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## Abstract

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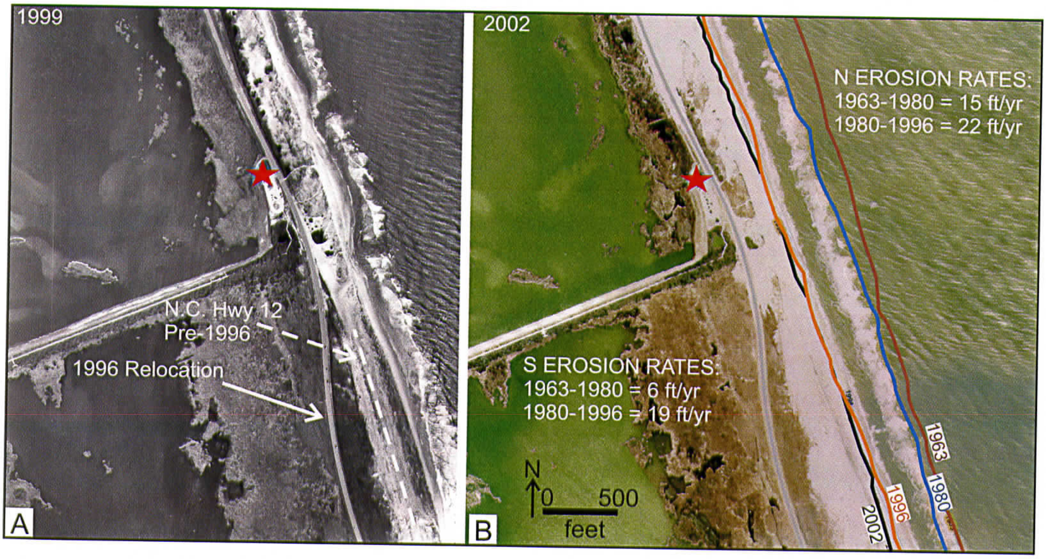
# SOUTHEASTERN GEOLOGY



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# SOUTHEASTERN GEOLOGY

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# CONSEQUENCES OF HUMAN MODIFICATIONS OF OREGON INLET TO THE DOWN-DRIFT PEA ISLAND, NORTH CAROLINA OUTER BANKS

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## ABSTRACT

**Oregon Inlet is a highly dynamic inlet-outlet system through the northern North Carolina Outer Banks that opened in 1846, separating Bodie and Pea Islands. Bodie Island extends northward from the inlet (about 9.3 miles) to the Nags Head-Kitty Hawk urbanized barriers and includes part of Cape Hatteras National Seashore (CHNS). South of the inlet is the 12 mile-long Pea Island National Wildlife Refuge (PINWR). By 1989, Oregon inlet had migrated southward about 2.9 miles to its southernmost location when it was pushed back north and hardened with a terminal groin and rock revetment along the south side in 1989-1991. In 1962-63 a 2.4 mile-long bridge, with a fixed navigational span, was constructed across the southward migrating Oregon Inlet, which led to immediate conflicts. In order to maintain the main inlet channel under the navigation span, dredging was initiated with offshore, deep-water disposal of the dredged sand. During the post-terminal groin period (1991-present), the northern Oregon Inlet shoreline continued to migrate southward into the inlet channel driven by the dominant energy of nor'easter storms. This necessitated a further increase in frequency and volume of dredging to "hold the channel" under the fixed navigation span.**

**The groin and rock-revetment secured the southern Oregon Inlet shoreline. This stabilization, however, also prevented the natural southward sediment transport system from replenishing the rapidly eroding Pea Island beaches. Consequently, between 1983 to 2009, over 12 million cubic yards of sand were dredged from Oregon Inlet and artificially by-passed to the Pea Island beaches between mileposts 1 and 3. Additionally, NCDOT spent a minimum of $100 million from 1983-2009 to maintain NC Highway 12 due to persistent ocean shoreline recession of the down-drift Pea Island beaches. Portions of the Pea Island ocean shoreline still have average rates of shoreline recession up to 13 ft/yr resulting in a constant and expensive battle to maintain NC Highway 12.**

**Today, in spite of all the nourishment, regular reconstruction of barrier dune ridges, construction of sand-bag walls, and the almost constant work of a fleet of bulldozers, NC Highway 12 is not a reliable road across Pea Island. Frequently, segments of this road flood with a spring tide, an extra high wind tide, or even just a heavy rainfall, to say nothing about major storm events. These Pea Island road segments are all in jeopardy today, so what will happen in the next 5, 10, or 25 years as sea level rises and storms continue to strike the coast? In addition, similar problem areas for NC Highway 12 exist further south at Avon to Buxton, Frisco to Hatteras, and on northeastern Ocracoke Island. Is it possible that we could be building a new $250 million dollar Oregon Inlet bridge to a fixed road system that cannot be maintained on a shifting pile of sand?**

## NORTH CAROLINA SHORELINE HARDENING LAW

In the 2003 North Carolina legislative session, both houses voted unanimously to ban the construction of new, permanent erosion control structures on North Carolina's ocean shorelines and inlets. This underscored the recognition that the NCCRC ban on coastal hard structures,

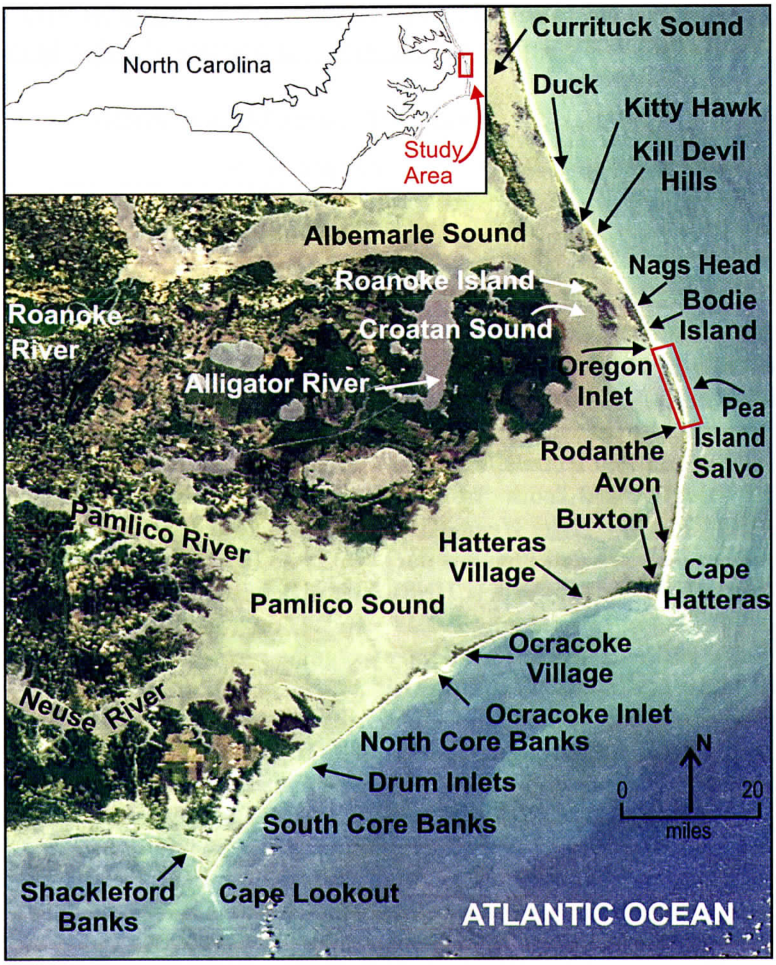

**Figure 1. This satellite image shows the location of the study area (red box) and associated coastal features within the northeastern North Carolina Outer Banks. The image is a National Aeronautics and Space Administration's MODIS image provided by the Institute for Marine Remote Sensing, College of Marine Science, University of South Florida.**

enacted in 1985, was sound fiscal, environmental, and management policy and critical to the future of North Carolina's beaches.

However, due to increased urban development within many of the State's inlet hazard zones (IHZ), the 2007 legislative session started to change the State policy. The NC Senate passed a bill that would permit hardening of shorelines with the construction of "terminal groins". This controversial bill did not pass the NC House in either the 2007 or 2008 sessions. In the 2009 legislative session, the House passed the bill with the requirement that a study be undertaken to determine the "feasibility and advisability of the use of a terminal groin as an erosional control device". That study was contracted to Moffatt & Nichol (2010) by the NC-CRC. The 2007-2009 legislation referred specifically to the Oregon Inlet terminal groin as an example of a successfully working structure to stabilize both inlets and adjacent barrier island shorelines. As part of the evaluation of the Moffatt & Nichol (M&N) study, portions of the present paper were prepared for the NC-CRC's Science Panel. During the 2010 legislative session, the House failed to allow the bill out of committee and, therefore, it died. However, the newly reconstituted legislature of 2011

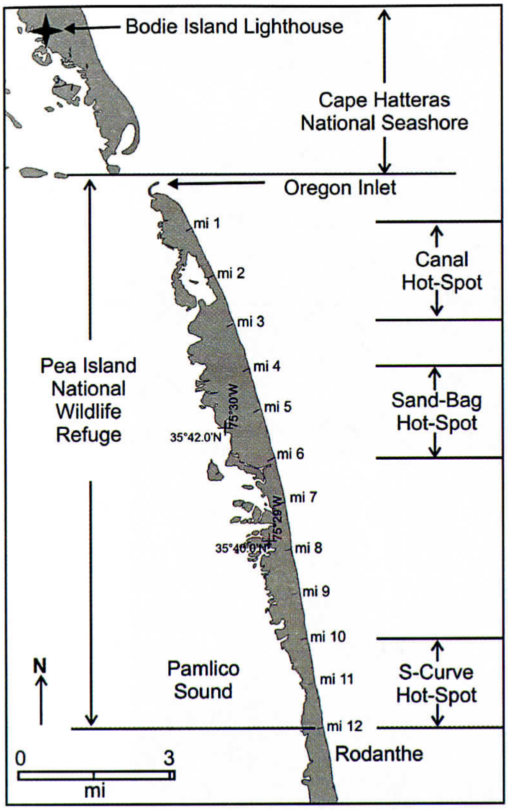

**Figure 2. Map of the study area shows the location of Oregon Inlet relative to the adjacent barrier islands: Bodie Island is to the north and Pea Island to the south. Mile markers are distance from the terminal groin with the 0 to 1 mile marker consisting of the sand fillet behind the terminal groin. The NC Highway 12 vulnerable areas (hot-spots) for Pea Island were initially defined by Stone et al. (1991) and are the areas where NCDOT continues to have severe problems today with maintaining the highway.**

passed a terminal groin law that allows for construction of four terminal groins as experiments to test their effectiveness along North Carolina's inlets.

## HISTORY OF OREGON INLET MODIFICATION

During the past half century, Oregon Inlet and adjacent barrier islands (Fig. 1) have been severely modified by human activities that embroiled them in controversy pitting natural barrier island and inlet dynamics against the economic development of coastal North Carolina. In 2009, Riggs et al. published a manuscript titled "Eye of a human hurricane: Pea Island, Oregon Inlet, and Bodie Island, northern Outer Banks, North Carolina" as an invited paper in the Geological Society of America's Special Publication on "America's Most Vulnerable Coastal Communities". The 2009 paper dealt with the geologic processes and evolutionary history of Oregon Inlet and adjacent barrier islands. The present manuscript is a follow-up to the 2009 paper that considers the physical and economic consequences of building a bridge with a fixed navigation span across a dynamic inlet, necessitating an ever increasing need for 1) dredging to maintain the channel under the navigation span, 2) stabilizing the inlet with hardened structures, 3) pumping beach nourishment sand to the downstream shoreline as it continues to recede, and 4) maintaining a highway that is repeatedly overwashed and frequently "goes-to-sea". As sea level rises and storms impact the coastal system, the engineering attempts to "hold the line" on this highly dynamic inlet-barrier island system are escalating.

Bodie Island extends for 9.3 miles from the southern boundary of the Nags Head-Kitty Hawk urbanized area to the north shore of Oregon Inlet (Figs. 1 and 2) and is part of Cape Hatteras National Seashore (CHNS). Pea Island extends 12 miles from the southern shore of Oregon Inlet to Rodanthe Village (Figs. 1 and 2) and comprises the Pea Island National Wildlife Refuge (PINWR). Bodie and Pea islands evolved as a simple inlet- and overwash-dominated (transgressive) barrier island that is now divided by Oregon Inlet (Riggs and Ames, 2003; Riggs et al., 2009, 2011). Oregon Inlet was opened by a hurricane in 1846 on Bodie Island, just south of the present Bodie Island lighthouse, which was built in 1872. The inlet subsequently migrated 2.9 miles south from its original location by 1989.

NC Highway 12 was constructed on Bodie and Pea islands in the early 1950s and was connected across Oregon Inlet by a 2.4 mile-long bridge in 1962-1963 (Fig. 3A). Construction of the highway and bridge were critical for developing the tourist economy for the Outer Banks

**Figure 3. Oblique aerial photographs show the Oregon Inlet bridge that was built in 1962-63. Panel A is looking SW from Pamlico Sound with Bodie Island on the left and Pea Island on the right. Panel B is a close-up of the south end of the bridge and shows the terminal groin and reinforced rock revetment (built in 1989-91) around the base of the bridge. Red stars show the location of the abandoned US Coast Guard Station. Both photographs were taken on 11-16-2009 by the Pea Island National Wildlife Refuge.**

and eight communities to the south of Oregon Inlet (Fig. 1). The Oregon Inlet bridge, with a fixed navigational span, was constructed across the southward migrating Oregon Inlet (Fig. 3). Thus, the navigation channel migrated from under the fixed span of the bridge and required almost continuous dredging (Fig. 4). In 1970, these problems led to plans to permanently fix the location of the inlet with a pair of two mile-long jetties (Pilkey and Dixon, 1996), which were never built. Inlet migration ultimately resulted in the exhumation of portions of the bridge's pilings. Those portions of the bridge subsequently subsided and required repiling. As the south shoreline of Oregon Inlet migrated southwards, the bridge was in danger of being stranded in Oregon Inlet.

