Journal of Coastal Research	22	4	836–846	West Palm Beach, Florida	July 2006

Foraminiferal and Sedimentary Record of Late Holocene Barrier Island Evolution, Pea Island, North Carolina: The Role of Storm Overwash, Inlet Processes, and Anthropogenic Modification

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ABSTRACT

CULVER, S.J.; AMES, D.V.; REIDE CORBETT, D.; MALLINSON, D.J.; RIGGS, S.R.; SMITH, C.G., and VANCE, D.J., 2006. Foraminiferal and sedimentary record of late Holocene barrier island evolution, Pea Island, North Carolina: the role of storm overwash, inlet processes, and anthropogenic modification. *Journal of Coastal Research,* 22(4), 836–846. West Palm Beach (Florida), ISSN 0749-0208.

Foraminiferal and sedimentary data, supplemented with geochemical dating and ground-penetrating radar transects, show that the barrier island at Pea Island National Wildlife Refuge just north of Rodanthe, North Carolina, has been dominated by a combination of inlet and overwash processes for at least 1000 years. The stratigraphic record of several vibracores does not preserve every, or even many, overwash events but, instead, is characterized by three to four fining-upward sequences. The last three commence with overwash sand or gravel that is overlain by a variety of finer-grained estuarine, inlet, and marsh deposits. The dynamic nature of this segment of the Outer Banks was muted in the late 1930s by construction of artificial barrier dune ridges, extensive planting of grass and shrubs, and construction of Highway 12 in 1953. Subsequently, the road and barrier dune ridge were rebuilt and relocated several times following storm events.

ADDITIONAL INDEX WORDS: *Foraminifera, barrier islands, overwash, inlets.*

INTRODUCTION

Historic and prehistoric storm events on the Atlantic and Gulf of Mexico coasts of North America have left their imprint on the sedimentary and micropaleontological record that has accumulated during the past several hundred years (Collins, Scott, and Gayes, 1999; Culver *et al.,* 1996; Donnelly *et al.,* 2001a, 2001b; Hippensteel and Martin, 1998; Liu and Fearn, 1993; Liu and Fearn, 2000; Woo, Culver, and Oertel, 1997). Liu and Fearn (1993, 2000) used lithologic criteria to recognize major storm-driven overwash events in coastal (beach-ridge plain) lake environments of Alabama and Florida. They were able to reconstruct the history of major hurricane strikes and concluded that the Alabama coast has been struck by a category 4 or 5 hurricane every ~600 years on average during the past 3000 years (Liu and Fearn, 1993). In the Florida Panhandle, quiescent (3400–5000 and 0–1000 y B.P.) and active periods were recognized during the past 7000 years (Liu and Fearn, 2000).

Along the Atlantic coast in New Jersey and southern New England, Donnelly *et al.* (2001a, 2001b) used sedimentary criteria to recognize the record of intense hurricane landfalls for the past 700 years. Interbedded overwash sands and marsh deposits provided a vivid record of hurricane strikes.

Foraminiferal data have also proven useful in recognizing barrier island overwash deposits. Culver *et al.* (1996) and Woo, Culver and Oertel (1997) showed that overwash fans on Virginia's barrier islands contain benthic foraminiferal assemblages distinct from those of adjacent coastal environments. Collins, Scott, and Gayes (1999) recognized a specific storm event in coastal South Carolina (Hurricane Hugo in 1989) by identifying offshore benthic foraminifera in an overwash sand, sandwiched between salt marsh deposits. Multiple storm events were recognized by Hippensteel and Martin (1999) in coastal South Carolina. In this case, the offshore assemblage of benthic foraminifera contained in overwash deposits included Oligocene species derived from submarine outcrops immediately offshore from the study area.

North Carolina's Outer Banks form the easternmost projection of the United States south of New England (Figure 1) and are characterized by one of the highest energy regimes on the east coast (Riggs, 2002). This region, in part because of its eastward projecting nature, is also the site of regular landfall or near misses of generally northward tracking hurricanes. Several hurricane landfalls in the 1950s resulted in the appellation, "Hurricane Alley" (Barnes, 2001). During succeeding decades, a relatively quiet interval of hurricane activity coincided with unprecedented development of the coastal zone (Pilkey *et al.,* 1998). Several hurricane landfalls in the 1990s, together with severe winter nor'easters (Dolan,

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DOI: 10.2112/03-0103.1 received 10 September 2003; accepted in revision 26 May 2004.

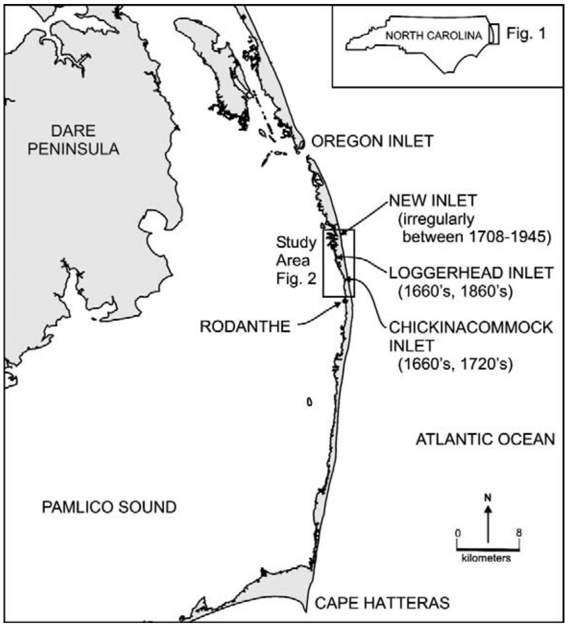


Figure 1. A portion of North Carolina's Outer Banks showing modern inlets and location of old inlets (New, Loggerhead, Chickinacommock) and their dates of opening (modified from Fisher, 1962) in the study area (boxed area enlarged in Figure 2) in the Pea Island National Wildlife Refuge.

LINS, and HAYDEN, 1988) illustrate the dangers of living in this zone.

The initial purpose of this project was to characterize the hurricane history of a portion of the Outer Banks by the overwash-event record preserved in the sediments and foraminiferal assemblages that have accumulated during the past several hundred years (*cf.* DONNELLY *et al.,* 2001a, 2001b). Therefore, we chose southern Pea Island as the study area, where historical records (BARNES, 2001) and sequential aerial photography (Figure 2) show frequent overwash events during the past 70 years. However, the stratigraphic record recovered in vibracores does not preserve a detailed overwash record. Rather the cores illustrate the combined roles of overwash, inlet processes, and human modification in this part of North Carolina's barrier islands.

