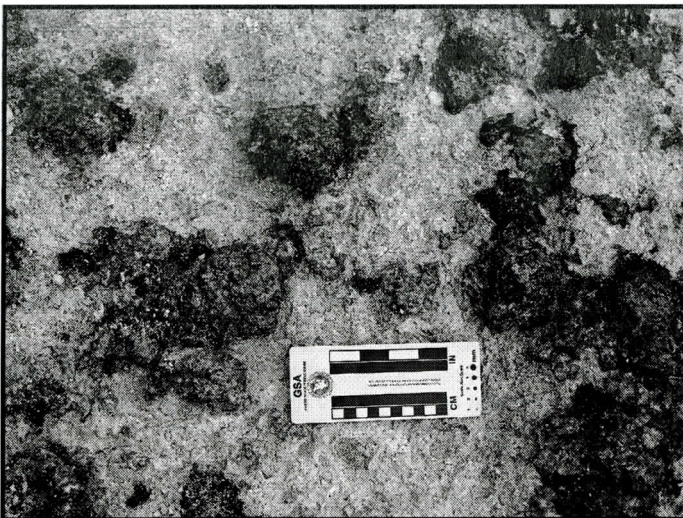


Figure 6. Rhodoliths weather out of a section of the Clayton Formation limestone at the Franklin Boat Landing. Scale in inches and centimeters.

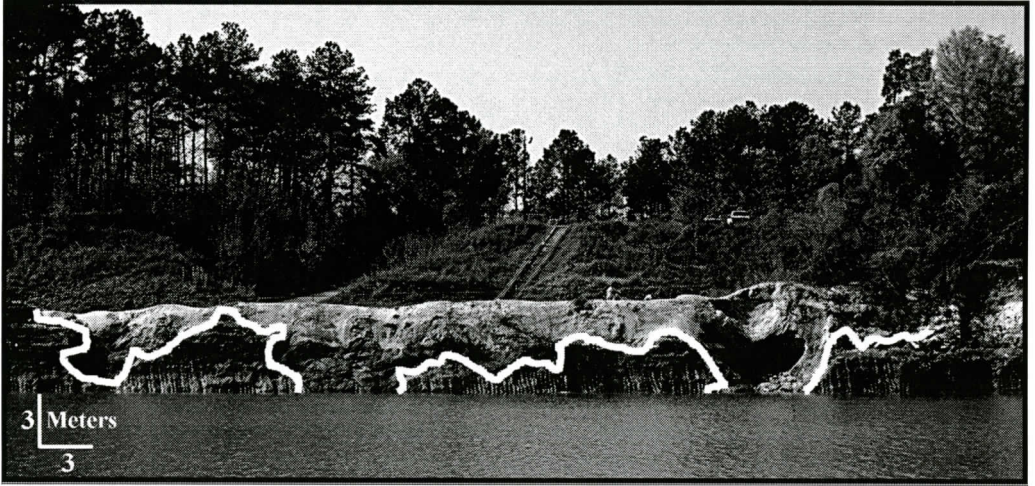


Figure 7. Numerous limestone pinnacles and intervening solution pits occur along the Chattahoochee River at the US Army Corps of Engineers, Franklin Boat Landing. The white line marks the contact between the limestone and overlying clastic sediments.