To control the migrating inlet channel, dredging was initiated in 1960, before bridge construction, and continued through 1979 with offshore, deep-water disposal of the dredged sand. With time, the combination of storm activity and sand loss from dredging and offshore disposal resulted in a dramatic increase in the rate of inlet migration from 75 feet/year (1849 to 1980) to 180 feet/year (1981 to 1988) (Inman

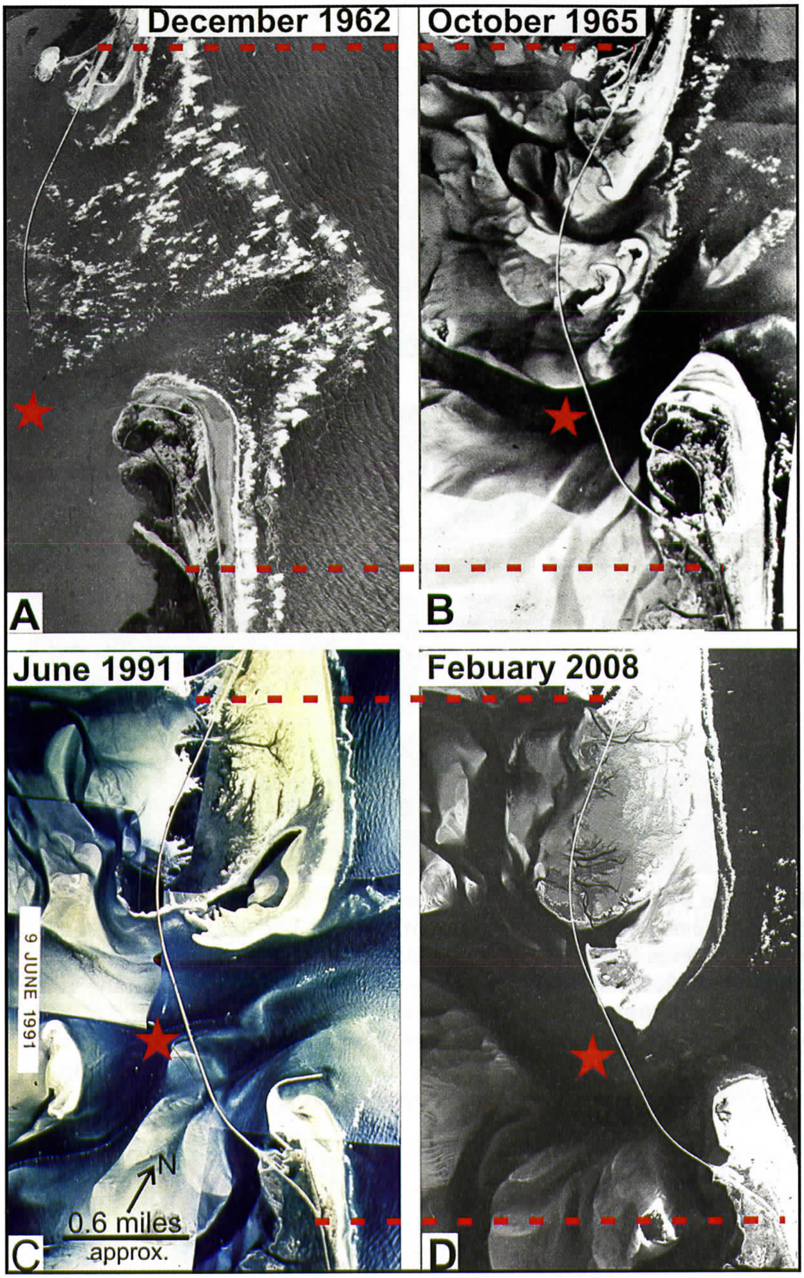

Figure 4. Panel A is an aerial photograph from 1962 showing Oregon Inlet during bridge construction and nine months after the Ash Wednesday Nor'easter blew out the sand shoals and opened the inlet to its widest extent. Panel B is a 1965 post-storm aerial photograph showing the redevelopment of the inlet shoals as they re-equilibrated to the natural non-storm hydraulic flow. Panel C is a 1991 aerial photograph showing Oregon Inlet immediately after construction of the terminal groin. Panel D is a 2008 aerial photograph showing a substantial southward migration of the northern inlet shoreline causing the apparent narrowing of the inlet and severe encroachment of the spit on the fixed navigational span of the bridge. Red stars mark the location of the fixed navigational span in each photograph. The red dashed lines connect the control points on each photograph.

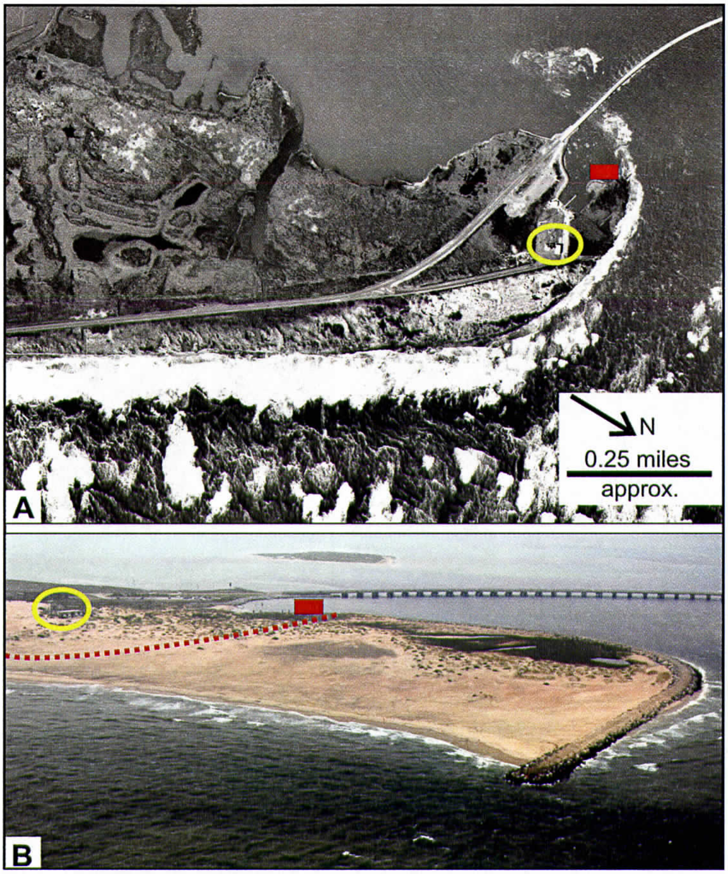

**Figure 5. Panel A is a March 11, 1989 aerial photograph taken after a storm, which caused a 1,146 foot southward recession of the south shore of Oregon Inlet, destroyed the harbor (red box), and threatened the buildings (yellow circle) of the US Coast Guard station. Panel B is an oblique aerial photograph (June 6, 2008) of the 3,077 foot-long rock groin that moved the southern shoreline back northward about the same distance as was lost in the 1989 storm. The red dashed line in Panel B is the approximate location of the 1989 shoreline in Panel A. Panel A is from the US ACE Field Research Facility, Duck, NC and Panel B is from the Program for the Study of Developed Shorelines at Western Carolina University, Cullowhee, NC.**

and Dolan, 1989; NCDOT, 1989; Pilkey et al., 1998; Riggs et al., 2009). Thus, by 1983 increased inlet dredging became necessary to maintain the channel under the fixed navigational span. Between 1983 and 1988 the USACE increased its hopper dredging operations and dredged 3.2 million cubic yards of sediment from the Oregon Inlet channel and ocean bar and discharged into the near-shore (> 20 ft water depth) of northernmost Pea Island (NCDOT, 1989).

In March 1989 a single storm caused the southern inlet shoreline to migrate southward about 1,146 feet (Inman and Dolan, 1989; NCDOT, 1989; Pilkey et al., 1998; Riggs et al., 2009). The storm and migrating inlet destroyed the harbor and threatened the buildings of the US Coast Guard Station (Figs. 3B and 5A) which forced relocation of Coast Guard operations to the north side of the inlet. The southern inlet migration threatened to erode the bridge attachment to Pea Island. This prompted NCDOT to apply for a variance from NCCRC to build the 3,077 foot-long Oregon Inlet terminal groin (Figs. 3B, 4C, 4D, and 5B) and to re-enforce the rock revetment around the south base

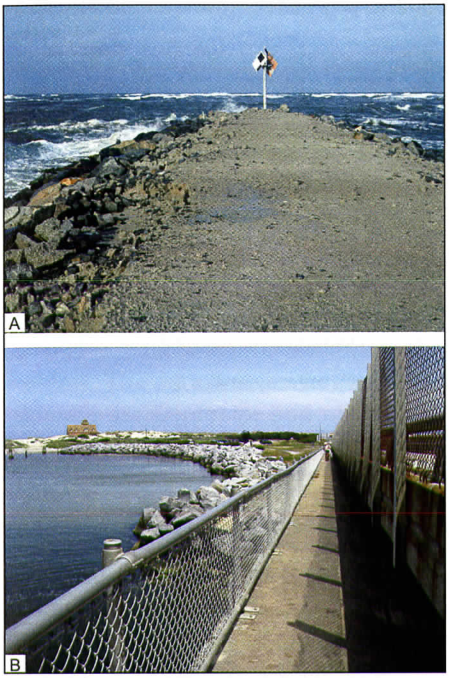

**Figure 6. Panel A is a 1993 photograph that shows the seaward portion of the 3,077 foot-long terminal groin on the south side of Oregon Inlet. The offshore waves are breaking on the outer bar or ebb-tide delta of Oregon Inlet. Panel B is a 6-2009 photograph that shows the re-enforced rock revetment built on the SE side of the Oregon Inlet bridge to prevent the southward inlet migration from abandoning the bridge within the inlet. Notice the old US Coast Guard Station in the upper left corner of Panel B.**

of the bridge (Fig. 3B). Groin construction took place from October 1989 to March 1991 to stabilize the southern side of Oregon Inlet (Fig. 6).

The past half century of problems since NC Highway 12 was built along Pea Island in the 1950s cluster within three specific areas. These "hot spot" areas were originally defined by Stone et al. (1991) and are known by NCDOT from north to south as follows (Fig. 2): the "canal area" (miles 1 to 3), the "sandbag area" (miles 4 to 6), and the "S-curves area" (miles 10 to 12). The "hot spots" represent 50% of Pea Island.

## PURPOSE OF THIS PAPER

The purpose of this paper is fourfold. First, it is a detailed addition to the more general summary paper of Riggs et al. (2009) which considered the basic barrier island processes, essential for a healthy barrier island-inlet system, operating at Pea Island, Oregon Inlet, and Bodie Island. Second, it evaluates the additional available data to examine an alternative premise to the Pea Island monitor study conclusion that there is "not a shoreline erosion problem on the Pea Island beaches." Third, it evaluates the potential long-term environmental impact of a new Oregon Inlet bridge and continued modification of Oregon Inlet to downstream barrier island systems. Fourth, this paper raises the question as to whether such continued human modification is economically feasible and environmentally sound in view of the well-known storm history, and well-documented rise in sea level.

## THE PEA ISLAND MONITOR STUDY

### The Monitor Study Reports

The basic function of the terminal groin and rock revetment at Oregon Inlet (Fig. 6) was to stop the southward migration of Oregon Inlet and keep the north end of Pea Island from abandoning the Oregon Inlet bridge within the inlet (NCDOT, 1989). These two structures did what they were designed to do within Oregon Inlet. But what was their impact upon the downstream beaches of Pea Island?

Whether or not the terminal groin at Oregon Inlet has had a negative impact on the downstream shoreline of Pea Island ocean beaches is an extremely important question. The NCDOT (1989) stated that the "severe ocean shoreline erosion that is taking place along the two mile stretch (mile markers 1-3) of shoreline south of the Oregon Inlet Coast Guard Station, a result of the inlet's inefficient sand bypassing, will continue. The problems associated with the severe ocean shoreline erosion....can only be addressed by a separate corrective measure. The most desirable solution for this problem would

**Table 1. Summary of Oregon Inlet dredging and Pea Island (PI) beach nourishment efforts from 1983 to 2009 (in million cubic yards).**

| | |
|---|---|
| 2006-2009* | ~1.9 m yds$^3$ in 2 pipeline dredge operations w/ PI beach disposal (miles 1-3) |
| 1989-2005*** | ~3.7 m yds$^3$ in 10 pipeline dredge operations w/ PI beach disposal (miles 1-3) |
| | |
| 2006-2007* | ~1.2 m yds$^3$ in 4 hopper dredge operations w/ nearshore disposal (off PI miles 1-3) |
| 1993-2005*** | ~2.0 m yds$^3$ in 10 hopper dredge operations w/ nearshore disposal (off PI miles 1-3) |
| 1983-1988** | ~3.2 m yds$^3$ in 8 hopper dredge operations w/ nearshore disposal (off PI miles 1-3) |
| | |
| 2009** | ~0.2 m yds$^3$ mined from fillet to build dune ridges on PI between miles 11-12 |
| 1996-1997** | ~0.5 m yds$^3$ mined from fillet to build dune ridges on PI between miles 4-6 |
| 1992-1993** | ~0.2 m yds$^3$ mined from fillet to build dune ridges on PI between miles 4-6 |

**TOTAL = ~ 12.9 million yds$^3$**

Sources: * Estimates from Pea Island Wildlife Refuge; ** N.C. Department of Transportation; *** U.S. Army Corps of Engineers

Fillet is the sand moving by long-shore transport that is trapped by the terminal groin in the angle between the groin and the shoreline.

be to undertake a program of periodic beach nourishment to offset the sediment deficit imposed by Oregon Inlet."

Thus, to minimize negative impacts of the Oregon Inlet terminal groin on the downstream Pea Island shoreline, USACE agreed to place sediment from routine Oregon Inlet channel dredging either directly on the Pea Island beach or in shallow nearshore of Pea Island (Table 1) between mile markers 1 to 3, known as the Canal Hot-Spot (Fig. 2). To answer the question as to whether the terminal groin at Oregon Inlet has a negative impact on the downstream shoreline of Pea Island ocean beaches, NCDOT-funded a long-term monitor study of the ocean shoreline along the northern six miles of the 12 mile-long Pea Island. Fisher and Overton (Report 1 in 1990 to Report 4 in 1992) Overton and Fisher (Report 5 in 1992 to Report 27 in 2005) and Overton (Report 28 in 2006 to Report 34 in 2008) were contracted to carry out this monitor study. Fisher et al. (2004) summarized the monitor data from 1989-2003 and utilized it as a basis for developing cost estimates for NCDOT in building and maintaining the new NC Highway 12 across Pea Island in conjunction with the 100-year life expectancy of the proposed Oregon Inlet bridge replacement.

According to the NCDOT (1989) the purpose of the monitor program was "to document the changes in the shoreline on the northern end of Pea Island, within six miles of the terminal groin….a known area of high shoreline erosion. It is anticipated that the groin will reduce this erosion and serve to stabilize the down-drift shoreline." However, NCDOT "agreed to provide (additional) beach nourishment if it can be shown that there is a significant increase in erosion rates (above the historical erosion rates) with the construction of the groin".

Table 1 is a general summary of sand volume artificially placed on and near the Pea Island beaches from 1983 to 2009. These numbers are based upon the scattered and incomplete records that are available to the public from three sources. Thus, these data are at best an approximation and are probably on the conservative side in terms of the volume of sand involved. However, the important point is that there has been a substantial effort to stop the Pea Island shoreline recession.

The monitor study and the study reports of Fisher and Overton (1990-1992), Overton and Fisher (1992-2005), Overton (2006-2008), and Fisher et al. (2004) have a series of fundamental problems.

1. The beach monitor reports were not made public or peer-reviewed by the NC scientific community until the recent discussions over the proposed terminal

groin legislation made the reports available.

2. There is a paucity of basic data within the reports that does not allow for a comprehensive re-evaluation or peer-review of the reports' conclusions. The data (including aerial photography; measured shoreline recession rates; timing, volume, and cost of dredging and beach nourishment projects; and data on highway maintenance costs, etc.) are still not available to the scientific community for review. The data that are in the public domain are imprecise and often have substantial gaps. Thus, what is presented in the present document is, therefore, conservative.

3. The monitor reports are generally all very similar documents with minor changes from one to the next. For example, all the reports since 2000 contain a five-line "Summary and Conclusions" of identical words that include the following statement: "the construction of the groin does not appear to have caused an adverse impact to the shoreline over the six-mile study area."