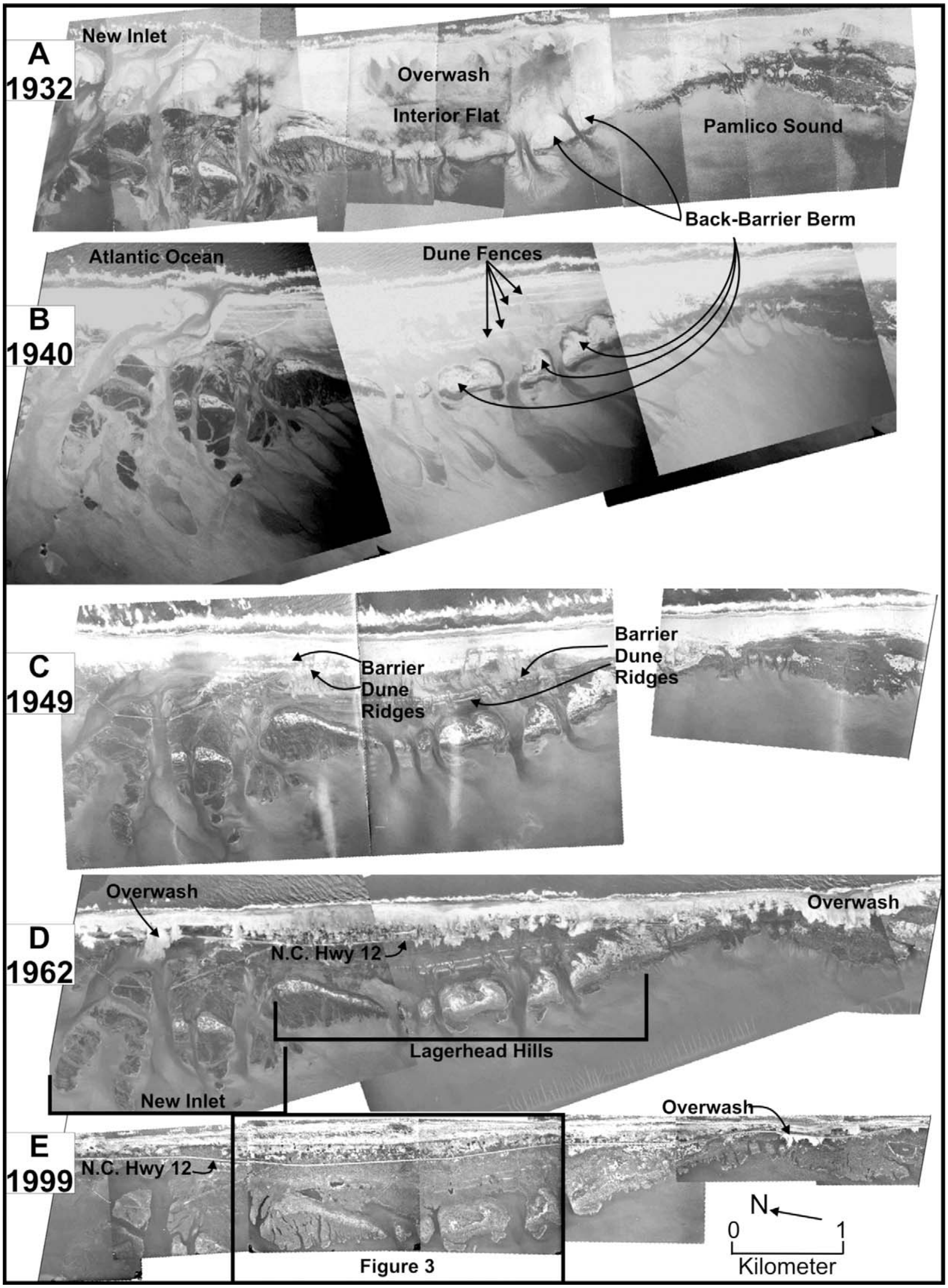
Study Area

The Pea Island National Fish and Wildlife Refuge, North Carolina, located on the easternmost extent of the barrier islands, about 40 km north of Cape Hatteras, has a documented history of inlets opening and closing since Europeans arrived in 1584. Chickinacommock Inlet, Loggerhead Inlet, and New Inlet (Figure 1) have produced an island morphology dominated by back-barrier flood tidal deltas at various stages of decay (Figure 2). The southern portion of the Refuge, between Rodanthe and the site of New Inlet (that closed in 1945), was a low-lying, barren sand island completely overwashed at high tides during the early 20th century (Figure 2a). In the late 1930s four parallel rows of sand fences were constructed (STRATTON and HOLLOWELL, 1940) to build barrier dune ridges to "protect" the island from the ocean's advances. By 1949, the artificial barrier dune ridges had effectively reduced oceanic overwash so that the low-lying flats behind the dunes became vegetated by salt marsh grasses in the lows and shrubs on higher ground (Figure 2c). Even the powerful Ash Wednesday Storm of 1962 did not overwash the island from sea to sound. Although the barrier dune ridges were breached, overwash was restricted to small fans that covered the highway that was constructed in 1953 (Figure 2d). Three hurricanes affected this area in 1999. Only the first, Hurricane Dennis, produced extensive overwash in the southern end of the study area where Pea Island is narrow and particularly prone to overwash (Figure 2d and 2e).

METHODS

Eight vibracores were taken along two transects (A, B) across the widest part of the overwash-dominated barrier island, as indicated by the 1932 aerial photograph from Highway 12 to the Lagerhead Hills back-barrier berm (Figures 2 and 3). Eleven additional augured holes provided information on the spatial extent of subsurface units (Figures 3 and 4). The cores were split, described, and subsampled for foraminifera. The distribution patterns of modern foraminifera were used as a model for paleoenvironmental interpretations of subsurface assemblages. Identification of benthic foraminiferal taxa were confirmed by comparison with type material housed in the Smithsonian Institution. Lead-210 (^{210}Pb) and cesium-137 (^{137}Cs) analyses were performed on fine-grained units at the Environmental Radioisotope Laboratory at East Carolina University (Greenville, North Carolina, U.S.A.). ^{137}Cs activities were measured using a well-type, high-purity germanium detector (Carberra Industries, Inc., Meriden, Connecticut, U.S.A.). The activity of ^{210}Pb was measured by alpha-spectrometry (alpha detector, Ortec, Oak Ridge, Tennessee, U.S.A.) following the methodology of NITTROUER *et al.* (1979). Supported ^{210}Pb was determined by gamma-emission of lead-214 (^{214}Pb) and bismuth-214 (^{214}Bi). Radiocarbon analyses were performed on bivalve shells and salt-marsh peat at Beta Analytic Inc. (Miami, Florida, U.S.A.).

Ground-penetrating radar (GPR) is an excellent tool for defining dune stratigraphy (AMES *et al.,* 2000; BRISTOW, CHROSTON, and BAILEY, 2000; BRISTOW, PUGH, and GOODALL, 1996; JOL, VANDERBURGH, and HAVHOLM, 1998; MALLINSON *et al.,* 2001) and barrier island stratigraphy within the fresh-water prism. Shallow-subsurface geophysical data were acquired using a GPR system (Subsurface Interface Radar System-2000, Geophysical Survey System Inc., North Salem, New Hampshire, U.S.A.) with a 200-MHz antenna. Data were acquired in the monostatic mode at a rate of 32 scans/s and a speed of 4 to 5 mi/h (8 km/h) along Highway 12 and off-road transects (Figure 3). Navigation data were acquired using a Trimble (Sunnyvale, California, U.S.A.) global positioning system (GPS), and differentially corrected positions were linked to the GPR data by waypoint and scan number. GPR data were processed (filtered and stacked) using RADAN software (version 2) (Geophysical Survey Systems, Inc., North Salem, New Hampshire, U.S.A.).


A
1932
New Inlet
Overwash
Interior Flat
Pamlico Sound
Back-Barrier Berm
B
1940
Atlantic Ocean
Dune Fences
C
1949
Barrier
Dune
Ridges
Barrier
Dune
Ridges
D
1962
Overwash
N.C. Hwy 12
Overwash
Lagerhead Hills
New Inlet
E
1999
N.C. Hwy 12
Overwash
Figure 3
N
0
1
Kilometer

RESULTS

Sedimentary Patterns

Transect B recorded the most extensive (deepest and oldest) sedimentary record. In the longest core (PI01S6), four fining-upwards sequences are present (Figure 4b). Other cores along transects A and B are shorter, and only two or three fining-upwards sequences were penetrated (Figure 4a, b). The basal unit of each sequence is a medium-to-fine, sometimes gravelly (especially in sequence 1; PI01S6, PI01S9), moderately to poorly sorted, clean-quartz sand. Organic matter increases up-core within each sequence, and the sediment changes to a slightly muddy, fine, miceous sand in sequence 3 (PI01S2); a salt-marsh peat rooted in mud in sequence 2 (PI01S6, PI01S8); a fine sand with irregular mud clasts in sequence 4 (PI01S6); or spherical mud balls in sequence 2 (PI01S20). In the western portion of transect B (Figure 4b), a sand-filled channel (coeval with sequence 1) cuts into sequence 2.