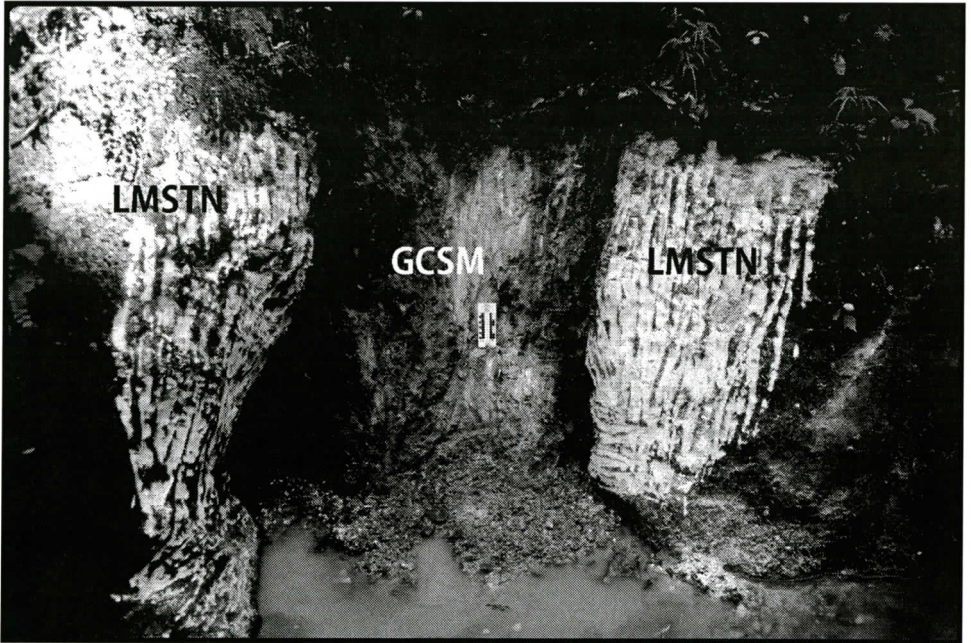


Figure 8. A cross-section through a vertical cylindrical conduit in the Clayton Formation limestone (LMSTN) exposed along Town Creek. The conduit is filled with Gravel Creek Sand Member (GCSM) sediments. The exposure has been scraped resulting in the striped pattern on the outcrop. Scale in the center of the image is in inches and centimeters.

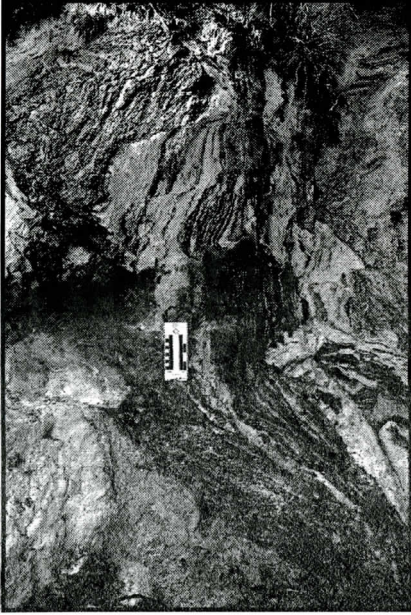


Figure 9. Sedimentary flow banding exhibited along a solution cavity sidewall at one of the pits located at the Franklin Boat Landing. As the limestone was dissolved, the overlying Gravel Creek Sand Member sediments flowed plastically into the expanding cavity. Scale in inches and centimeters.

others (1894) interpreted the clay-filled pits exposed along the top of the Clayton Formation limestone as potholes filled with sand lenses and clay. Likewise, Veatch and Stephenson (1911) defined the depressions in the limestone as scour-derived potholes that were later filled by overlying sediments. Cooke (1943) was the first to suggest that the pits formed by limestone dissolution. Toulmin and LaMoreaux (1963) described the solution pits as large and subcylindrical with some extending more than six meters deep. Today, access to the dissolution contact between the Clayton Formation limestone and overlying Nanafalia Formation clastic sediments is largely restricted to areas south of the Walter F. George Lock and Dam along the Chattahoochee River and Town Creek (Figures 7 and 8).

In the late 1970s, the US Army Corps of Engineers conducted a geological assessment of the Clayton Formation limestone as part of the ongoing maintenance activities associated with

the Walter F. George Lock and Dam. The carbonate unit was determined to be approximately 50 meters thick with cavity development occurring primarily along joints and joint sets (trending N 10°E and a secondary set at N 80°E with dips near vertical) within the upper 10 to 22 meters of limestone (US Army COE, 1978). The joints within the Clayton limestone probably developed in association with the regional uplift this area experienced since the close of the Upper Cretaceous (e.g., Stephenson, 1928; Cooke, 1943; Froede and Williams, 2004; Riggs, 1979; Reinhardt and others, 1984). The dissolutional pits and cavities originate from the surface of the carbonate and do not appear to support development in the subsurface by either historic groundwater upwelling or other paleo-hydrologic conditions.

Within the solution pits, we noted features suggestive of soft sediment flow (Figure 9). This was especially noteworthy along many of the cavity sidewalls where the sedimentary fabric occurred in a wall-parallel orientation reflective of plastic flow. Away from the karst sidewalls some of the infilled clastic sediments appear to retain its original bedding. However, the orientation of these sediments within the karstic pits may not reflect the original depositional conditions.

In many instances, iron oxides (i.e., ferrihydrite and goethite) occur within the clastic sediments that line the solution pit sidewalls. Previous investigators have suggested that the iron is possible evidence of a subaerially-developed paleosol (Carter and Manker, 1995). However, based on the sedimentology of the infill materials and position of the iron within the solution cavity, it is more likely that the iron was precipitated along the solution pit sidewalls with the neutralization of the acidic fluids. The iron would have been mobilized by the anaerobic and acidic conditions associated with the breakdown of the organic-rich sediments (see Peterson, 1971; Norton, 1973; Mann and Ollier, 1985). The dissolved iron would then move into the developing cavity as the acidic ferrous carbonate fluids were expelled downward by compaction.