4. The reports do not include consideration of the critical impacts of either coastal processes or of human modifications that occurred within the inlet and in the maintenance of NC Highway 12 on Pea Island. If an inlet is highly managed (e.g., channels dredged for navigation and sediment discharged offshore, channels relocated, inlet deltas mined for beach nourishment sand, and/or inlet flanks fixed in place with hardened structures such as terminal groins) the critical inlet-beach sediment couplet becomes destabilized, with potential consequences. If the beaches and associated highway are highly managed (e.g., nourishment sand is pumped onto a beach segment; sand-bag walls are emplaced, and barrier dune ridges constructed to prevent shoreline recession and overwash), the short-term maintenance and long-term evolution of the barrier island system are jeopardized. Since the latter factors greatly impact shoreline-change rates, they also will influence the interpretation of the monitor report data. However, the processes listed above routinely took place during the study but were rarely factored into data evaluations.

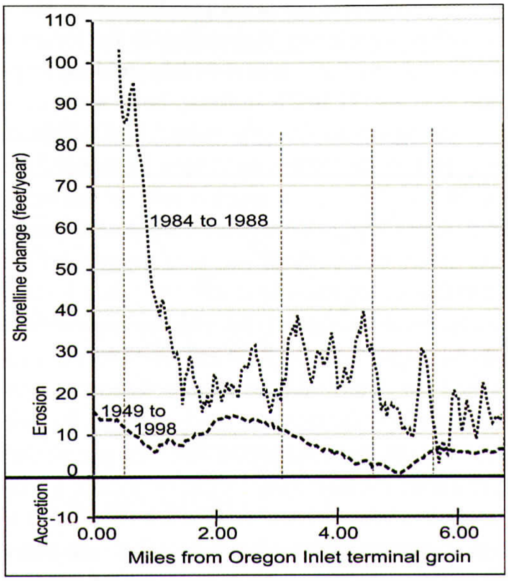

**Figure 7. This plot shows the annual rates of shoreline change for two reference shorelines along the six-mile beach monitor segment south of the Oregon Inlet terminal groin. The upper dashed line is the annual shoreline-change rate for 1984 to 1988 utilized in all of the monitor study reports as the "historic erosion rate" of Fisher and Overton (1990-1992), Overton and Fisher (1992-2005), and Overton (2006-2008). The lower dashed line represents the NCDCM average annual shoreline-change rate for the period of 1949 to 1998 utilized by Fisher et al. (2004).**

## Historical Erosion Rate For The Monitor Study

All of the monitor reports (numbers 1 to 34) of Fisher and Overton (1990-1992), Overton and Fisher (1992-2005), and Overton (2006-2008) utilized a "historical erosion rate" for the study (Fig. 7). The "historical erosion rate" was the baseline for comparing the post-terminal groin monitor data with pre-terminal groin shoreline conditions. According to the monitor study reports, there was a widely held assumption that the "USACE initiated large scale hopper dredging in Oregon Inlet" and offshore disposal in the 1980s could have influenced the accelerated shoreline erosion rate on the north end of Pea Island. Thus, the purpose of the monitor study comparison was to determine if the terminal groin built in 1989-1991 had further accelerated Pea Island shoreline erosion. Aerial photographs from 9-19-84 and 10-9-88 were selected for determination of the "historical erosion rate" for the monitor study (Fig. 7). In their reports, the authors argued that "the use of earlier aerial photography might introduce a bias towards a lower historical erosion rate" and the use of photography after a March 1989 storm "had the potential to bias the historical erosion rate analysis to higher values."

An interpretation problem rises when utilizing the 1984-1988 shoreline erosion data as the baseline for the "historical erosion rate". Utilizing this four-year time period Fisher and Overton calculated an average erosion rate of 27.4 ft/yr for the northern six miles of Pea Island (Fig. 7). This four-year data set represents a short time interval with high rates of inlet migration. It was also a period of increased inlet dredging and offshore disposal that led to the construction of the terminal groin to stop inlet migration and to anchor the bridge to Pea Island.

The Fisher and Overton, Overton and Fisher, and Overton reports from 1990 to 2008 are titled "Shoreline Monitoring at Oregon Inlet Terminal Groin". The main goal was to document the shoreline changes on the northern six miles of Pea Island. "As a precaution against any unforeseen adverse impacts of the structure on the shoreline, NCDOT has agreed to provide beach nourishment if it can be shown that there is a significant increase in erosion rates with the construction of the groin" (Fisher and Overton, Overton and Fisher, and Overton reports from 1990 to 2008). If the post-terminal groin erosion rates for the monitor site are less then the 1984-1988 baseline, which is a worst case scenario, then NCDOT has a low likelihood of having to add additional beach nourishment sand to Pea Island (Table 1).

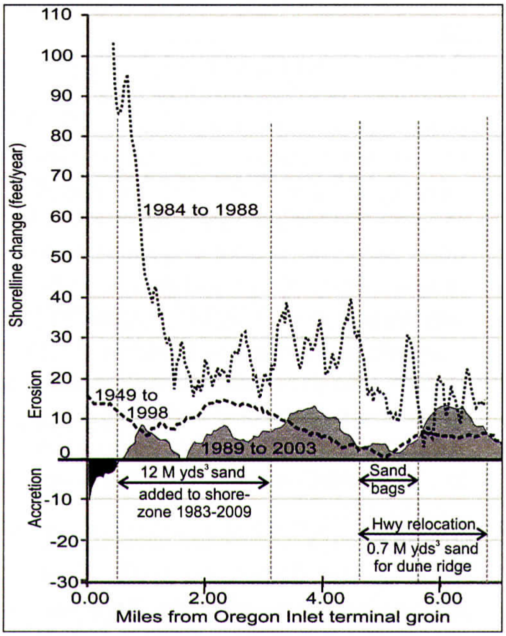

**Figure 8. This figure shows the same two reference plots (dashed lines) as shown in Figure 7, as well as the cumulative annual shoreline-change rate for the monitor site from 1989 to 2003 (from Fisher et al., 2004) in solid gray and black. In addition, the plot shows the island zones that have been the focus of extensive beach nourishment efforts from 1983 to 2009 and that have been characterized by a sand-bag emplacement and road relocation, respectively. The high cost efforts within mileposts 1 to 3 and 5 to 7 (Tables 1 and 2) contribute to the general decreased erosion rates within the northern 1 to 3 mile zone. However, major portions of the 3 to 7 mile zone have doubled the erosion rates relative to the NCDCM reference shoreline, in spite of the extensive human efforts.**

For developing the cost estimates for the new Oregon Inlet bridge—Pea Island Highway 12 project, the Fisher et al. (2004) study utilized the NCDCM erosion data (1949 to 1998) (Benton et al., 2007) for their historic erosion rate (Fig. 7). Use of this longer-term historical data set resulted in a mean annual erosion rate for the monitor site of 8.1 ft/yr, substantially less than the 1984-1988 mean erosion rate for the monitor study site of 27.4 ft/yr. In contrast, the main

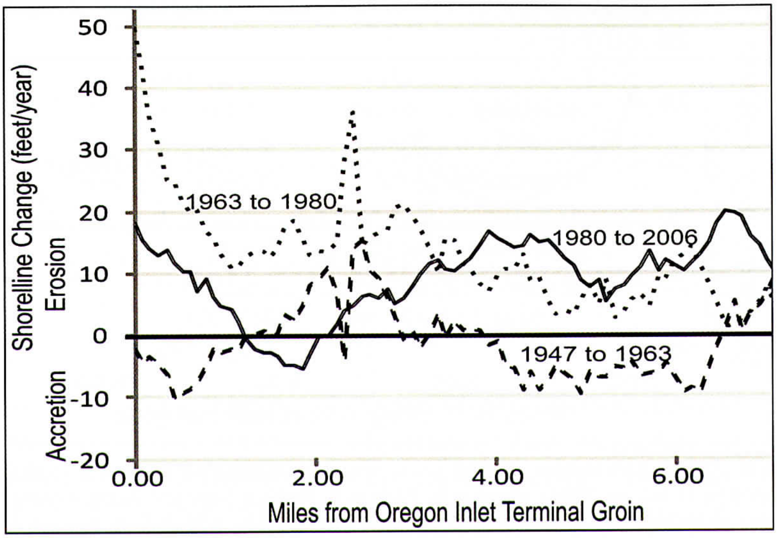

**Figure 9. A plot of shoreline-change rates for three different time segments of the long-term average shoreline-change data for the monitor study area. The dark dashed line represents the average shoreline-change rate for the time period 1947 to 1963 that pre-dates most major shore-zone modifications. During this period rates of shoreline change generally range from erosion rates of -10 ft/yr to accretion rates of +10 ft/yr. The dotted line represents the shoreline-change data during 1963 to 1980, a period of initial channel dredging and offshore dumping that demonstrates the direct impact upon the adjacent down-drift shoreline. The solid line represents the shoreline-change data for 1980 to 2006, a period of major human modifications (inlet stabilization with rock revetments and terminal groins, channel dredging, beach nourishment, barrier dune-ridge construction, sand-bag implants, bulldozing and mining overwash sand, and highway relocations, etc.). The shoreline data for the three time intervals were based upon the historic shoreline-change maps of Everts et al. (1983). The US Army Corps of Engineers at the Field Research Facility, Duck, NC, converted the historical shorelines to a digital format that was supplied to Dare County and the scientific community for their use. We calculated the shoreline change for the three time intervals from the USACE digitized maps to produce Figure 9. The 2006 data set is from the USNPS.**

goal of the Fisher et al. (2004) study titled "Pea Island Shoreline: 100-Year Assessment" was to calculate the "cost for beach nourishment to protect highway 12 over the next 100 years." Using the longer-term NCDCM reference line (Fig. 7) minimized the total estimated project cost.

The lower annual erosion rate based upon the 1949 to 1998 data set represents a mixed time period that includes erosion rates that are pre- and post-inlet dredging, bridge construction, and terminal groin emplacement, making it impossible to sort out the direct impacts of either change. Everts et al. (1983), Riggs and Ames (2007), Riggs et al. (2009), and Pietrafesa (pers. comm., 2009) demonstrated that when shoreline erosion rates are considered on short-time intervals, they result in highly variable patterns of alternating erosion and accretion. However, the shoreline recession data considered over long time intervals (~150 years) show an overall net long-term recession for Pea Island. Additionally, shoreline erosion-rate data are extremely variable for any given portion of the shoreline and depend upon the degree and frequency of storms, type of human modification, associated inlet dynamics, and variability in the underlying and shore-face geology (Fig 7). Thus, the time frame selected for measuring the end points becomes critical and will determine whether it is a low, medium, or high rate of recession. Utilizing long-term time slices can mask some important short-term variations and result in generally smooth lines. Whereas, using

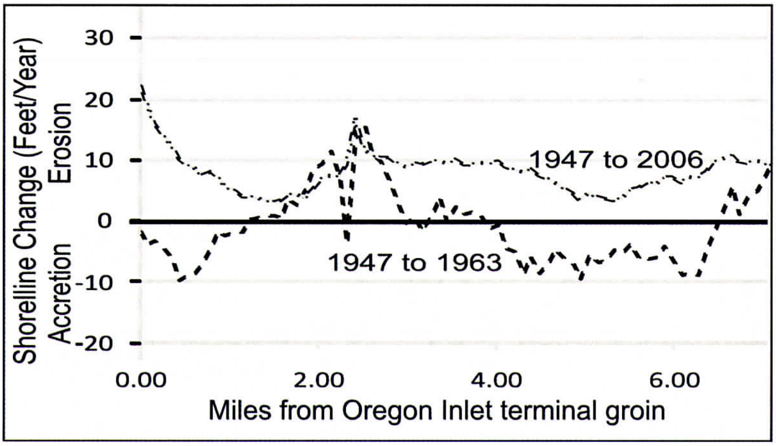

**Figure 10. This plot shows the combined long-term shoreline-change rates (upper line) for all three time periods (1947 to 2006) plotted in Figure 9. Notice how the longer-term data tend to smooth out the shoreline recession line. The dark dashed line represents the shoreline-change rates for 1947 to 1963 that pre-dates most major shore-zone modifications as plotted on Figure 9. The shoreline data for the two time intervals were based upon the historic shoreline-change maps of Everts et al. (1983). The US Army Corps of Engineers at the Field Research Facility, Duck, NC, converted the historical shorelines to a digital format that was supplied to Dare County and the scientific community for their use. We calculated the shoreline change for the two time intervals from the USACE digitized maps to produce Figure 9. The 2006 data set is from the USNPS.**

short-term time slices allow for the recognition of impacts resulting from individual events such as storms, storm patterns, beach nourishment, and other human modifications.

## IMPACT OF HUMAN MODIFICATION ON PEA ISLAND SHORELINE EROSION

Each bi-annual report for the monitor study (Fisher and Overton, Overton and Fisher, and Overton reports from 1990 to 2008) produced a plot of shoreline recession data for that particular time period. However, only the Fisher et al. (2004) report produced a cumulative plot covering the period from 1989 to 2003 and referred to as the Oregon Inlet Monitor Data (OIMD) in their report. This data set is very robust as it represents data points every two months for the 15-year time interval. The OIMD data are plotted in Figure 8 against the two data sets from Figure 7. When comparing the three data sets in Figure 8 it becomes clear that the erosion rate for milepost 1 to 3 segment of northern Pea Island was reduced by deposition of beach nourishment sand. However, the shoreline erosion rate substantially increased in the milepost 3 to 7 segment relative to the 1949 to 1998 data. In addition, extensive barrier dune-ridges were constructed and maintained through the milepost 3 to 7 segment along with emplacement of sandbags to hold NC Highway 12 in place. Ultimately in 1996, much of the NC Highway 12 in this latter segment was moved westward in response to severe shoreline recession.

To better address the question of terminal groin impact upon Pea Island, it is recommended that a series of three shoreline-change rates be utilized along the six miles of northern Pea Island adjacent to Oregon Inlet (Figs. 9 and 10). The three periods would represent a period of pre-major human modification (1947 to 1963), a period of minor human modification (1963 to 1980), and a period of major human modification (1980 to present). These intervals more accurately represent the pre- and post-terminal groin shoreline responses. As shown in Figures 9 and 10, these shoreline-change rates demonstrate substantial differences in erosion rates along the shoreline, and have a higher potential of demonstrating differences in beach dynamics during these time periods.