Sequence 1 in transects A and B is composed of normal-graded gravel and medium sand (Figure 4) capped with thin (*ca.* 10 cm), *Juncus roemarianus,* marsh peat (transect A, PI01S2); thin (1 cm), microbial mats (transect A, PI01S6, PI01S8); or a few tens of centimeters of mud deposited in small, shore-normal, elongate ponds located in former channels in overwash fans (transect A, PI01S3). The lateral equivalents to these modern peats and mats that occupy the low, interior flats of the barrier island are fine, wind-blown sands of the artificial barrier dune ridges to the east and the fine sands of the back-barrier berm (Figure 4), formed by a combination of aeolian and overwash processes that are driven by the interaction between oceanic and estuarine dynamics. One (transect A) or two (transect B) small (<1 m high), denuded, artificial barrier dune ridges divide the interior flats (Figure 4).

The general pattern of sedimentation within the vibracores is a series of fining-upwards sequences formed by several depositional processes within the barrier island system. The components of the sequences at this scale have sheet geometrics and were deposited as overwash fans, inlet-channel shoals, estuarine-muddy sands, and salt-marsh deposits. Locally, these sheet deposits are cut by back-barrier tidal creek-channel deposits (Figure 4b).

The specific characteristics of any fining-upwards sequence is dependent on its location within the barrier island system (*e.g.,* berm crest, interior flat, or back-barrier intertidal platform). Thus, each of the vibracore sequences has a degree of uniqueness and consists of portions of idealized fining-upwards sequences (Figure 4). This high degree of variability reflects the lateral variation in depositional and erosional environments at any one moment in time (see, for example, Figures 2 and 3). Correlation between vibracores, in many cases, is achieved through recognizing the between-core equivalence of fining-upwards sequences rather than individual beds, although overwash sand and salt-marsh peat can form distinctive "event" beds (Figure 4). Vertical lithologic variation between storm-generated overwash units reflects changing conditions of both type and amount of energy input for any given storm event.

Foraminiferal Patterns

Several distinctive foraminiferal assemblages characterize the modern barrier island subenvironments in eastern North Carolina (GROSSMAN and BENSON, 1967; VANCE, CORBETT, and CULVER, 2002; WORKMAN, 1981;) and form the basis for paleoenvironmental interpretations of foraminiferal assemblages in the down-core material. Beach and offshore environments are characterized by the calcareous benthic species *Elphidium excavatum, Elphidium subarcticum, Hanzawaia strattoni,* and *Buccella inusitata* (normal marine assemblage). In comparison, the back-barrier, nearshore estuarine sands of Pamlico Sound contain a low-diversity assemblage dominated by the coarsely agglutinated *Ammobaculites dilatatus* (estuarine assemblage). The modern back-barrier marsh deposits are characterized by an assemblage of finely agglutinated taxa, *Trochamma inflata, Miliammina fusca, Tiphotrocha comprimata, Jadammina macrescens, Arenoparrella mexicana,* and *Haplophragmoides wilberti* (salt-marsh assemblage). The small, elongate pond at PI01S3 (transect A) contains a calcareous assemblage dominated by *Ammonia tepida* and *Ammonia parkinsoniana.*

Figure 4 interprets the subsurface, foraminiferal assemblages based on a comparison with modern assemblages. Sequence 4 (transect B, PI01S6) has so far proven to be barren of foraminifera (foraminifera are not usually abundant in clean, mobile sand where food is scarce; BOLTOVSKOY and WRIGHT, 1976), but based on its lithologic similarity to overlying sands, it is tentatively interpreted as inlet-shoal sand (Figure 4b). Sequence 3 commences with a fine, shelly sand containing components of the normal marine assemblage, *Elphidium excavatum* and *Buccella inusitata* (transect B, PI01S20). This sand is interpreted to be the result of an overwash event. It is overlain by a muddier unit (PI01S6, PI01S20, PI01S21) that contains a mix of estuarine (sound) foraminifera (*Ammobaculites* sp.) and marsh foraminifera (*e.g., Trochammina inflata* and *Jadammina macrescens*); a back-barrier estuarine environment adjacent to a salt marsh is indicated (Figure 4).

Sequence 2 commences with a shelly sand (PI01S20, PI01S21) containing a normal marine-salinity assemblage of foraminifera (*Elphidium excavatum, E. subarcticum, E. mexicanum, E. galvestonense, Hanzawaia strattoni, Ammonia parkinsoniana,* and *Buccella inusitata*). Similar assemblages oc-

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Figure 2. Georeferenced, sequential, aerial photographs of the Pea Island study area: (A) 1932, (B) 1940, (C) 1949, (D) 1962, (E) 1999; box shows location of Figure 3. Sources: 1932, Field Research Facility, Duck NC, U.S. Army Corps of Engineers; 1940, Cape Lookout National Seashore, Harkers Island, NC, U.S. National Park Service; 1949 and 1962, Cape Hatteras National Seashore, Manteo, NC, U.S. National Park Service; 1999, NC Department of Transportation, Raleigh, NC.