Figure 10. A diagenetically altered clay (kaolin?) fills a cavity in the Clayton Formation limestone. This exposure is along the Chattahoochee River south of the Franklin Boat Landing. Scale in centimeters and inches.

KAOLIN DEVELOPMENT IN SOLUTIONAL VUGS

We noted several areas where the vug-filling clays had altered from their typical medium-gray color to a white (kaolin?) clay (Figure 10). Recent work on the kaolins in central Georgia suggests that microorganisms contribute to the formation of kaolin. An organic-rich mud can, through a combination of aerobic and anaerobic environments, stimulate bacteria to transform the organic-rich silts and clays into kaolin (Kogel and others, 2000). The alteration processes are also mediated by acids generated during the decomposition of the organic material (Pickering and others, 2003). Even without the aid of bacteria, kaolin can form under acidic anaerobic groundwater conditions; the leaching of minerals from silts and clays transform the remaining aluminosilicates into kaolin (Froede and Rucker, 2006; Wright and others, 1992).

SUMMARY AND CONCLUSIONS

The Clayton Formation limestone exposed in

our area of study likely formed in relatively clear water conditions along the northern Gulf Trough/Suwannee Strait. Tectonic uplift of the Piedmont across southwestern Georgia dropped sea level and allowed the organic-rich estuarine to lagoonal Gravel Creek Sand Member sediments to prograde seaward across the top of the Clayton Formation limestone. The breakdown of the organic materials within these sediments created acidic connate water expelled downward with additional burial and compaction. Concomitant joint development within the limestone provided preferential zones for chemical dissolution and karstic cavity formation. The overlying Gravel Creek Sand Member sediments flowed plastically into the developing solution pits as additional sediments were deposited.

Dissolved iron derived from the organic materials and clastic sediments migrated with the acidic connate water into the developing solution pits. Neutralization of these fluids caused the precipitation of iron from solution along cavity sidewalls. Acidic and anaerobic conditions within many of the solution pits, possibly

SUBAQUEOUS KARSTIFICATION

in combination with bacterial action, promoted the authigenic conversion of some of the infilling clays to kaolin. The end of acid production terminated further cavity development and the Gravel Creek Sand Member sediments were then buried by the estuarine to lagoonal *Odonotryphaea thirsae* beds of the Nanafalia Formation.

Solution cavities within the Clayton Formation limestone developed downward from the limestone surface with smooth sidewalls and floors. We found no indication that these features formed by sediment abrasion or subterranean karst development. The original bedding of the overlying Gravel Creek Sand Member has been altered in and around the solution pits. Sedimentary flow features occur parallel to cavity sidewalls. The bedding of the sediments infilling the various solution pits does not support the concept that they were deposited into pre-existing karst pits. Instead, the karst surface that developed on the top of the Clayton Formation limestone formed under subaqueous conditions due to chemical dissolution by overlying acid-producing organic-rich sediments.

ACKNOWLEDGMENTS

We thank A.J. Akridge and W.J. Neal for their helpful and constructive comments. Both T. Harmon-Unongo and J.N. Wright furnished excellent reference assistance. We are grateful for the excellent help and field assistance provided by E.L. Williams and C.R. Froede Sr. Mr. J.H. Sanders, with the U.S. Army Corps of Engineers, supplied valuable geologic information about the Clayton Formation limestone. For the senior author, this work neither represents the views or opinions of the U.S. Environmental Protection Agency, nor was this investigation conducted in any official capacity.