**Table 2. Oregon Inlet bridge and Pea Island (PI) NC Highway 12 Maintenance costs from 1983 to 2009.**

| Dates | Costs | Action |
|---|---|---|
| 1988 & 1996* | ~ $ 4,300,000 | NC Hwy 12 Relocations |
| 1989-1991* | ~ $15,000,000 | Terminal Groin & Revetment |
| 1987-1999* | ~ $ 6,062,500 | NC Hwy 12 Maintenance |
| 2000-2002 | $ ?? | NA |
| 2003-2006 | $ 1,796,750 | NC Hwy 12 Maintenance |
| 2007-2009** | ~ $ 2,869,300 | NC Hwy 12 Maintenance |
| 2009** | ~ $ 2,733,700 | NC Hwy 12 Relocation |
| SUBTOTAL | > $32,762,250 | |
| 1983-1988$^{EST}$ | ~ $ 8,300,000 | Hopper Dredging w/ Nearshore Disposal |
| 1993-2005*** | ~ $ 8,154,000 | Hopper Dredging w/ Nearshore Disposal |
| 2006-2007$^{EST}$ | ~ $11,788,000 | Hopper Dredging w/ Nearshore Disposal |
| 1989-2005*** | ~ $29,105,000 | Pipeline Dredging w/ PI Beach Disposal |
| 2006-2009$^{EST}$ | ~ $ 9,471,000 | Pipeline Dredging w/ PI Beach Disposal |
| SUBTOTAL | > $66,818,000 | |
| **GRAND TOTAL** | **> $99,580,250** | |

* Outer Banks Task Force; **N.C. Department of Transportation;
***U.S. Army Corps of Engineers; $^{EST}$Estimate based on Fisher et al., 2004

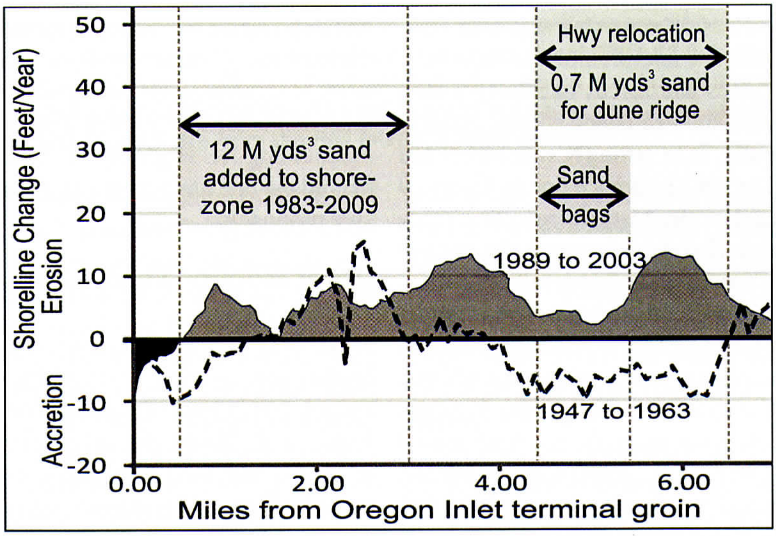

**Figure 11. Plot shows the annual shoreline-change rate for the monitor site from 1989 to 2003 (Fisher et al., 2004) in solid gray and black colors. The monitor data are plotted against the 1947 to 1963 historic reference shoreline-change rate. The digital shoreline upon which the shoreline-change rate was calculated is from the USACE-FRF and based on Everts et al. (1983). In addition, the plot shows the island zones (gray boxes) that have been the focus of extensive beach nourishment efforts from 1983 to 2009 and that have been characterized by sand-bag emplacements and road relocation.**

In order to recognize the actual impacts that human modification in Oregon Inlet had upon the adjacent Pea Island beaches, a different reference line should be utilized than that used by the monitor studies of Fisher and Overton, Overton and Fisher, and Overton reports from 1990 to 2008. The historic Pea Island erosion rate data set utilized as a reference should predate major human modification. This historic reference baseline should be based upon the natural dynamics of the inlet-barrier island system; the processes that have created this coastal system and will determine how it will respond to storms and sea-level rise through time. Thus, a more realistic shoreline analysis would be based on the general patterns of relative change that pre-date major human modification. This latter natural and historic data set should be utilized as the reference line to separate out the impacts of human modification upon barrier island dynamics, including the impact of the terminal groin. This is not an argument over the data gathering methodology, absolute numbers, error bars, or small differences of change. Rather it concerns the basic approach to the data analysis and the ultimate interpretation of the role of specific processes and forces operating within the Oregon Inlet and Pea Island coastal system.

Consequently, it is strongly recommended that the 1947 to 1963 reference line in Figures 9 and 10 be used as the historic base line. This shoreline more closely represents the natural barrier island processes and generally pre-dates most human modification efforts associated with inlet dredging, beach nourishment, and highway maintenance and relocation efforts. Comparing the shoreline-change rate from the downstream monitor study for the time period 1989-2003 (Fisher et al., 2004) with the natural shoreline-change rate for the time period 1947 to 1963 results in a much different interpretation as shown in Figure 11. Using this baseline it can be seen that the downstream impacts of the terminal groin and inlet dredging are severe, in spite of the human efforts to hold the line. Thus, NC Highway 12 on Pea Island still barely exists due to the tremendous effort associated with extensive beach nourishment, bulldozed barrier dune-ridge construction and maintenance, sand-bag emplacements, and highway relocations (Tables 1 and 2).

Table 2 is a general summary of the Oregon Inlet bridge and Pea Island highway 12 maintenance cost from 1983 to 2009. The costs are broken into two categories based upon 1) cost for NCDOT to maintain NC Highway 12 on Pea Island as shoreline erosion increasingly impacted the road, and 2) cost of beach nourishment in efforts to stop the increased shoreline erosion along the northernmost 1 to 3 miles of Pea Island. Based upon the 2004 costs, Fisher et al. (2004) calculated that a one million cubic yard pipeline nourishment project would cost about $5 million and a hopper nourishment project would cost about $7.5 million. These cost figures were applied to USACE dredging volumes to estimate the 2006 to 2009 dredging costs in Table 2.

The cost numbers in Table 2 are generally based upon scattered and incomplete records that are available to the public from the indicated sources. These data are, at best, an approximation of maintenance costs related to storms and ongoing barrier island dynamics and do not include the general day-to-day maintenance costs. Consequently, the numbers in Table 2 must considerably underestimate the cost of maintaining NC Highway 12. Thus, attempting to hold the line has become an extremely expensive proposition.

## Other Monitor Study Considerations

NCDOT (1989), as well as the monitor study (Fisher and Overton, 1990-1992; Overton and Fisher, 1992-2005; Overton, 2006-2008; and Fisher et al., 2004), did not consider the impact of large-scale, long-term processes (e.g., sediment budgets and transport, island migration, sea-level rise, etc.) in efforts to stabilize Oregon Inlet, minimize the erosion of Pea Island, and hold NC Highway 12 in its present location. NCDOT (1989) stated that "barrier island migration will not affect the integrity and function of the terminal groin....(since) barrier island migration is a phenomenon that occurs very slowly rather than over time spans that are normally associated with man's activities on these

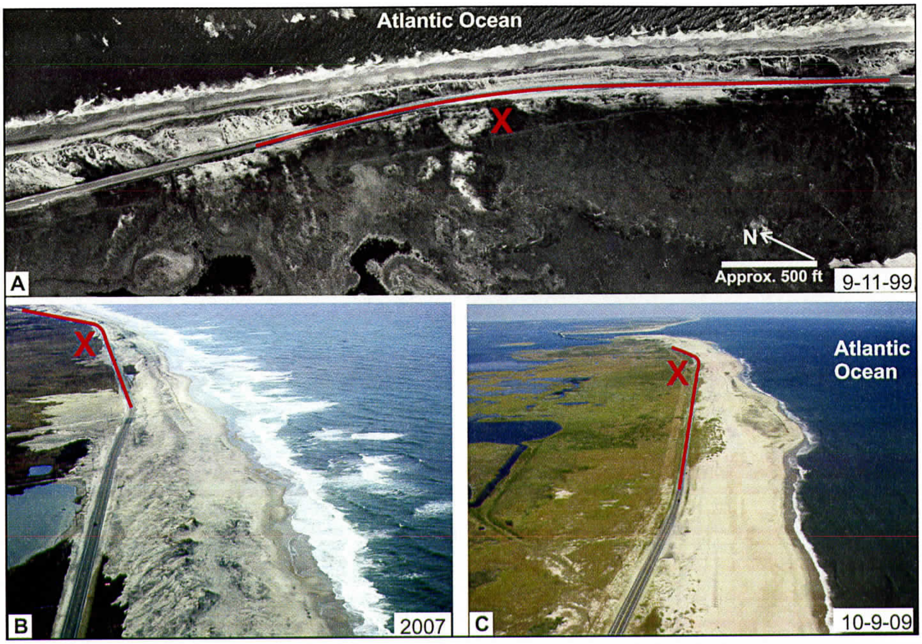

**Figure 12. Pea Island Canal Hot-Spot Area. Panel A is a 1999 aerial photograph showing the northern highly vulnerable zone of Stone et al. (1991) with NC Highway 12 immediately adjacent to a large constructed barrier dune ridge and narrow and steep beach. Notice the abundant highway overwash fans. Panel B is a 2-18-2007 oblique aerial photograph showing a very narrow and steep beach with a large constructed barrier dune ridge immediately adjacent to NC Highway 12. Notice the large highway overwash (at the south end of the red line). Panel C is a 10-9-2009 oblique aerial photograph taken after the completion of a pipeline dredge, beach nourishment project that widened the beach in the seaward direction. The red X marks the same spot on all photographs. Photographs in Panels B and C are from the Pea Island Wildlife Refuge.**

landforms." None of the monitor study reports through 2008 took sediment budgets and transport, island migration, or sea-level rise into consideration, even though substantial data on these processes was being developed for NC's Outer Banks coastal system (Dolan et al., 1973; Godfrey and Godfrey, 1976; Everts et al., 1983; Inman and Dolan, 1989; Pilkey and Dixon, 1996; Pilkey et al., 1998; Riggs and Ames, 2003; Zervas, 2004; Mallinson et al., 2005; Culver et al., 2007; Gutierrez et al., 2007).

Also, the monitor study did not take into consideration the timing of opening and closing of paleo-inlets within Pea Island and their role in modifying the patterns of adjacent shoreline erosion and accretion. The only portion of Pea Island that shows a net accretion on the NCDCM data set (Mallinson et al., 2008a; Smith et al., 2008; Riggs et al., 2009) happens to be exactly where the paleo-New and paleo-Loggerhead inlets have repeatedly opened and closed since Europeans arrived in this region in the late 16th century. When a longer term data set of Everts et al. (1983) is considered, Riggs et al. (2009) demonstrate that this portion of Pea Island displays a net recession rather than net accretion.

With construction of the terminal groin and all associated efforts dealing with dredging, beach nourishment, and maintenance of NC Highway 12 on Pea Island, the processes of erosion have not been stopped in the monitor study area. The human efforts have temporarily slowed down the process of shoreline recession in a small portion of the study area by the regular addition of dredged sand between mileposts 1 to 3, the Canal Hot-Spot area of northern Pea Island (Figs. 2 and 11) at a very high cost (Table

**Figure 13. Figures show the Oregon Inlet dredging and beach nourishment in the Canal Hot Spot area of Pea Island. Panel A shows a pipeline dredge working in the navigational channel of Oregon Inlet. Panel B is an oblique aerial photograph showing a nourished beach being constructed. Notice NC Highway 12 adjacent to the beach in the upper right corner. Panel C shows a pipeline dredge delivering sand to the nourished beach. Panel D shows bulldozers constructing a new barrier dune ridge. All photographs are from the Pea Island National Wildlife Refuge.**

2). But the new sand associated with each beach nourishment project is quickly eroded away leaving the NC Highway 12 in jeopardy again. Meanwhile, the ongoing shoreline recession along much of the rest of Pea Island has forced NCDOT to repeatedly rebuild barrier dune ridges, emplace sand-bag walls, and relocate NC Highway 12, particularly at mileposts 4 to 7 and 10 to 12, the Sand-Bag and S-Curve Hot-Spots (Figs. 2 and 11).

## RECENT HISTORY AND LONG-TERM PROGNOSIS FOR PEA ISLAND

### Canal Hot-Spot Area

The Canal area is located between mileposts 1 and 3 (Fig. 2). The area between the terminal groin and milepost 1 is part of the relatively stable fillet that forms immediately adjacent to and is controlled by the terminal groin. NC Highway 12 comes off the bridge on the sound side of the island and runs SSE across the island towards the ocean beach. At about milepost 1 the highway curves southward and runs parallel to the beach (Fig. 12) for the next two miles forming the Canal Hot-Spot Area. The location of the road immediately adjacent to a narrow beach and receding shoreline results in a serious conflict. The sand dredged from Oregon Inlet and utilized for beach nourishment projects (Table 1) is deposited onshore between mileposts 1 to 3. If there has been a recent nourishment project, the beach along this segment is wide and shallow. With time, however, and depending upon the storm frequency and intensity, the beach becomes narrow and steep (Figs. 12B and 12C).

An unknown amount of dredging was done to keep the Oregon Inlet channel under the fixed navigational bridge span from 1963 to 1982 (NCDOT, 1989). Between 1983 and 2009, approximately 6.4 million cubic yards (Table 1) of

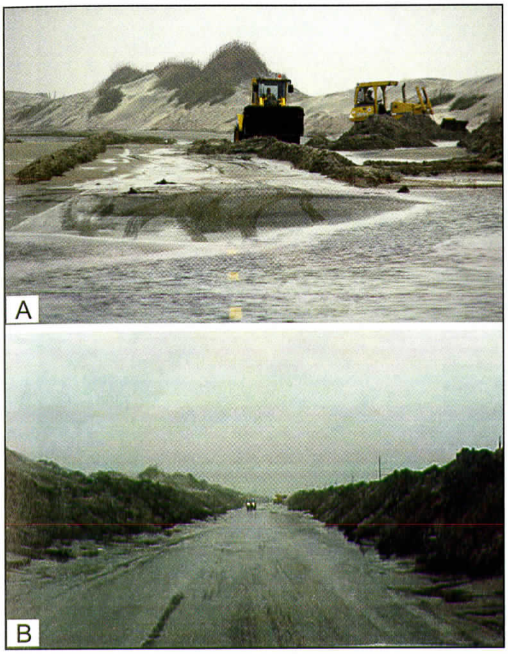

**Figure 14. Photographs of NC Highway 12 at the "Canal Hot-Spot" area show the serious problem with overwash sand frequently burying the road. Panel A was taken during the Veteran's Day nor'easter storm (11-2009) and Panel B was taken during Hurricane Dennis (9-1999). Both photographs are from Pea Island National Wildlife Refuge.**

Oregon Inlet hopper dredged sediment were deposited as beach nourishment in the shallow near-shore between mileposts 1-3 of northern Pea Island beaches. Between 1989 and 2009, approximately 5.6 million cubic yards (Table 1) of Oregon Inlet dredged sediment were pipelined to and deposited directly as beach nourishment on the Pea Island beaches between milepost 1 and 3 (Fig. 13).

The barrier dune ridge at the Canal site benefits from the human conflict, since this is the location of beach nourishment disposal. Abundant "new sand" is washed and blown from the beach onto the dune ridge in response to the day-to-day processes. With the help of bulldozers and extensive sand fencing, the barrier dune ridge grows into a narrow and almost vertical wall of sand (Figs. 14 and 15). However, the newly nourished shoreline continues to recede causing a long-term net narrowing of the beach and the shoreface to become increasingly steeper through time (Fig. 12) (Everts et al., 1983; Riggs et al., 2009). Thus, with each small storm, the wave energy impacting the beach is increased causing waves to more readily erode and overtop the unstable dune ridge (Figs. 14 and 15). The resulting overwash fans bury the highway with water and sand. The sand is promptly bulldozed back into the dune ridge (Figs. 14 and 15).