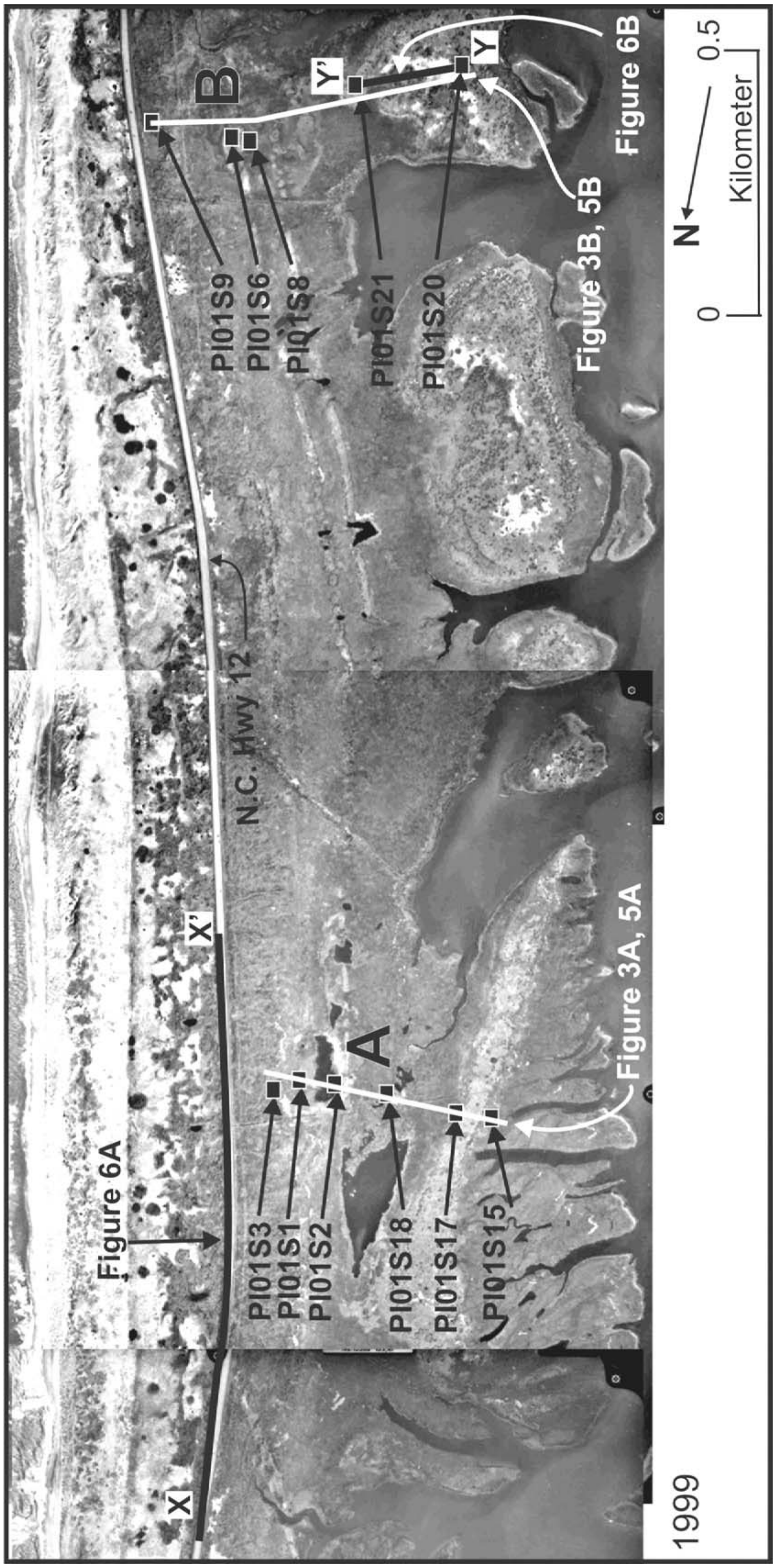


Figure 3. Location of vibracores along Transects A and B. GPR transects (X–X^1 and Y–Y^1) are indicated by black lines.

cur today at water depths of several meters off the Outer Banks barrier islands (SCHNITKER, 1971; WORKMAN, 1981). This shelly sand, therefore, is interpreted as an overwash deposit (Figure 4). It is overlain by a fine, clean sand (transects A and B) that is barren of foraminifera except for a few specimens of *Elphidium excavatum.* Such a depauperate assemblage characterizes the modern sands of Oregon Inlet to the north (VANCE, CORBETT, and CULVER, 2002). Thus, this sand, which comprises much of the stratigraphic record along transects A and B, is interpreted as an inlet-shoal deposit (Figure 4). Sequence 2 fines upward and is capped, in the eastern portion of transects A and B, with mud and peat containing *Trochammina inflata, Milammina fusca, Jadammina macrescens,* and other rarely recorded marsh foraminifera (SCOTT and MEDIODI, 1980) such as *Polysaccammina ipohalina* (Figure 4). An *in situ* salt marsh is clearly indicated. In PI01S20 (transect B), mud balls in a fine sand barren of foraminifera near the top of sequence 2 contain the marsh taxa *Trochammina inflata, Tiphotrocha comprimata, Arenoparrella mexicana,* and *Miliammina fusca.* An inlet channel close to an eroding salt marsh is the interpretation that best fits these data.

The sands and gravels of sequence 1 have so far proven to be barren of foraminifera, although they contain broken and abraded bivalve shell material (*e.g., Donax variabilis*) that is typical of the modern beach to the east of the artificial barrier foredune. This sand and gravel unit (Figure 4) represents the lag resulting from extensive overwash events that (based on 19th century maps and 1930s aerial photographs) took place in the late 19th to early 20th century on this segment of Pea Island. This material presumably forms the light-colored, unvegetated surface of Pea Island clearly seen in 1932 and 1940 aerial photographs (Figure 2a, b).

Age Determination

Because of the limited number of samples available and the noncontinuous, fine-grained sequences, exact ages could not be calculated. We were able to estimate relative ages based on the presence (<120 y) or absence of excess ^{210}Pb (>120 y) and the ^{137}Cs profile. The pond deposits at site PI01S3 contain excess ^{210}Pb indicating an age of less than 120 years (Figure 5). The underlying peat and correlative peaty mud in PI01S1 contain no excess ^{210}Pb indicating an age in excess of 120 years in this unit. Differences in the absolute activity of the surface samples in these two cores may be a function of age or sediment characteristics (*i.e.,* grain size). ^{137}Cs data does not provide additional insight but reiterates the ^{210}Pb interpretation. There is no discernable peak in either of the ^{137}Cs profiles that would be indicative of the early 1960s. However, there is measurable ^{137}Cs in samples younger than 120 years, albeit low activities, and activities below detection in samples with no excess ^{210}Pb (>120 years).

The age of the peat at the top of sequence 2 is further confined by a conventional radiocarbon age of 240 ± 50 years (Table 1; Figure 4) from a sample obtained beneath the small, artificial dune ridges along Transect B (PI01S23). Calibrated calendar dates of 1520–90 A.D., 1620–80 A.D., 1730–1810 A.D., and 1930–50 A.D. are possible, although the latter date can be rejected based on aerial photographic and ^{210}Pb data.

The shelly, overwash sand at the bottom of sequence 2 (PI01S21) was also radiocarbon dated. A well-preserved, single valve of the cross-barred venus (*Chione cancellata*) yielded an accelerator mass spectrometer (AMS) radiocarbon age of 1,380 ± 40 years and a calibrated calendar age of 960–1080 A.D. (Table 1; Figure 4).

Ground-Penetrating Radar

Data along Highway 12 (Figure 3) reveal the general, stratigraphic framework to a depth of approximately 4-m subsurface. The southern half of the data from the Highway 12 transect reveals a high-amplitude reflector, designated R1, at a depth of approximately 1 m (Figure 6). This reflector is truncated to the north by a zone of discontinuous, steeply dipping reflectors (clinoforms); chaotic bedding; and cut-and-fill structures at a depth of ~0.5 to 4 m (Figure 6). These structures are indicative of inlet fill. The majority of clinoforms prograde toward the south. Overlying the inlet fill are multiple, horizontal, high-amplitude, semicontinuous reflectors and low-amplitude, discontinuous reflectors.