REFERENCES CITED

- Baum, G.R., and Vail, P.R., 1987, Sequence stratigraphic concepts applied to Paleogene outcrops, Gulf and Atlantic Basins: Lafayette, Louisiana, Lafayette Geological Society guidebook.
- Bryan, J.R., 1993, Late Eocene and early Oligocene carbonate facies and paleoenvironments of the eastern Gulf Coastal Plain, in Kish, S.A., ed., Geologic field studies of the Coastal Plain in Alabama, Georgia, and Florida: Southeastern Geological Society, Tallahassee, FL, Guidebook 33, p. 23-47.
- Carter, B., and Manker, P., 1995, Stop 5: Franklin Landing, Henry County, AL., Paleocene karst surface on the Clayton Formation, in Carter, B.D., ed., Paleogene carbonate facies and paleogeography of the Dougherty Plain region: Georgia Geological Society, Guidebook 15, p. 86.
- Carter, B.D., Manker, J.P., and Bryan, J.R., 1995, Chapter 3: Facies and paleogeography, in Carter, B.D., ed., Paleogene carbonate facies and paleogeography of the Dougherty Plain region: Georgia Geological Society, Guidebook 15, p. 29-51.
- Cooke, C.W., 1943, Geology of the Coastal Plain of Georgia: Washington, DC, US Geological Survey Bulletin 941.
- 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., 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: Southeastern Geological Society, Tallahassee, FL, Guidebook 33, p. 42.
- Fluegeman, R.H., Jr., 2005, Personal communication.
- Froede, C.R., Jr., and Rucker, B.R., 2006, Iron Mountain, Santa Rosa County, Florida: A paleogroundwater table inverted relief feature: Southeastern Geology, v. 44, p. 137-145.
- 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., 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 Geological Survey Information Circular 53, p. 53-63.
- Huddlestun, P.E., 1993, A revision of the lithostratigraphic units of the Coastal Plain of Georgia the Oligocene: Atlanta, Georgia, Georgia Geological Survey Bulletin 105.
- Kogel, J.E., Pickering, S.M., Jr., Shelobolina, E.S., Yuan, J., Chowns, T.M., and Avant, D.M., Jr., eds., 2000, Geology of the commercial kaolin mining district of central and eastern Georgia: Atlanta, Georgia, Georgia Geological Society Guidebook 20.
- Langdon, D.W., Jr., 1891, Variations in the Cretaceous and Tertiary strata of Alabama: Geological Society of America Bulletin, v. 2, p. 587-606.
- Mann, A.W., and Ollier, C.D., 1985, Chemical diffusion and ferricrete formation: Catena Supplement 6, Soils and Geomorphology, v. 6, p. 151-157.
- Marsalis, W.E., and Friddell, M.S., eds., 1975, A guide to

- select Upper Cretaceous and Lower Tertiary outcrops in the lower Chattahoochee River Valley of Georgia: Atlanta, Georgia, Georgia Geological Survey Guidebook 15.
- Neuendorf, K.K.E., Mehl, J.P., Jr., and Jackson, J.A., eds., 2005, *Glossary of geology*. Fifth edition. American Geological Institute. Alexandria, Virginia.
- Norton, S.A., 1973, Laterite and bauxite formation: *Economic Geology*, v. 68, p. 353-361.
- Peterson, U., 1971, Laterite and bauxite formation: *Economic Geology*, v. 66, p. 1070-1071.
- Pickering, S.M., Jr., Elser, A.M., Shelobolina, E.S., Anderson, J. R., Jr., and Avant, D. M., Jr., 2003, Minerals in transition; Examples of intensive weathering alteration in the kaolin mining district of central Georgia, *in* Elliot, C.W., ed., *Classic clays and minerals*: Athens, Georgia, Clay Mineral Society and Mineralogical Society of America field trip guidebook, p. 68-84.
- Reinhardt, J., and Gibson, T.G., 1980, Upper Cretaceous and lower Tertiary geology of the Chattahoochee River Valley, western Georgia and eastern Alabama, *in* Frey, R.F., ed., *Excursions in southeastern geology, Volume II: Georgia Geologic Survey Guidebook 22*, p. 385-463.
- 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.
- Riggs, S.R., 1979, Phosphorite sedimentation in Florida — a model phosphogenic system: *Economic Geology*, v. 74, p. 285-314.
- Smith, E.A., Johnson, L.C., and Langdon, D.W., Jr., 1894, Report on the geology of the Coastal Plain of Alabama: Brown Printing, Montgomery, Alabama, Alabama Geological Survey 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: *Transactions of the Gulf Coast Association of Geological Societies*, v. 30, p. 387-395.
- Toulmin, L.D., and LaMoreaux, P.E., 1963, Stratigraphy along the Chattahoochee River, connecting link between Atlantic and Gulf Coastal Plains: *American Association of Petroleum Geologists Bulletin*, v. 47, p. 385-404.
- Toulmin, L.D., LaMoreaux, P.E., and Newton, J.G., 1964, Profile showing geology along the Chattahoochee River: Tuscaloosa, Alabama, Alabama Geological Survey Map 28.
- 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.
- US Army Corps of Engineers, 1978, Study of permanent solutions to underseep problems, design memorandum: Mobile, Alabama.
- 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.
- Wright, V.P., Sloan, R.J., Valero Garcés, B., and Garvie, L.A.J., 1992, Groundwater ferricretes from the Silurian of Ireland and Permian of the Spanish Pyrenees: *Sedimentary Geology*, v. 77, p. 37-49.