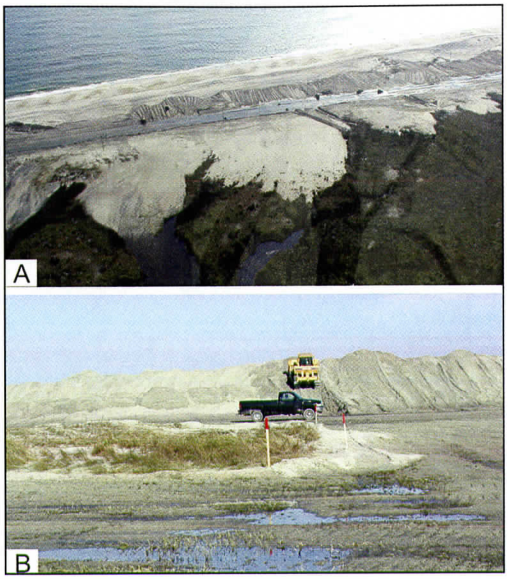

**Figure 15. Photographs of NC Highway 12 at the "Canal Hot-Spot" area show the serious problem with overwash sand that buried the road during Hurricane Isabel (9-2003). Panel A is an oblique aerial photograph that shows the large overwash fans with the bulldozers rebuilding the barrier dune ridge. Panel B is a ground photograph of the same area that shows how the new sand that increased the elevation (foreground and lower right side), has been mined from the overwash fan and bulldozed back into the dune ridge. Both photographs are from Pea Island National Wildlife Refuge.**

## Sand-Bag Hot-Spot Area

The Sand-Bag area is located between mileposts 4 and 6 (Fig. 2), the barrier segment that lies between the PINWR Visitor's Center on the north and PINWR's maintenance center on the

**Figure 16. Photographs show the succession of efforts from January 1992 to February 1996 to protect NC Highway 12 in the Sand-Bag area. Panel A shows the NCDOT bull-dozers attempting to rebuild a barrier dune ridge during a January 1992 storm (Photograph is from Pilkey and Thieler, 1992). Panel B shows a new wall of tan sand bags built adjacent to the highway between January and May 1992, along with remnants of the old barrier dune ridge. Panel C is an early February 1996 photograph that displays two additional sets of sand bags used to repair the sand-bag wall, first with black bags and then topped with white bags. Panel D shows a small storm surge that washed over the top of the sand-bag wall in early February 1996.**

south. NC Highway 12 in this segment was initially threatened in the early 1990s after construction of the terminal groin at Oregon Inlet. A storm in January of 1992 destroyed the dune ridge even though bulldozers were working to hold the highway (Fig. 16A). After the storm and prior to May of 1992, NCDOT built a massive sand-bag wall adjacent to the highway (Fig. 16B). Subsequently, during 1992 and 1993, about 200,000 cubic yards of sand was mined from the terminal groin fillet (Table 1), trucked to the Sand-Bag area, and used to rebuild the dune ridge covering the sand-bag wall. Over the next four years the shoreline continued to recede, the sand bag wall was repaired several times with different colored sets of sandbags, and reburied under the barrier dune ridge Figure 16C. Just prior to an early February 1996 storm (Figure 16D), the ocean overtopped the sand-bagged barrier dune ridge.

The rate of shoreline recession within northern segment of the Sand-Bag Area increased significantly from the 1963 to 1980 and the 1980 to 1996 periods (Fig. 17). Finally in late February 1996, about 3.5 miles of NC Highway 12 was relocated about 600 feet westward by NCDOT (Figs. 17 and 18). During 1996 to 1997, about 500,000 cubic yards of sand were mined from the Oregon Inlet terminal groin fillet (Table 1) and used to construct barrier dune ridges along the newly constructed highway between mileposts four and six (Fig. 18B). The highway relocation cost $4.3 million dollars, including sand bag removal (Table 2).

Figure 19A is a 1999 aerial photograph that shows the old and new portions of NC Highway 12 at the south end of the Sand-Bag Area. Today, as the shoreline continues to recede, small storms routinely breach the constructed barrier dune ridge and frequently bury the new road with overwash sand. Figures 19B and 20 are located at the southern end of the sand-bag area and demonstrate the total loss of the entire barrier dune ridge. Each storm continues to remove the barrier dune ridge, move the shoreline slowly westward, and produce frequent overwash fans that extend completely across the highway and into the wildlife ponds. The shoreline will

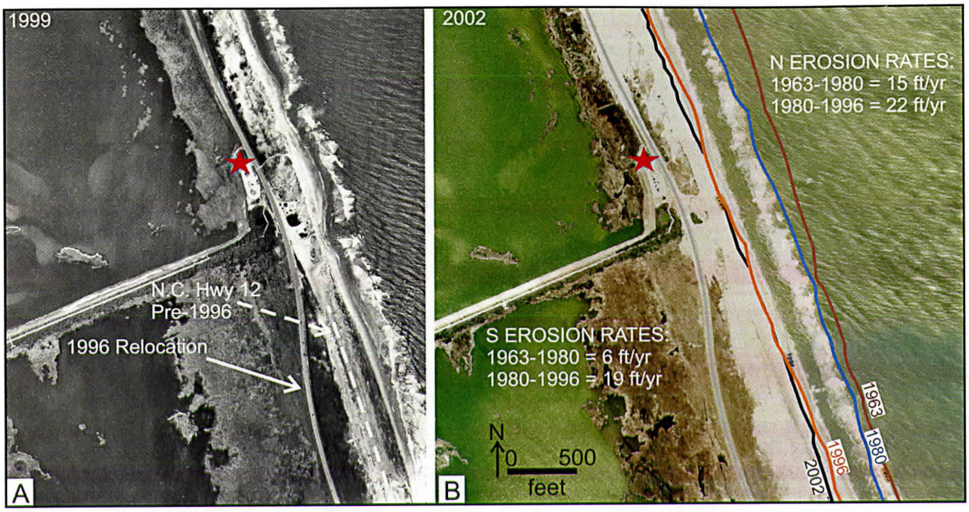

**Figure 17. Aerial photographs from 1999 and 2002 show the northern portion of the Sand-Bag Area of Pea Island (Fig. 2). Panel A shows both the former track of NC Highway 12 (white dashed line) prior to relocation and the 1996 relocated highway. Panel B shows the paleo-shorelines (from Everts et al., 1983) for 1963 (brown line), 1980 (blue line), 1996 (orange line), and 2002 (black line). Note the substantially different erosion rates for the two time intervals and for the northern and southern sections. The red star indicates the PINWR Visitor's Center and parking area.**

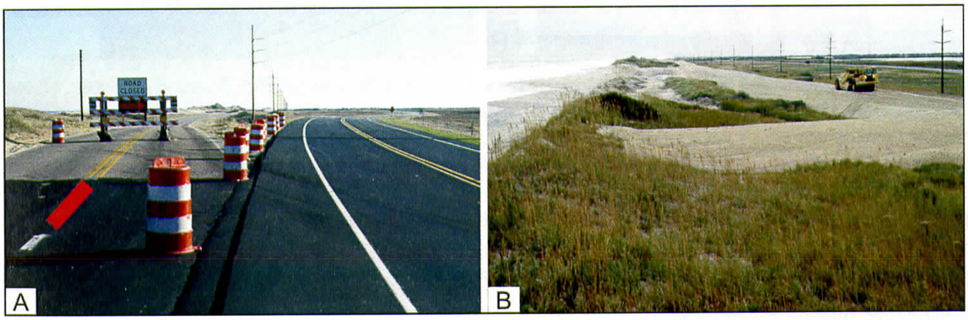

**Figure 18. Panel A. A late February 1996 photograph, looking south at the northern end of the sand-bag area, shows the old (on the left) "going to sea" NC Highway 12 and the relocated portion of the highway (on the right). Panel B is a December 1997 photograph looking south at the same general location and shows the construction of a new barrier dune ridge adjacent to the relocated NC Highway 12.**

soon jeopardize NC Highway 12 once again.

## S-Curves Hot-Spot Area

The narrow and vulnerable portion of PINWR (Riggs et al., 2009) that occurs between mileposts 10 to 12, just north of Rodanthe (Fig. 2), is known as the S-Curves. The curves that characterize NC Highway 12 reflect the long-term conflict that has resulted in multiple road relocations. When the highway was paved in the 1950s it had a single broad curve that was well back from the ocean (Fig. 21A). Prior to the Ash Wednesday Storm in March, 1962, the road had already been destroyed and relocated westward to form a small curve superimposed upon the large curve (Fig. 21B). In response to numerous storms, the shoreline within the S-Curves area continued to recede with erosion rates that ranged from 10 to 16 feet/year (Stone et al., 1991). Consequently, this area continued to be frequently overwashed, requiring almost

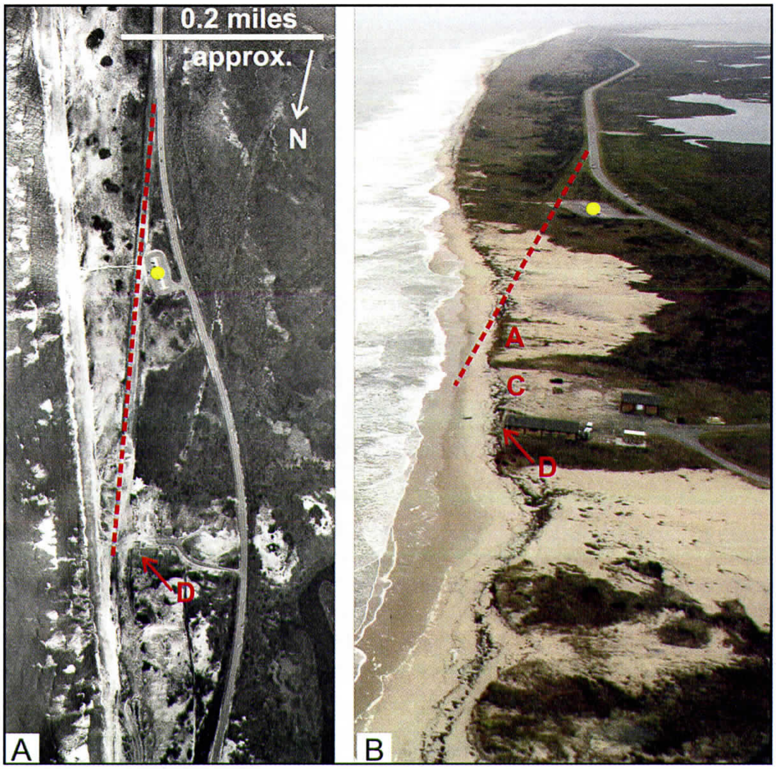

**Figure 19. Panel A is a 1999 aerial photograph of the south end of the Sand-Bag Area showing the location of the 1996 NC Highway 12 as it "goes to sea" (red dashed line) and the southern segment of highway that was relocated in February 1996. The yellow dot indicates a parking area and the red D marks the eastern end of the PINWR office building. Panel B is a November 14, 2009 oblique aerial photograph, looking south, of the same area as in Panel A. The red dashed line marks the location of the 1996 NC Highway 12, the yellow dot marks the same parking area as in Panel A. The red A, C, and D mark the locations of Figures 20A, 20C, and 20D. The photograph in Panel B is from the Pea Island National Wildlife Refuge**

continuous reconstruction of the barrier dune ridge. In 1988, NCDOT relocated a 1.2 mile segment of the road over 100 feet westward (Stone et al., 1991) (Fig. 21C).

The Halloween Day Nor'easter of 1991 threatened the road (Fig. 22B), as did Hurricane Dennis in 1999, and Hurricane Isabel in 2003 (Fig. 23A). By 2007, the erosion and overwash was so severe that NCDOT built a sand-bag core for a newly constructed barrier dune ridge (Fig. 24A). Ongoing erosion continued to routinely expose the sand bags that were subsequently reburied. Finally, the Veteran's Day Nor'easter of November 10, 2009 took out a section of the barrier dune ridge, sand-bag wall, and road bed (Figs. 24B, 24C, and 24D). For a cost of $2.734 million (Table 2), a small portion of the road was relocated slightly westward within NCDOT's right of way (red-dashed line in Fig. 23B) and a new barrier dune ridge, cored with a sand-bag wall, was built with over 207,000 cubic yards of sand trucked from the Oregon Inlet terminal groin fillet. This road segment continues to be overwashed regularly and frequently destroyed.

## SUMMARY AND CONCLUSION

The long-term Pea Island ocean shoreline has been systematically receding westward at rates up to about 13 feet/year (Everts et al., 1983; Stone et al., 1991; USACE, 1993; Benton

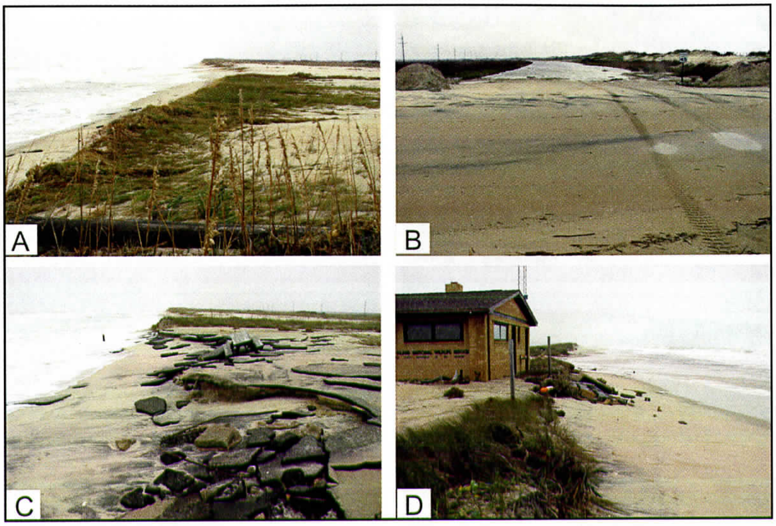

**Figure 20. These four photographs were taken immediately after a small nor'easter impacted the Sand-Bag Area on 11-14-2009. The locations of Panels A, C, and D are indicated by the red letters on Figure 19. Panels A and C look to the south and Panels B and D look north. Notice that the constructed barrier dune ridge has been completely eroded away (Panels A and C), the parking lot has been damaged, the office building has been threatened (Panels C and D), and the overwash fan extends all the way across NC Highway 12 (Panel B and Figure 19B). All photographs are from the Pea Island National Wildlife Refuge.**

et al., 1997; Fisher et al., 2004) as the island attempted to migrate in response to ongoing sea-level rise (Riggs and Ames, 2003; Horton et al., 2009; Kemp et al., 2009; Pilkey and Young, 2009; Williams and Guitierrez, 2009; NCDCM, 2010). This erosion rate is the result of a complex interaction of natural and anthropogenic factors that have resulted in "island narrowing". Each storm that breached the constructed barrier dune-ridges, some with sand-bag cores, either destroyed the road or buried it with overwash sand, which was then mined and used to reconstruct the barrier dune ridges. The island narrowing also increases the vulnerability of weak barrier segments to future inlet formation. Engineering of the ocean front impedes the natural island processes of inlets and overwash that build island width and elevation, as well as critical island habitat (Riggs et al., 2009 and 2011).

Large segments of the down-drift Pea Island ocean shoreline continue to recede causing the beaches to narrow and steepen against the barrier dune ridges constructed to protect the adjacent highway. The constructed barrier dune ridges are out of equilibrium with the high energy Atlantic Ocean and are routinely breached, requiring extensive rebuilding of both the dune ridges and NC Highway 12 with teams of bulldozers, graders, and haul trucks. Inevitably, the recession of the shoreline increases the conflict associated with the need to relocate both the barrier dune ridges and highway further westward into the Pea Island National Wildlife Refuge (Riggs et al., 2009).