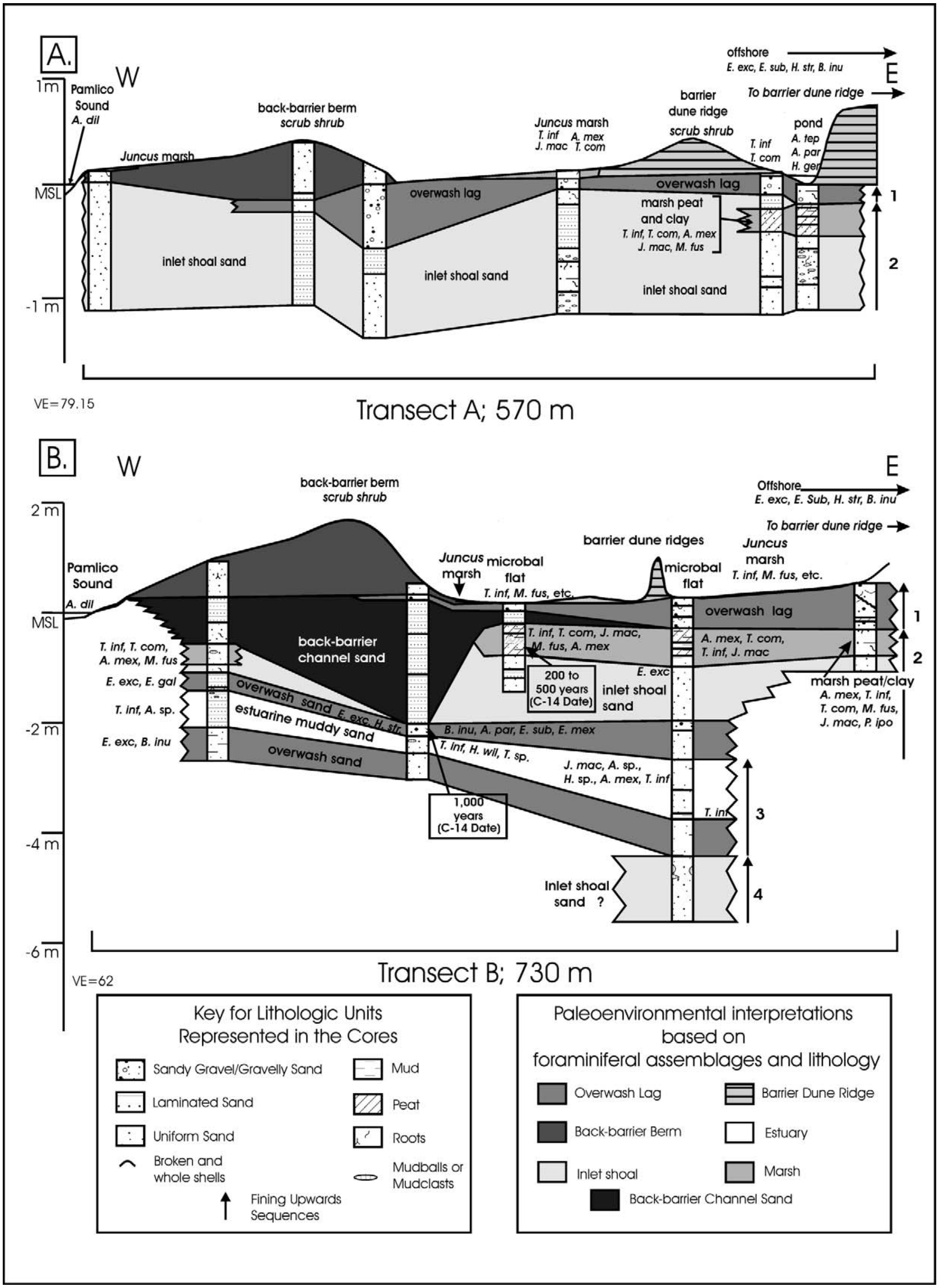
On the interior flats (*e.g.,* Transect B; Figure 3), penetration is less (~2-m subsurface) as a result of a shallower salt–water interface. Data from Transect B (Figure 7) reveal a moderately high-amplitude reflector (R1) at a subsurface depth of 1–1.5 m. Multiple clinoforms overlie R1 and dip at varying low angles to the west (predominantly) and east. These clinoforms occur beneath the Lagerhead Hills.

The high-amplitude, horizontal reflector (R1) noted in the GPR data along Highway 12 (Figure 6) correlates to a back-barrier marsh-peat bed that was recovered in cores and auger holes (Figure 4) along Transect A. The chaotic bedding and clinoforms are interpreted as inlet fill. Multiple inlet cut-and-fill events are indicated by the numerous truncation surfaces and onlapping and downlapping relationships of reflectors. Shallow (<1 m depth), horizontal reflectors are interpreted as overwash facies occurring above the peat layer (reflector R1). On the basis of cross-cutting relationships, the peat layer (R1) predates the inlet fill.

The GPR record along Transect B shows a major reflector (R1) that correlates with the boundary seen in cores PI01S20 and PI01S21 between back-barrier channel sand or overwash gravel and the overlying, finer, back-barrier berm sand (Figures 4 and 7). Low-amplitude reflectors above R1 (Figure 7) indicate the aggradation and predominantly westward progradation of the back-barrier berm but with a minor progradational component to the east. This composite structure shows that these fine sands cannot be explained simply as aeolian sand derived from the overwash plain (visible on the 1932 and 1940 aerial photographs; Figure 2) to the east. A combination of aeolian and back-barrier overwash is probably responsible for formation and subsequent modification of the Lagerhead Hills back-barrier berm.

DISCUSSION

The stratigraphic record at Pea Island is similar to that recorded on the southern Outer Banks by MOSLOW and HER-


A.
W
E
1m
MSL
-1 m
Pamlico Sound
A. dil
Juncus marsh
back-barrier berm
scrub shrub
Juncus marsh
T. inf A. mex
J. mac T. com
barrier dune ridge
scrub shrub
T. inf
T. com
pond
A. tep
A. par
H. ger
offshore
E. exc, E. sub, H. str, B. inu
To barrier dune ridge
overwash lag
overwash lag
marsh peat and clay
T. inf, T. com, A. mex
J. mac, M. fus
inlet shoal sand
inlet shoal sand
inlet shoal sand
1
2
VE=79.15
Transect A; 570 m
B.
W
E
2 m
MSL
-2 m
-4 m
-6 m
back-barrier berm
scrub shrub
Pamlico Sound
A. dil
Juncus marsh
microbal flat
T. inf, M. fus, etc.
barrier dune ridges
microbal flat
Juncus marsh
T. inf, M. fus, etc.
Offshore
E. exc, E. Sub, H. str, B. inu
To barrier dune ridge
T. inf, T. com,
A. mex, M. fus
E. exc, E. gal
T. inf, A. sp.
E. exc, B. inu
back-barrier channel sand
overwash sand E. exc, H. str.
estuarine muddy sand
overwash sand
T. inf, T. com, J. mac,
M. fus, A. mex
200 to 500 years (C-14 Date)
E. exc
inlet shoal sand
overwash lag
A. mex, T. com,
T. inf, J. mac
marsh peat/clay
A. mex, T. inf,
T. com, M. fus,
J. mac, P. ipo
B. inu, A. par, E. sub, E. mex
T. inf, H. wil, T. sp.
J. mac, A. sp.,
H. sp., A. mex, T. inf
T. inf
1,000 years (C-14 Date)
Inlet shoal sand ?
1
2
3
4
VE=62
Transect B; 730 m
Key for Lithologic Units Represented in the Cores
Sandy Gravel/Gravelly Sand
Laminated Sand
Uniform Sand
Broken and whole shells
Mud
Peat
Roots
Mudballs or Mudclasts
Fining Upwards Sequences
Paleoenvironmental interpretations based on foraminiferal assemblages and lithology
Overwash Lag
Back-barrier Berm
Inlet shoal
Barrier Dune Ridge
Estuary
Marsh
Back-barrier Channel Sand

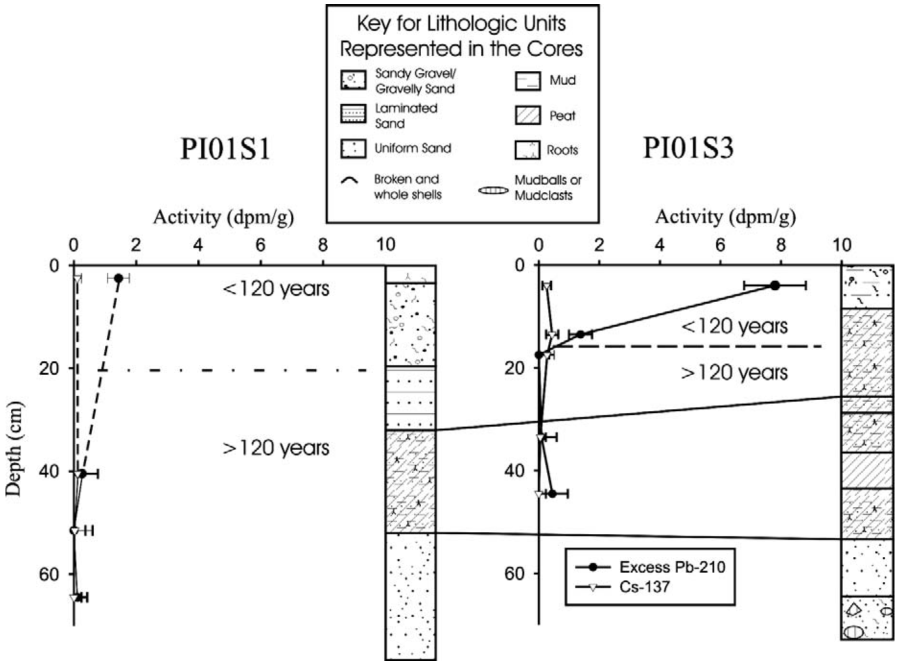


Figure 5. ^{210}Pb and ^{137}Cs profiles in cores PI01S1 and PI01S3 along transect A. Activity measured in dpm g^{-1}.