National Wildlife Refuges have specific functions with highly managed ecosystems designed to meet those functions. PINWR's function is to preserve and manage Pea Island for migratory birds and other wildlife. Federal legislation passed in 1997 protects the function of National Wildlife Refuges by prohibiting construction of roads that interfere with refuge functions. However, the cumulative impact of sea-level rise and numerous storms (hurricanes and nor'easters) through time have promulgated increased efforts to maintain and/or reconstruct the transportation infrastructure, unfortunately at the expense of the barrier island and refuge functions within PINWR. PIN-

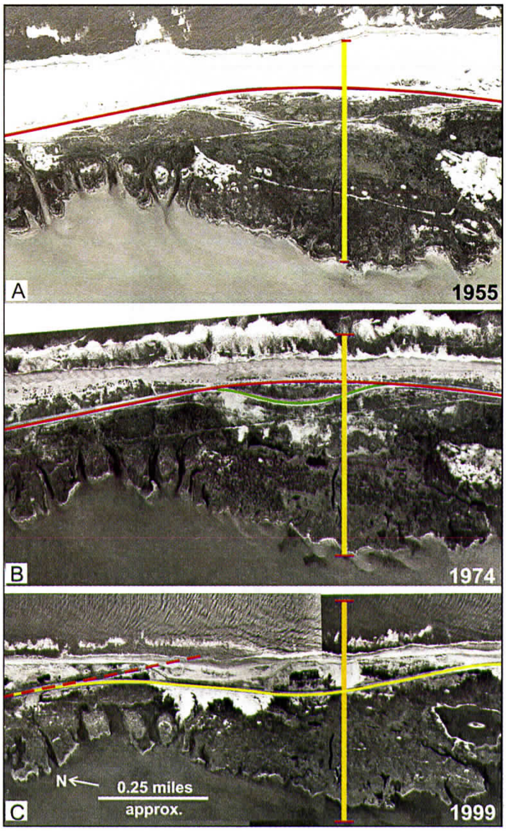

**Figure 21. Aerial photographs of the S-Curves hot-spot area within PINWR show the process of "island narrowing" (orange vertical line). Notice that the island has narrowed by about 30% during the 44 years between 1955 and 1999. Panel A shows the 1955 NC Highway 12 shortly after it was paved as a simple broad curved road (red line). Panel B shows the first road relocation that superimposed a small curve (green line) on the larger curve of the original road (red line). This relocation occurred prior to the Ash Wednesday Nor'easter storm of March 1962 as indicated on Figure 22A. Panel C is a 1999 photograph that shows a much larger 1.2 mile-long segment of the road (yellow line) that was relocated over 100 feet westward in 1988 (Stone et al., 1991). Notice the red dashed line indicating where the original road "goes-to-sea".**

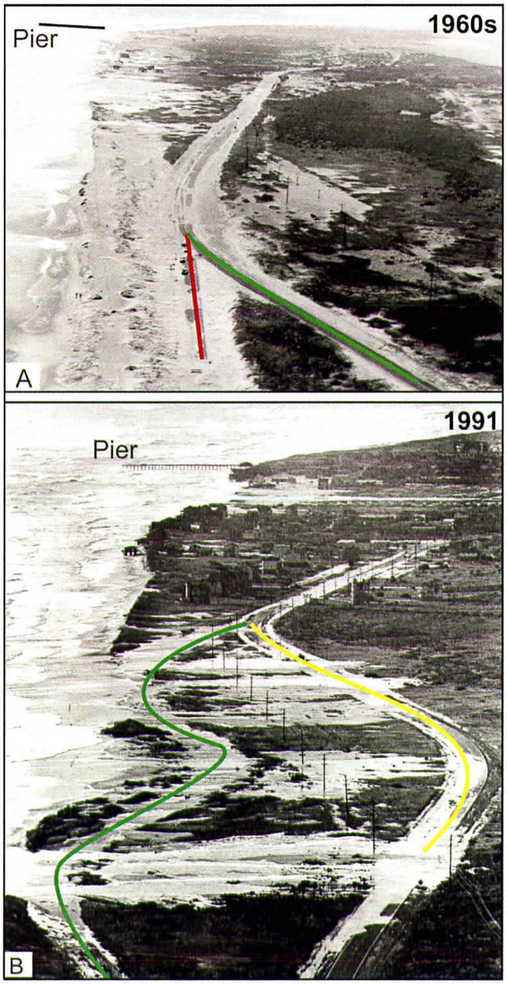

**Figure 22. Oblique aerial photographs look south at the S-Curves in the southern segment of PINWR and the northern portion of Rodanthe Village. Panel A was probably taken immediately after the Ash Wednesday Nor'easter of March 1962. The original road (red line) was paved in the early-mid 1950s. The road "went-to-sea" and was relocated (green line) prior to the Ash Wednesday Nor'easter, which overwashed the road again. Panel B was taken after the Halloween Day Nor'easter of October 1991. The original highway (red line) has completely "gone-to-sea". In 1988 the relocated NC Highway 12 (green line) was again relocated westward (yellow line) and was overwashed by a 1991 nor'easter. Photographs are from the Outer Banks History Center. Panel B is by Drew Wilson.**

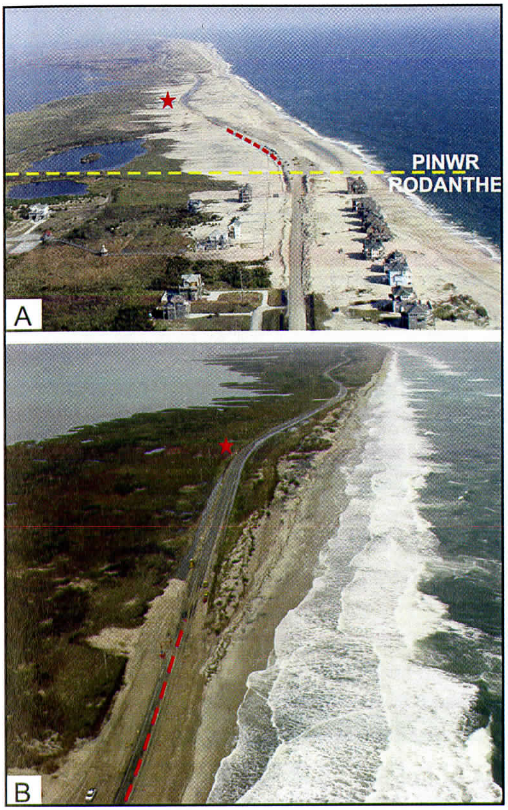

**FIGURE 23. Panel A is an oblique aerial looking north that shows the elimination of the constructed barrier dune ridge and a large overwash fan that resulted from Hurricane Isabel on September 18, 2003. Panel B is an oblique aerial looking north that shows only the PINWR portion of Panel A and the complete loss of NC Highway 12 (red dashed line in both panels) in response to the Veteran's Day Nor'easter storm (11-19-2009). The sand-bags have already been reburied beneath a newly constructed barrier dune ridge in the lower portion of the panel. Compare the two panels and notice the amount of shoreline recession in six years (red stars). Yellow dashed line is the boundary between PINWR and Rodanthe Village. Photographs are from the Pea Island National Wildlife Refuge.**

WR has not only lost substantial land area over the last half century, but has lost much of the wide, shallow beach habitat and the critical overwash-plain habitats that so many shore species are dependent upon.

Low-gradient, wide beaches provide essential feeding habitats for nesting shorebirds, as well as adequate nesting sites for sea turtles. An eroding and receding beach backed by a constructed barrier dune-ridge that is fixed in space and time results in an anomalously steep beach that gets steeper with time until the dune-ridge is scarped and then breached by storms. High-gradient beaches are too high energy for turtle and shore bird nesting sites. Beach nourishment projects temporarily stop the short-term erosion, but do not stop the long-term recession and quickly return to the same unstable, steep beach profile. Beach nourishment also negatively impacts the benthic infauna within the beach and adjacent surf zone (Dolan et al., 2004, 2006), which in turn negatively impacts the swash and surf zone feeding habitats critical for shorebirds, and fish, respectively. Further, constructed barrier dune-ridges prevent the natural overwash that produce the broad overwash ramps (Riggs et al., 2008), which are nesting habitats for piping plovers, terns, oyster catchers, black skimmers, etc.

With the Oregon Inlet terminal groin in place, Fisher et al. (2004) estimated, based upon the most conservative assumptions, that the beach nourishment necessary to hold the proposed new NC Highway 12 along the length of Pea Island for the next 100 years would take a minimum of 105.7 million cubic yards of dredged sand at a minimum cost of $930 million. So one can seriously ask if the terminal groin has solved the erosion problem or stabilized the beach of downstream Pea Island.

Riggs et al. (2011) asked the following questions. "Should North Carolina build a $1.5 billion (or more) Oregon Inlet Bridge and associated highway system on a 12-mile-long, dynamic, migrating barrier island? How will we maintain this infrastructure when the climate is warming, sea level is rising, and there is a likelihood of more frequent and intense tropical storms?" Clearly, a new bridge can be built in the same location as the present bridge across the throat of a high-energy inlet. But the real issue is that the bridge must be attached to a road on Pea Island that will be stable for the long-term (50 to 100 years). Based upon the record of the past six decades, with the ongoing rise of sea level and with a storm-dominated barrier,

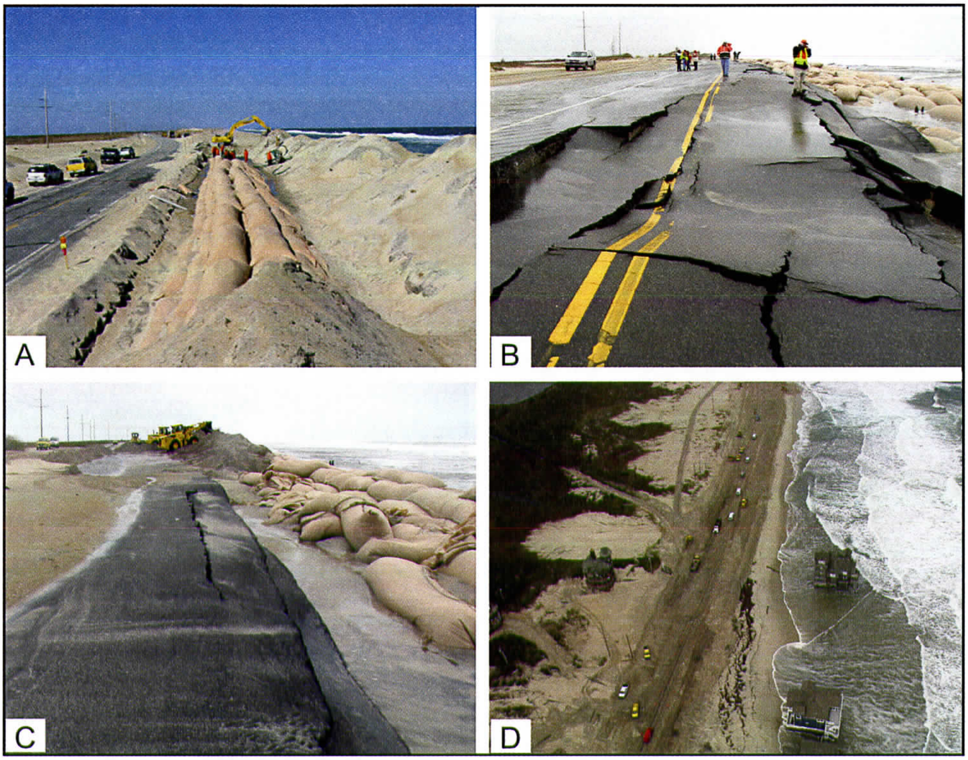

**Figure 24. Ground and oblique aerial photographs of the S-Curves Hot Spot illustrate recent maintenance activity on NC Highway 12 in response to the Veteran's Day Nor'easter of November 11, 2009. These photographs are at the same location as the red stars on Figure 23. Panel A shows the NCDOT construction of a sand-bag core for the barrier dune ridge in 2007. Panel B shows the destroyed sand-bag wall and NC Highway 12 (11-14-2009). Panel C shows the subsequent mining of the overwash sand and reconstruction of the barrier dune ridge on top of the broken sand bag wall (11-14-2009). Panel D is an oblique aerial photograph (11-19-2009) that shows the temporary vehicle by-pass while NCDOT relocates a portion of the road and reconstructs a new sand-bag-cored barrier dune ridge. Notice the two houses in north Rodanthe that are in the surf zone.**

maintaining a long-term road on Pea Island is not possible without a highly engineered platform for the road at an extremely high cost.

Over the past eight decades, engineering efforts have not stopped the westward recession of the ocean shoreline. But the bulldozers, sandbag walls, and barrier dune ridges have prevented most of the overwash and possible inlets that would have built both the elevation and width of Pea Island. Thus, the land west of the present highway is largely near mean sea level (supratidal to inter-tidal) and extremely narrow in places. As sea level continues to rise, there is an increasing likelihood for collapse of portions of Pea Island with new inlets and massive storm overwash (Riggs et al., 2009). Consequently, a long-term future for NC Highway 12 on Pea Island is not realistic since it is virtually impossible to maintain a fixed road on a constantly shifting pile of sand. About 18,000 years ago the North Carolina coastline was 15 to 60 miles to the east and 410 feet below its current location. Its migration westward will continue into the future as sea level rises. What will North Carolina do in response to this inevitable fact?

## ACKNOWLEDGMENTS

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# PALEOSEISMITES WHICH FORMED PRIOR TO AND DURING THE 31 AUGUST 1886 CHARLESTON EARTHQUAKE IN COLONIAL DORCHESTER, SOUTH CAROLINA

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## ABSTRACT

**The causative fault of the 1886 Charleston earthquake is unknown and different types of studies (modern seismicity; moment magnitude; geomorphic analysis; fracture analysis) have indicated that it might have different orientations: NW-trending fault, NE-side up; NW-trending fault, SW-side up; NE-trending fault, NW-side up; or NE-trending strike-slip fault. One area exists where many features which were formed near the epicenter of the 1886 earthquake are still preserved essentially undisturbed by either modern development or agricultural use. This area, within a South Carolina State Park, is Colonial Dorchester and the adjacent Fort Dorchester. As part of ongoing archaeological/geological work there, we reviewed earlier archaeological excavation-records which showed that sand-blows occurred prior to construction of the fort in 1758/60. Our preliminary gradiometer surveys of the town also indicate possible relict features of the 31 August 1886 Charleston or earlier earthquakes. Several large depressions (0.5-m-deep; 2-3-m diameter) are located within the old 12 x 60-m market place. A survey over one depression showed a segmented, N30-35E-trending, linear band of locally reduced magnetism at depth which is consistent with a clastic dike beneath a sand-blow vent. Another survey showed a 7 x 9-m-square structure (kiln?), at depth, with a 0.5-m component of left-lateral reverse offset along a ~N45W-trend. This is consistent with the recent reinterpretation of the Ashley River seismic zone which confirmed the NW-striking, SE-dipping fault-model for the causative fault of the 1886 Charleston earthquake as determined from the published analysis of joints and faults first observed by Dutton (1889) in walls of the old fort. It is consistent with geomorphic evidence, includ-**

**ing combined shoreline and river deflections, which indicate E-side-up across the causative fault. This offset of a Dorchester kiln(?) may be the first identified surface fault, which can be verified by excavation, associated with the 1886 Charleston earthquake. As such, verification of its actual orientation and slip-vector is crucial to a resolution of the causative fault of the 1886 Charleston earthquake (NW-striking, NE-dipping reverse fault versus NE-striking, right-lateral strike-slip fault).**

## HISTORICAL PERSPECTIVE

### Founding of Dorchester (1697) and Construction of Fort Dorchester (1758-60)

South Carolina was neither the first nor the last English colony in the new world. King Charles II granted Carolina to the Earl of Clarendon and associates in 1663. Old Charleston was settled by the Carteret County Colony on the Ashley River in 1670, just 63 years after a fort was built in 1607 at Jamestown, Virginia marking the first successful English colony in what is now the United States (Kelso, 2006; Kelso and Staube, 2004; Lange, 2002). In 1680 these colonists moved down the Ashley River to its confluence with the Cooper River (present-day Charleston), a good defensible port which prospers today as a deep-water harbor.

Colonial Dorchester (Note: present-day Dorchester was established much later along a railroad 17 miles to the northwest) was founded in 1697 on a strategic bluff 18 miles northwest and upstream of Charleston (Figure 1) where the Ashley River constricts and was not navigable upstream by larger vessels or rafts. Colonial Dorchester served as a transfer place for goods from the interior, which were shipped as larger boat-loads to Charleston, and for goods from Charlestown, which were destined for overland trade to the northwest and west into heavily forested areas along blazed trails, identified only by notches on trees. But colonial Dorchester was destined to be short-lived once Oglethorpe's colony settled Savannah in 1733 near the mouth of the Savannah River. Oglethorpe's

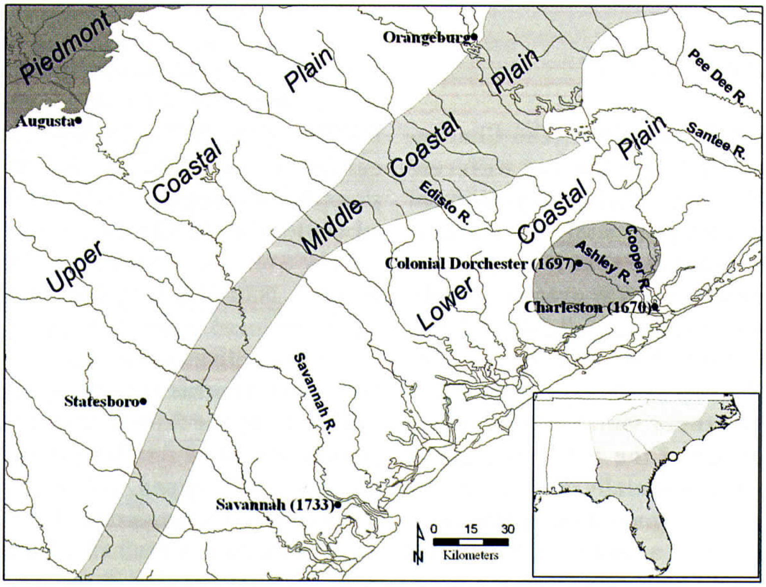

**Figure 1. Geographic map showing location of colonial Dorchester in relation to other colonial towns, the principal rivers, physiographic divisions of the Atlantic Coastal Plain (modified after Colquhoun, 1965, 1969; Hoyt and Hails, 1974; Willoughby et al., 1999) and the epicentral area of the 31 August 1886 Charlestown earthquake (elliptical shaded area, modified after Bollinger, 1977).**

treaty with the Indians and the grant by King George II in 1743, gave him the territory between the Savannah and Altamaha rivers which he named Georgia, the last of the 13 English colonies. Savannah controlled the Savannah River, which was navigable inland to the fall line where Augusta is located. Hence goods moved over short routes to the Savannah River and thence quickly by boat to Savannah versus much longer routes to colonial Dorchester for the short river trip to Charleston. Thus began a centuries-long competition between Charleston and Savannah to be the dominant port-city along the southeastern Atlantic coast.

Built as a key trade site, colonial Dorchester was the first victim of this colonial economic struggle. Declining trade, poor town-planning, and overcrowding resulted in gradual abandonment of colonial Dorchester as its residents migrated (ca. 1752-56) to Georgia (Carrillo, 1973). Largely abandoned by 1756, the site was resuscitated when Fort Dorchester was built (1758-60) during the French and Indian War as part of Charleston's northern line of defense (Carrillo, 1973; Kornwolf, 2002; Smith, 1905; Johnson, 1905). After languishing for more than a decade the fort was again occupied during the Revolutionary War, but was not strategically important (Kornwolf, 2002). Afterwards, its parish church served the rural countryside until 1820 and its cemetery up to the present-day. Scavenged for bricks, the colonial town was never completely leveled and converted to fields for cultivation, hence many foundations still exist at or near the surface. The old market place (Figure 2), a 60 x 12-m area, remained cleared and intermittently farmed until ca.1960 when the property became part of the state park system (South Carolina Department of Parks, Recreation and Tourism, 2009). Thus, colonial Dorchester is an "intact" archaeological site of early colonial South Carolina as well as a fortification of the French and Indian war era.

## Effects of the 31 August 1886 Charleston Earthquake on Colonial Dorchester and Fort Dorchester

Colonial Dorchester, abandoned for the 3rd time about 1820, was near the epicenter (Figures 1 and 3) of the 31 August 1886 Charleston earthquake (Dutton, 1889; Bollinger, 1977). This earthquake was the largest earthquake to occur in the eastern USA during historic time, with an estimated moment magnitude of 7.3 (Johnston, 1996). In 1887, after the disaster, Dutton (1889) and associates visited the region north and west of Charleston and described extensive damage from the earthquake. Along one traverse between Woodstock and Fort Dorchester, Dutton described large fissures in the ground, sand blows, small surface cracks and subsurface cracks in wells along his route. At colonial Dorchester, he described the church's toppled bell tower and cracks formed in the fort's walls, but neglected old foundations of the town, abandoned more than half a century earlier. During the 125 years since the 1886 Charleston earthquake, many changes have occurred both in Charleston and to the north in the epicentral region and most features described

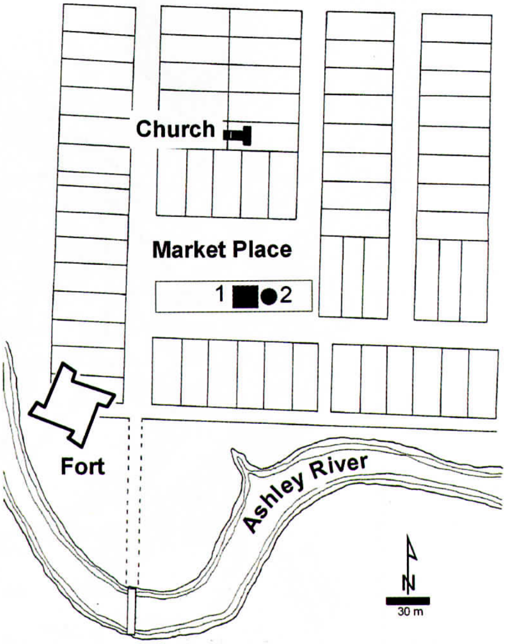

**Figure 2. Map of town lots in colonial Dorchester showing location of church, Fort Dorchester, and features (1 and 2) within the marketplace which may have formed during the 1886 Charleston earthquake (modified after Carrillo, 1976).**

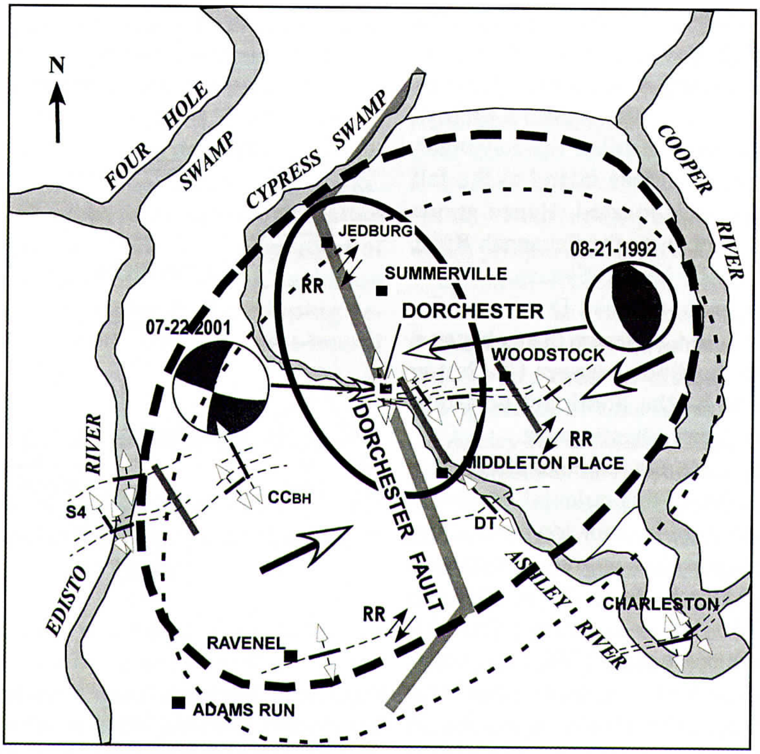

**Figure 3. Map (modified after Bartholomew and Rich, 2007) of epicentral region of the 1886 Charleston earthquake showing location of Dorchester (white square) to: NE-trending ellipse (light dashed ellipse) of MMI of X (from Bollinger, 1977) shifted slightly northwestward so that it encloses the NW-trending zone of modern seismicity (solid black ellipse) delineated by Dura-Gomez and Talwani (2009) and approximately coincides with the perimeter of the uplift (light shading) east of the Ashley River (Rhea, 1989) marking the deflections of the Cooper River and Cypress Swamp (Bartholomew and Rich, 2007); fault-plane solutions of the representative and well located 21 August, 1992 M4.1 and 22 July, 2001 M2.3 earthquakes (from Dura-Gomez and Talwani, 2009); SH$_{MAX}$ (large open arrows) determined by Madabhushi and Talwani (1993); relative right-lateral strike-slip displacements of railroad tracks (RR) (Dutton, 1889; Bodin and Johnston, 1999, 2000) and extension directions from joint-trends (small open arrows) (Dutton, 1889; Bartholomew et al., 2000; Talwani, 2000; Bartholomew and Rich, 2007) and extension direction (Zoback et al., 1978); and NW-trending kink-trends (NW-trending gray lines).**

by Dutton are no longer visible. Considerable urban/suburban/military development has drastically altered the former land surface between Charleston and Summerville, thus subsurface stratigraphy is minimally accessible for examination. Also many areas, once cleared and farmed, are now forested which even limits examination of the surface for sandblows. Because of such changes since the earthquake, colonial Dorchester represents a unique intact research site for the 1886 earthquake. Here the fort and old foundations embedded in the ground at colonial Dorchester have remained relatively undisturbed since the 1886 earthquake. In fact, this abandoned site may be the only place, prior to the next big earthquake in this region, to unravel what type of fault caused the 1886 earthquake, which happened decades before seismometers were invented to detect magnitudes and locations of earthquakes.

## GEOLOGICAL PERSPECTIVE

### Tectonic Setting

Dutton's (1889) exhaustive description of

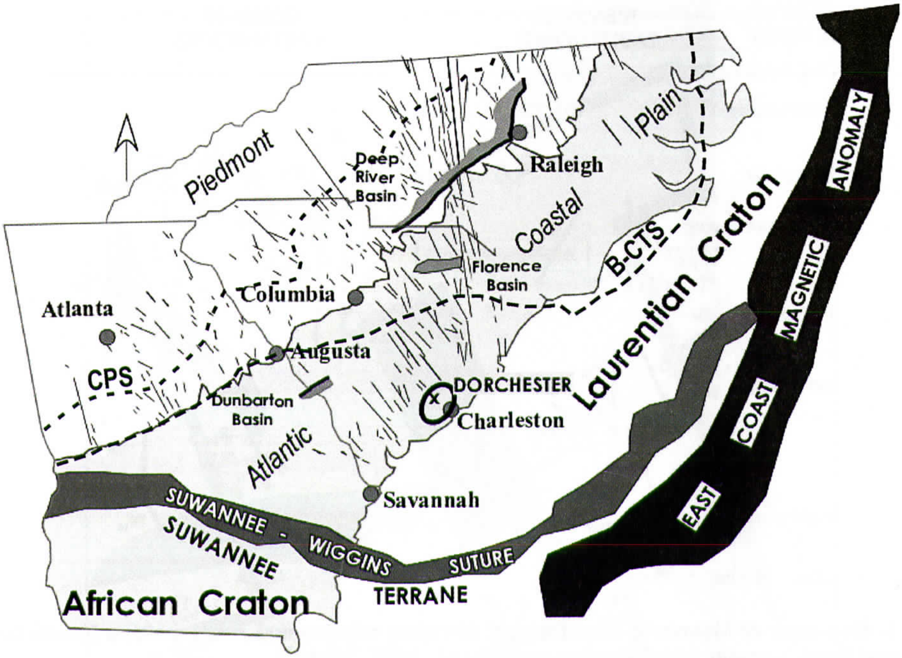

**Figure 4. Generalized geologic map showing colonial Dorchester (X) and the epicentral area (black ellipse) of the 1886 earthquake in relation to the Mesozoic diabase dike swarm, Mesozoic rift basins, Suwannee-Wiggins suture, and the east coast magnetic anomaly (modified after Evans and Bartholomew, 2010; with Central Piedmonts suture (CPS) and Brunswick-Charleston terrane suture (B-CTS) shown as dashed lines (after Hatcher et al., 2007).**

features formed at the time of the earthquake remains the classic paper for research about the earthquake. More recently, re-evaluation of the earlier work (e.g., White and Long, 1989) and extensive new studies were done on the 1886 Charleston earthquake, which occurred in an intraplate setting, and its possible causative fault (e.g., Dewey, 1985; Gohn, 1984; Johnston, 1996; Marple and Miller, 2006; Marple and Talwani, 1993, 2000; Rankin, 1977; Talwani, 1989; Weems and Lewis, 2002; Weems and Obermeier, 1990). It is unlikely to have been related to reactivation of an older first-order Paleozoic feature because it does not lie along or near either terrane-boundary (Figure 4) of the Brunswick-Charleston terrane (e.g., Hatcher et al., 1990, 2007; Hibbard et al., 2006; Thomas et al., 1990). It does, however, lie near both the northern margin of the large E-W-trending Triassic-Jurassic basin associated with Mesozoic rifting of Pangaea (e.g., Hatcher et al., 2007; Schlische, 1993; Thomas et al., 1990) and the convergence-point of the N-trending Mesozoic diabase dike swarm which extends from South Carolina to Virginia (e.g., Ragland et al., 1983) (Figure 4). Thus, the causative fault of the Charleston earthquake may be along a fault zone developed during Mesozoic rifting and later reactivated within the modern stress field.