ON (1978) and SUSMAN and HERON (1979). On southern Core Banks, North Carolina (Figure 1), MOSLOW and HERON (1978) showed that inlet-fill deposits have a high-preservation potential within this environment representing about 15% of the Holocene sediments beneath Core Banks. Further to the south, on Shackleford Banks (Figure 1), SUSMAN and HERON (1979) also reported the importance of inlet deposits in Holocene barrier-island stratigraphy. A similar pattern is seen elsewhere; for example, BARNHARDT *et al.* (2002) using GPR recognized former inlet deposits in the subsurface of Tavira Island, a large barrier island on Portugal's Algarve coast.

Although a detailed history awaits further work, in particular more temporal resolution, the record of environmental change in the study area can be summarized as follows. Sometime before 1000 A.D., an inlet through the barrier island was infilled with fine sand (sequence 4, transect B, PI01S6; Figure 4). A major overwash event (or period of events) then occurred, and a shelly sand, containing open marine, inner shelf foraminifera, was deposited across the entire width of the barrier island (base of sequence 3, transect B; Figure 4). There was adequate accommodation space available for a back-barrier, estuarine muddy sand to be deposited over the overwash sand (top of sequence 3; Figure 4). This muddy sand unit contains a mixed assemblage of estuarine (sound) and salt-marsh foraminifera (Figure 4). Such assemblages are found today in Pamlico and Roanoke (North Carolina) Sounds adjacent to back-barrier salt-marsh VANCE, CORBETT, and CULVER, 2002).

Approximately 1000 years ago, based on carbon-14 (^{14}C) dating (Table 1), another major overwash event (or interval) deposited shelly sand, containing open marine, inner-shelf foraminifera, across the entire width of the barrier island (base of sequence 2; Figure 4). For the next several hundred years, the study area was affected by inlet activity, but the resulting sedimentary record is a mere meter or so of fine sand containing a sparse assemblage of inlet tidal delta foraminifera (Figure 4). Thus, the inlets must have been shallow and ephemeral, much like those that characterize Core Banks today, rather than large, more-persistent inlets such as the modern Oregon and Ocracoke inlets. This is borne out by the historical record of small, inlet openings in southern Pea Island (Figure 1; FISHER, 1962).

Sometime between 500 and 200 years ago (based on ^{14}C dating, Table 1), back-barrier salt-marsh peat and peaty clay accumulated over the inlet sand, particularly in the eastern

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Figure 4. Lithology, fining upwards sequences, foraminiferal assemblages, and paleoenvironmental interpretations along Transects A and B. VE = vertical exaggeration. Note vertical scale differences in A and B. Benthic foraminifera: *A. dil* = *Ammobaculites dilatatus*; *T. inf* = *Trochammina inflata*; *A. mex* = *Arenoparrella mexicana*; *J. mac* = *Jadammina macrescens*; *T. com* = *Tiphotrocha comprimata*; *A. tep* = *Ammonia tepida*; *A. par* = *Ammonia parkinsoniana*; *H. ger* = *Haynesina germanica*; *E. exc* = *Elphidium excavatum*; *E. sub* = *Elphidium subarcticum*; *H. str* = *Hanzawaia strattoni*; *B. inu* = *Buccella inusitata*; *M. fus* = *Miliammina fusca*; *E. gal* = *Elphidium galvestonense*; *P. ipo* = *Polysaccammina ipohalina*; *E. mex* = *Elphidium mexicanum*; *H. wil* = *Haplophragmoides wilberti*; *A.* sp. = *Ammobaculites* sp.; *T.* sp. = *Trochammina* sp.; *H.* sp. = *Haplophragmoides* sp.

Table 1. *Radiocarbon dates from Pea Island, North Carolina. (AMS = accelerator mass spectrometer)*

Laboratory Number	Core	Sample Depth in Core	Sample Depth Relative to Mean Sea Level	Material	Conventional ^{14}C Age (y B.P.)	Calibrated 2σ Calendar (y A.D.)
Beta-162645	P101S23	150 cm	−74 cm	*In situ* salt-marsh peat	240 ± 50	1520–1590 1620–1680 1730–1810
Beta-164489 (AMS)	P101S21C2	258 cm	−204 cm	Bivalve *Chione cancellata*	1,380 ± 40	960–1080

part of the study area (top of sequence 3, Figure 4; reflector R1, Figure 6). This unit may have extended further west and been removed later by small, back-barrier tidal channels (transect B; Figure 4). This interpretation is supported by the presence of salt-marsh foraminifera within mud balls in fine sand in PI01S20. Salt-marsh peat can accumulate rapidly on flood-tide delta sands after inlet closure (50 cm in 150–200 y; GODFREY and GODFREY, 1976). An analogous situation is the vegetated, relict, flood-tide delta of New Inlet that can be seen in the northern end of the study area (Figure 2).

The barrier that protected this salt-marsh from the ocean was breached by two (and perhaps three) inlets in the 1860s (HAIRR, 1999, 1862 map showing location of Civil War Union forces—Burnside Expedition and 1865 U.S. Coast Survey map of Virginia, North Carolina, and South Carolina). The northern inlet, New Inlet, remained open intermittently until 1945 (see Figure 2). The southern, Loggerhead Inlet (from which the name Lagerhead Hills is presumably derived), soon closed and the southern two-thirds of the study area (Figure 2) became characterized by low, sandy gravel, overwash flats (Figure 6) with a back-barrier berm (Figure 7) formed by a combination of overwash, aeolian, and back-barrier processes. Fine sand was winnowed from the overwash flats and transported to the back-barrier berm (this process can be seen on Core Banks today; WHITE *et al.,* 2002), leaving a gravel and shell-rich lag (base of sequence 4, Figure 4).

This was the situation during the early 1930s, when the latest reincarnation of New Inlet cut through the barrier island (Figure 2a). In the late 1930s, four parallel rows of sand fences were erected along Pea Island (Figure 2b). The two easternmost rows were designed to form parallel barrier dune ridges to protect the island from erosion, and the two westernmost fence rows were built to increase the elevation of the central part of the previously overwash-dominated barrier island (STRATTON and HOLLOWELL, 1940). An extensive planting program (grasses and shrubs) was associated with the sand-fence construction (STRATTON and HOLLOWELL, 1940). By 1949 (Figure 2c), the back-barrier was vegetated; Highway 12 was constructed in 1953 (and sections have been rebuilt and relocated several times since). The sand fencing pro-

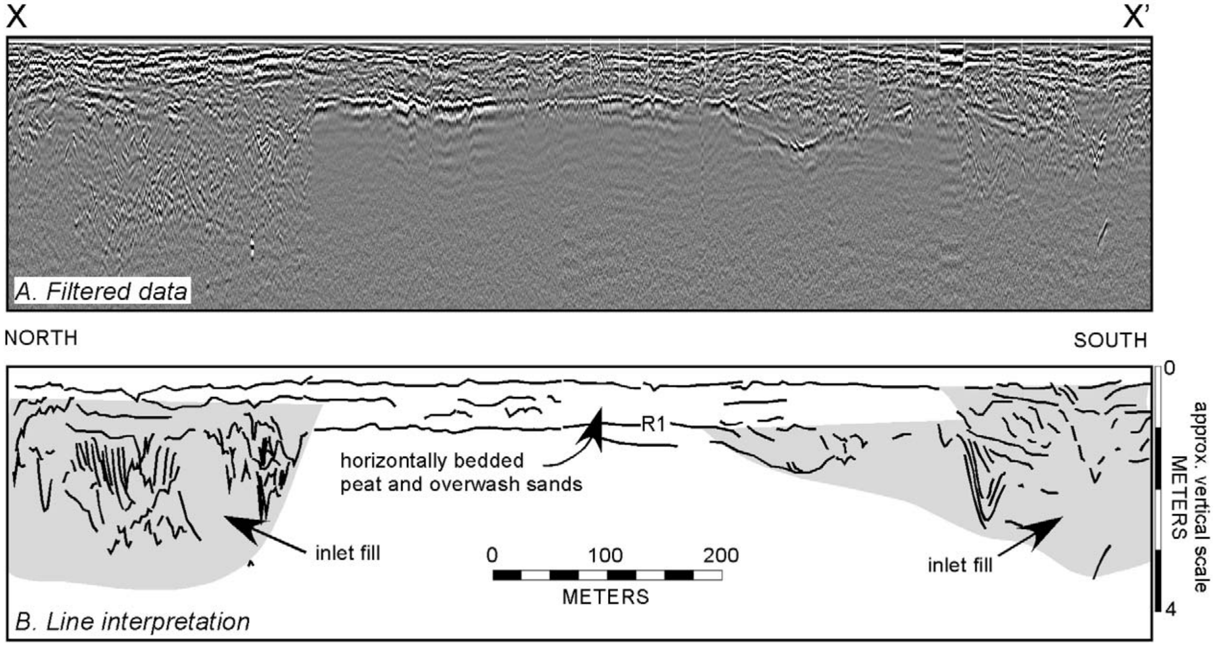

Figure 6. (A) Ground-penetrating radar data (filtered and stacked), acquired with a 200-MHz antenna from the Highway 12 transect, and (B) line interpretation of the GPR data shown in panel A. See Figure 3 for location of GPR transect.

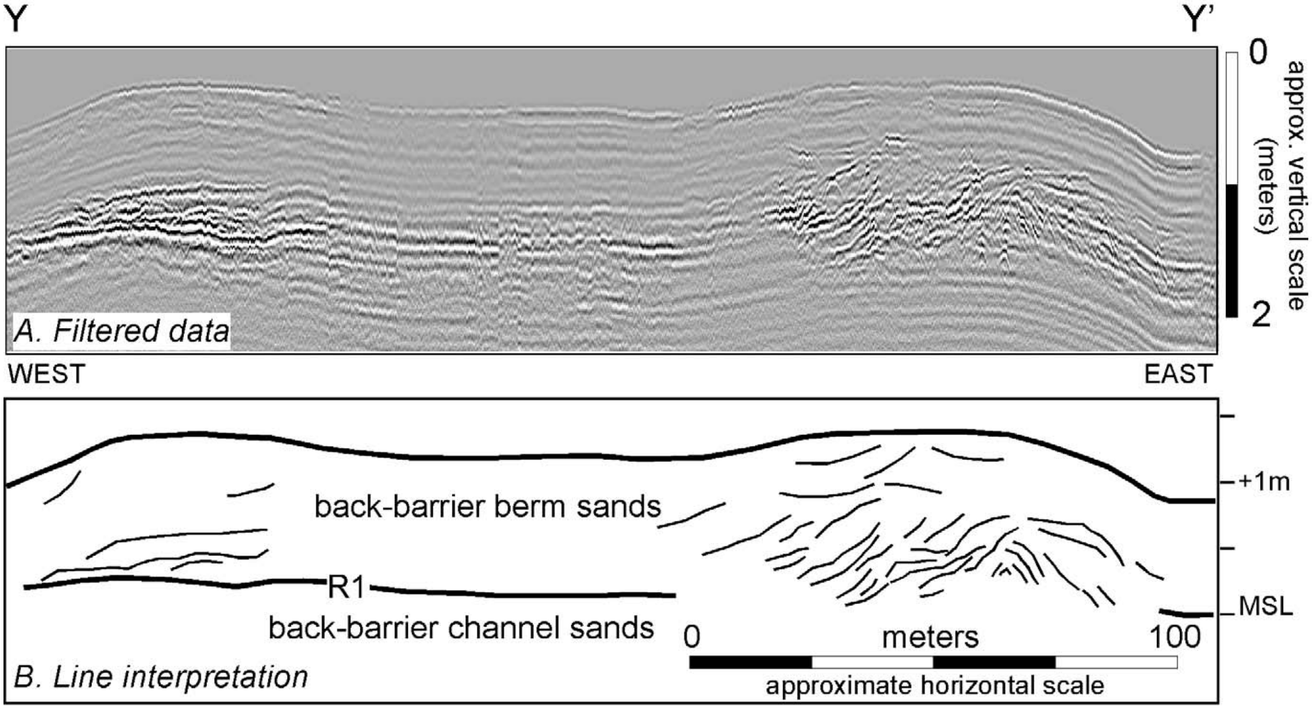

Figure 7. (A) Ground-penetrating radar data (filtered and stacked), acquired with a 200-MHz antenna from Transect B, and (B) line interpretation of the GPR data shown in panel A. The data were obtained from Transect B between PI01S21 and PI01S20 (Figure 3).

duced barrier dune ridges that only allow relatively minor overwash (*e.g.,* Figure 2d, e), thus enhancing sound-side erosion (Riggs and Ames, 2003). The westernmost sand fences resulted in 0.5–1 m high dunes, which have since been cut through, probably by hurricane-driven, overwash events from the sound side of the barrier (Figure 2).

CONCLUSIONS

The study area at Pea Island National Wildlife Refuge on North Carolina's Outer Banks is a region that has been dominated by oceanic overwash during the past century. The stratigraphic record underlying the island is dominated, however, by a combination of overwash and inlet-related deposits representing at least 1000 years. This concurs with historical data stretching back to 1584; as recently as 1863, the barrier island in the study area was cut by three inlets. Foraminiferal and sedimentary data obtained from vibracores and augured holes show four major cycles of deposition that commence with overwash sands and fine upwards, sometimes via inlet-shoal sands, to estuarine or salt-marsh sandy mud or peat. The dynamic nature of this stretch of the Outer Banks has been partially, but temporarily, muted by the construction of artificial barrier dune ridges in the late 1930s. The dunes reduced the extent of overwash, which together with artificial plantings have resulted in a vegetated barrier island vastly different from its natural state of just 70 years ago.

ACKNOWLEDGMENTS

This research is part of the North Carolina Coastal Geology Cooperative Program (NCCGC). Funding for the USGS Cooperative agreement award 02ERAG0044 is gratefully acknowledged. We thank Jim Watson, Matt Allen, Dare Merritt, and Megan Murphy of East Carolina University; George Barnes of Jockey's Ridge State Park; Bill Birkemeir of the Army Corps of Engineers' facility at Duck; and Steve Culver for their logistical support. Permission to work on the Pea Island National Wildlife Refuge is gratefully acknowledged.

LITERATURE CITED

Ames, D.; Riggs, S.; Sager, E.; Wenell, B.; Havholm, K., and Whittecar, R., 2000. The evolution of Jockey's Ridge Dune Field, Nags Head, NC. *Southeast Geological Society of America Abstracts with Program,* SEGSA Regional Meeting, Charleston, SC, p. 2.

Barnes, J., 2001. *North Carolina's Hurricane History.* Chapel Hill, North Carolina: University of North Carolina Press, 319p.

Barnhardt, W.A.; Gonzales, R.; Kelley, J.T.; Neal, W.J.; Pilkey, O.H., Jr.; Jose, E., and Dias, J.A., 2002. Geologic evidence for the incorporation of flood tide deltas at Tavira Island, southern Portugal. *Journal of Coastal Research,* Special Issue No. 36, pp. 28–36.

Boltovskoy, E. and Wright, R., 1976. Recent Foraminifera. The Hague: Dr. W. Junk b.v., 515p.

Bristow, C.; Pugh, J., and Goodall, T., 1996. Internal structure of aeolian dunes in Abu Dhabi determined using ground-penetrating radar. *Sedimentology,* 43, 995–1003.

Bristow, C.S.; Chroston P.N., and Bailey, S.D., 2000. The structure and development of foredunes on a locally prograding coast:

insights from ground-penetrating radar surveys, Norfolk, U.K. *Sedimentology,* 47, 923–944.

Collins, E.S.; Scott, D.G., and Gayes, P.T., 1999. Hurricane records on the South Carolina coast: can they be detected in the sediment record? *Quaternary International,* 56, 15–26.

Culver, S.J.; Woo, H.J.; Oertel, G.F., and Buzas, M.A., 1996. Foraminifera of coastal depositional environments, Virginia, U.S.A.: distribution and taphonomy. *Palaios,* 11, 459–486.

Dolan, R.; Lins, H., and Hayden, B., 1988. Mid-Atlantic coastal storms. *Journal of Coastal Research,* 4, 417–433.

Donnelly, J.P.; Roll, S; Wengren, M.; Butler, J.; Lederer, R., and Webb, T., III, 2001a. Sedimentary evidence of intense hurricane strikes from New Jersey. *Geology,* 29, 615–618.

Donnelly, J.P.; Bryant, S.S.; Butler, J.; Dowling, J.; Fan, L.; Hausmann, N.; Newby, P.M.; Shuman, B.; Stern, J.; Westover, K., and Webb, T., III, 2001b. A 700-year sedimentary record of intense hurricane landfalls in southern New England. *Geological Society of America Bulletin,* 113, 714–727.

Fisher, J.J., 1962. Geomorphic expression of former inlets along the Outer Banks of North Carolina. University of North Carolina, Chapel Hill, Master's thesis, 102p.

Godfrey, P.J. and Godfrey, M.M., 1976. Barrier Island Ecology of Cape Lookout National Seashore and Vicinity, North Carolina. *National Park Service Scientific Monograph Series,* 9, 160p.

Grossman, S. and Benson, R.H., 1967. Ecology of Rhizopodea and Ostracoda of southern Pamlico Sound region, North Carolina. *The University of Kansas Paleontological Contributions,* 44, 1–90.

Hairr, J., 1999. *Outer Banks.* Charleston, North Carolina: Arcadia, 128p.

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

Jol, H.M.; Vanderburgh, S., and Havholm K.G., 1998. GPR studies of coastal aeolian (foredune and crescentic) environments: examples from Oregon and North Carolina, U.S.A. *Proceedings of the Seventh International Conference on Ground-penetrating radar (GPR'98),* May 27–30, University of Kansas, Lawrence, KS, USA, 2, pp. 681–686.

Liu, K-B. and Fearn, M.L., 1993. Lake-sediment record of late Holocene hurricane activities from coastal Alabama. *Geology,* 21, 793–796.

Liu, K-B. and Fearn, M.L., 2000. Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records. *Quaternary Research,* 54, 238–245.

Mallinson, D.; Ames, D.; Riggs, S.; Crowson, R.; Foster, N., and Hoffman, C., 2001. Ground-penetrating radar defines the Holocene and Pleistocene geology of the North Carolina Outer Banks. Abstracts with Program, GSA National Meeting, Boston, Nov. 2001, p. 166.

Moslow, T.F. and Heron, S.D., Jr., 1978. Relict inlets: preservation and occurrence in the Holocene stratigraphy of southern Core Banks, North Carolina. *Journal of Sedimentary Petrology,* 48, 1275–1286.

Nittrouer, C.A.; Sternberg, R.W.; Carpenter, R., and Bennett, J.T., 1979. The use of ^{210}Pb geochronology as a sedimentological tool: an application to the Washington continental shelf. *Marine Geology,* 31, 297–316.

Pilkey, O.H.; Neal, W.J.; Riggs, S.R.; Webb, C.A.; Bush, D.M.; Pilkey, D.F.; Bullock, J., and Cowan, B.A., 1998. *The North Carolina Shore and its Barrier Islands: Restless Ribbons of Sand.* Durham and London: Duke University Press, 318p.

Riggs, S.R., 2002. Life at the edge of North Carolina's coastal system: the geologic controls. *In*: Beal, C., and Prioli, C. (eds.), *Life at the Edge of the Sea: Essays on North Carolina's Coast and Coastal Culture.* North Carolina State University: Coastal Carolina Press, pp. 63–95.

Riggs, S.R. and Ames, D.V., 2003. Drowning the North Carolina coast. Sea-level rise and estuarine dynamics. NC Sea Grant Program Publication, Raleigh, NC, 152p.

Schnitker, D., 1971. Distribution of foraminifera on the North Carolina continental shelf. *Tulane Studies in Geology and Paleontology,* 8, 169–222.

Scott, D.B. and Medioli, F.S., 1980. Quantitative studies of marsh foraminiferal distributions in Nova Scotia: their implications for the study of sea-level changes. *Cushman Foundation for Foraminiferal Research, Special Publications,* 17, 58p.

Stratton, A.C. and Hollowell, J.R., 1940. *Sand fixation and beach erosion control.* U.S. Department of the Interior, National Park Service, Office of Chief Scientist, 102p.

Susman, V.R. and Heron, S.D., Jr., 1979. Evolution of a barrier island, Shackleford Banks, Carteret County, North Carolina. *Geological Society of America Bulletin,* 90, 205–215.

Vance, D.J.; Corbett, D.R., and Culver, S.J., 2002. Foraminiferal distributions, sedimentation rates and patterns in the Albemarle estuarine system, North Carolina. Fall Meeting Supplement, Abstract OSB22B-0283, *EOS Transactions,* 83(47).

White, R.M.; Riggs, S.R.; Mallinson, D.A., and Ames, D.V., 2002. Process-response, time-slice geomorphic and ecologic mapping of Core Banks, Cape Lookout National Seashore, NC. Fall Meeting Supplement, Abstract O571B-0288, *EOS Transactions,* 83(47).

Woo, H.J.; Culver, S.J., and Oertel, G.F., 1997. Benthic foraminiferal communities of a barrier-lagoon system, Virginia, U.S.A. *Journal of Coastal Research,* 13, 1192–1200.

Workman, R.R., Jr., 1981. *Foraminiferal assemblages of the nearshore inner continental shelf, Nags Head and Wilmington areas, North Carolina*: Greenville: East Carolina University, Master's thesis, 161p.