Long-term development and analysis of an extensive database of Mesozoic and Cenozoic brittle fracture sets (e.g., Bartholomew, 1998; Bartholomew and Fleischmann, 1993; Bartholomew et al., 1994, 1998, 2002b, 2007, 2009a; Evans and Bartholomew, 2010; Wooten et al., 2001) in Alleghanian granites of the Appalachian Piedmont and in their country rocks (GA and SC), in the Deep River Triassic Basin and proximal Piedmont rocks (NC), and in strata of the Atlantic Coastal Plain (GA and SC) has established a sequence of formation of these fracture sets of faults and joints (Figure 5). Ongoing analysis of this fracture database is providing a detailed view of both initial formation and sub-

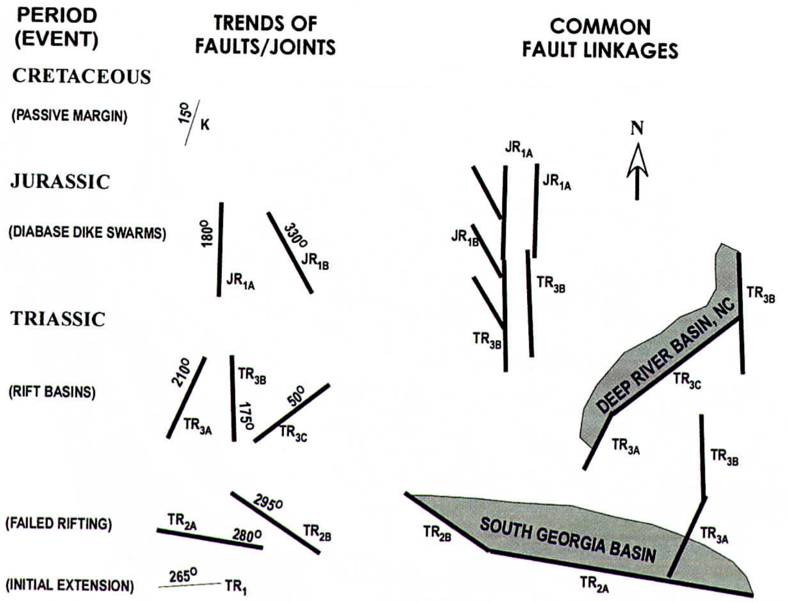

**Figure 5. Map view of Mesozoic fracture sets showing relative age relationships (modified after Evans and Bartholomew, 2010; Bartholomew et al., 2007, 2009a).**

sequent reactivation of these different fracture sets (e.g., Bartholomew and Rich, 2007; Bartholomew et al., 1994, 1998, 2000, 2002b, 2007, 2009a; Evans and Bartholomew, 2010; Wooten et al., 2001). For example, Bartholomew et al. (2007, 2009a) demonstrated multiple reactivations of faults in crystalline rocks of both the Augusta quarry, GA and the quarries near Columbia, SC. Evans and Bartholomew (2010) used fluid inclusions to document phases of Mesozoic uplift and exhumation of the Piedmont associated with these fracture sets. Bartholomew et al. (2007, 2009a) also used age relationships and fracture-reactivations to show that the Late Eocene stress field progressively rotated 55 degrees counterclockwise in the region near the U.S. D.O.E. Savannah River Site, SC. Bartholomew et al. (2002b, 2009a) demonstrated that multiple syndepositional events, on a Late Eocene steeply dipping, reverse fault, first produced deformation of the ground-surface, and formation of orthogonal sets of small conjugate normal faults across the uplift which was followed by rotation and reactivation of some of these faults as reverse faults. Bartholomew and Rich (2007) documented that similar orthogonal sets of both joints and conjugate sets of normal faults developed in the walls of Fort Dorchester during the 1886 earthquake (Figure 6) and suggested that the fort might be on an arched area above a steeply dipping reverse fault. Thus, analysis of all brittle fracture sets, is a method to determine how deeper subsurface faults in crystalline rock formed and subsequently moved during earthquakes which occurred prior to development of modern technology such as seismographs and GPS. Furthermore, the orientations and interconnections of the existing Mesozoic brittle fracture sets will largely determine which faults are favorably or unfavorably oriented (e.g., Sibson, 1990) and might be reactivated in the modern stress field. The orientation of the Late Eocene stress field was very similar to that of the modern stress field; hence, the orientations of faults documented to have moved in the Late Eocene are excellent indicators of the orientation of active faults in the Piedmont, and beneath the Coastal Plain in the vicinity of Charleston today.

## Geologic Setting and Seismicity

The absence of an obvious surface rupture during the 1886 Charleston, South Carolina,

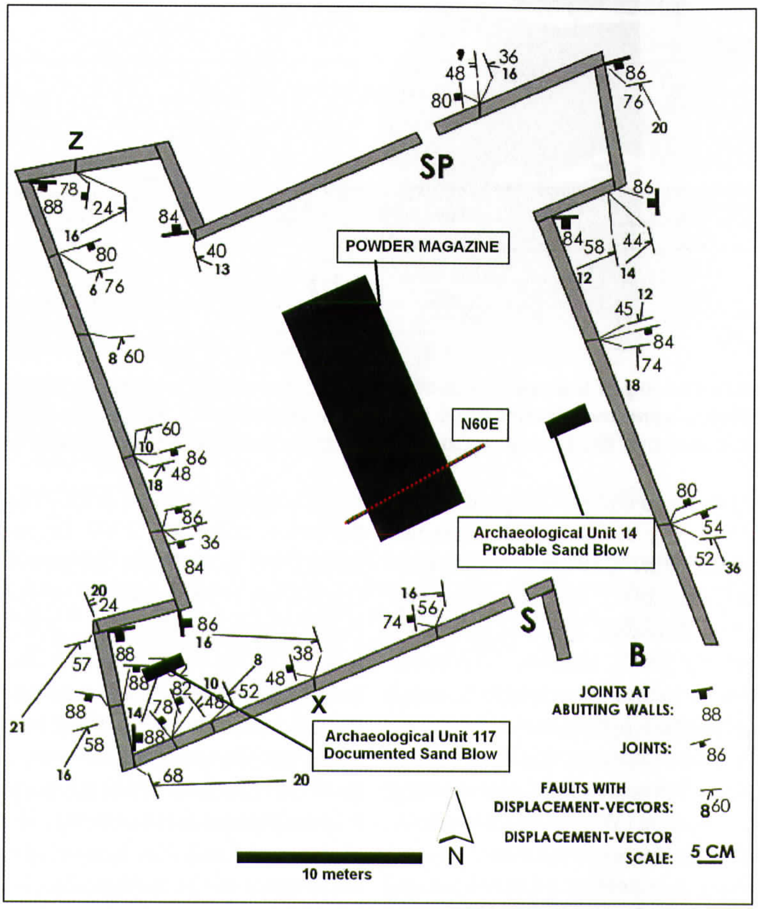

**Figure 6. Map of Fort Dorchester showing fracture sets in the walls of the fort (from Bartholomew and Rich, 2007), locations of two older archaeological trenches (Carrillo, 1973, 1976) with paleoseismites, possible N60E-trending fault across the southern part of the powder magazine, and the two NNW-trending normal faults (X and Z), with WNW-trending and SW-trending "normal" slip-vectors, which were incorrectly connected by Talwani (2000) and Talwani et al. (2011) as a "left-lateral strike-slip fault".**

earthquake (Dutton, 1889) has hindered identification of the causative fault for that event (e.g., Bartholomew and Rich, 2007). Extensive research by the U.S. Geological Survey and other individuals (e.g., Rankin, 1977; Gohn, 1984; Dewey, 1985; Amick et al., 1990; Weems and Lewis, 2002) has helped constrain possible locations, types, and orientations of faults which might have caused the 1886 earthquake. But seismicity has only been monitored since ca.1974 (Tarr and Rhea, 1983; Madabhushi and Talwani, 1993; Talwani, 2000), long after the big earthquake, and its usefulness as an indicator of the actual fault which moved in 1886 is limited both because of changing interpretations of the short 35-year data set (Talwani, 1982, 1989, 2000, or Marple and Talwani, 1993, compared with Marple and Talwani, 2006, compared with Tarr, 1977, or Tarr and Rhea, 1983) and because modern seismicity might just reflect changes in the shallow crust well above the fault that actually moved in 1886 (Bartholomew and Rich, 2007). For nearly two decades, the prevailing interpretation of the seismicity suggested a SE-striking, SW-dipping reverse fault (SW-side up) (Madabhushi and

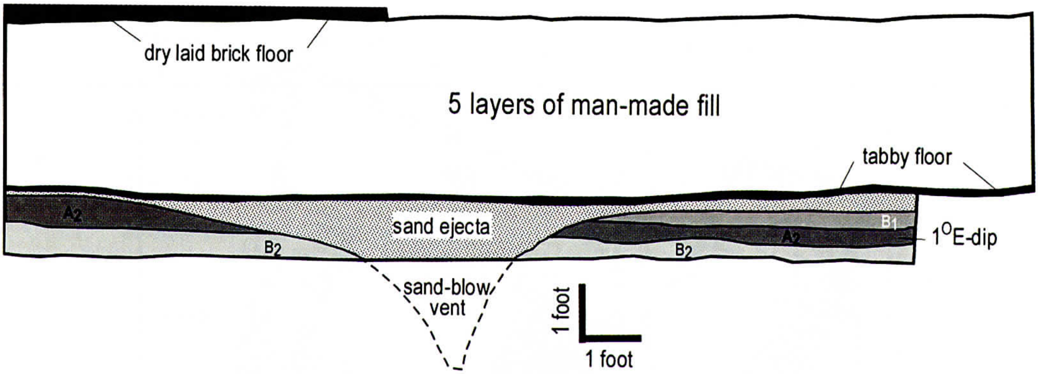

**Figure 7. Generalized log of the north-wall of trench 117 (modified from Carrillo, 1973) showing a possible sand-blow vent and ejected sand beneath the man-made fill associated with construction of the fort and above the buried $A_2$- and $B_2$-soil horizons observed in trench 14 (Figure 8).**

Talwani, 1993) in sharp contrast to geomorphic evidence which clearly indicates long-term uplift of the NE-side (Tarr and Rhea, 1983; Bartholomew and Rich, 2007). Modern seismicity (Madabhushi and Talwani, 1993) is primarily along the relatively small, shallow NW-trending Ashley River seismic zone which is much smaller than the rupture length indicated by the moment magnitude (Johnston, 1996). Furthermore, the sense of displacement along many earthquakes in this zone (W-side up) is opposite to that indicated by the geomorphic evidence (E-side up) which is indicative of sustained uplift (e.g., Rhea, 1989; Bartholomew and Rich, 2001, 2002). Thus an independent means of establishing the probable orientation and sense of displacement along the causative fault is needed.

Analysis of fractures in an uplifted area above a causative fault, even if it did not experience surface rupture, can yield patterns from which the two possible orientations of the causative fault can be deduced (e.g., Bartholomew et al., 2002b). This is analogous to the two fault-plane solutions determined from focal mechanisms for an earthquake. This approach was applied to the fracture sets formed during the 1886 earthquake in the thick, "tabby" walls of colonial Fort Dorchester (Bartholomew and Rich, 2007). Systematic fracture sets in the walls of the fort are consistent with the geomorphic data, indicating that the fault that caused the 1886 earthquake was probably a NW-striking, steeply NE-dipping, reverse fault (NE-side up) (Bartholomew and Rich, 2007; Bartholomew et al., 2000). Although the facture-set from Fort Dorchester is limited to 23 joints and 24 normal faults (Bartholomew et al., 2000), it is consistent with regional fracture patterns and borehole breakouts (Bartholomew and Rich, 2007). Recent reinterpretation of the regional seismicity (Dura-Gomez and Talwani, 2009; Talwani and Dura-Gomez, 2009) supports this interpretation although these authors still propose that a strike-slip fault, not a reverse fault, was the main cause of the earthquake.

## ARCHAEOLOGICAL INVESTIGATIONS OF COLONIAL DORCHESTER

### Previous Studies

Archaeological excavations within the fort (Figure 6) were described in the early 1970s (Carrillo, 1973, 1976). We have examined trench logs from some of these excavations within the fort and have identified several paleoseismites (Mickelson et al., 2010): 1) a probable sand blow-vent; 2) a sand layer, between two A-soil horizons, that may be ejected sand; and 3) a feature related to either a possible fault, or a liquefaction feature, or a shallow landslide.

The first feature, which is on the log of Test Unit 117 (Figure 7), was identified as a posthole by the archaeologists (Carrillo, 1973), who

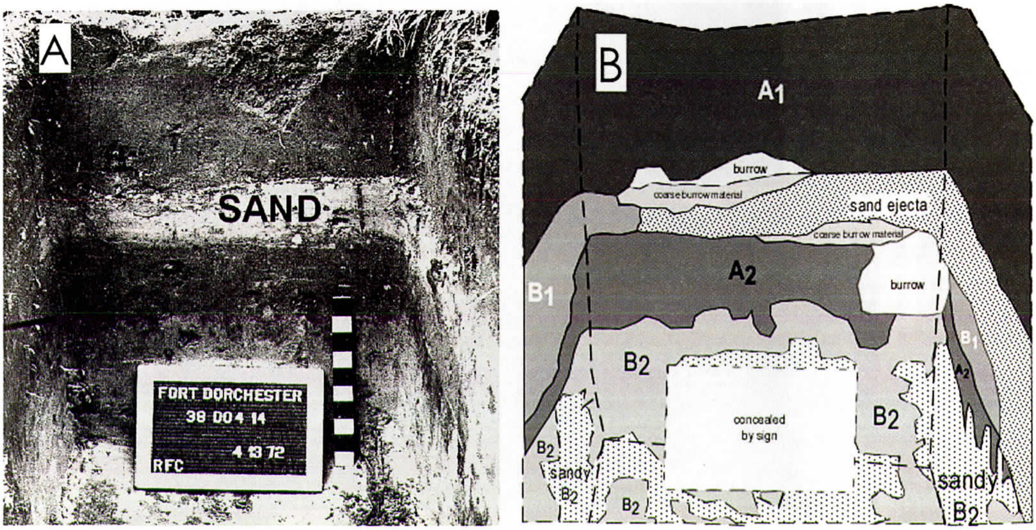

**Figure 8. A. Photograph of the north-wall of unit 14 (reproduced with permission of South Carolina Institute of Archaeology and Anthropology from Carrillo, 1973); and B. Generalized log of unit 14 showing relationship of layer of sand ejecta to both the modern $A_1$- and $B_1$-soil horizons and the buried $A_2$ and $B_2$ horizons encountered in unit 117 (Figure 7).**

were unaware that paleoseismites might be present. This vertical feature is at the base of, and continuous with a massive horizontal sand layer. We interpret the vertical sand-filled hole as the vent of a sand blow which distributed sand ejecta on the surface to form the sand layer. The layers overlying this likely sand blow are fill from the colonial period to present, and include the prepared floor of the fort which immediately overlays the sand layer. Thus, the sand blow is interpreted as predating construction of Fort Dorchester, i.e., it predated the 1886 Charleston earthquake.

The second feature is in a photograph of Test Unit 14 (Figure 8), (Carrillo, 1973). Within this trench a "light yellow sandy fill", which is unique to that unit, overlies brown humus and is overlain by another humus layer. In all other units the upper-most dark humus layer, where present, was topped by the fort's tabby floor (Carrillo 1973, p. 24). This sand also suggests that ejected sand from a sandblow predated construction of the fort.

The third feature of interest is the powder magazine (Figure 6). The northern two thirds of the foundation retained its structural continuity, as observed in the photographs after it was excavated (Carrillo, 1973, 1976), whereas the southern wall was detached and collapsed during the 1886 earthquake. The visible break (Figure 9), along which the detachment occurred, trends ~N60E. This is *favorably oriented* (e.g., Sibson, 1990) to one (N69E) of the two fault-plane solutions for the causative fault determined from fracture data in the fort's walls (Bartholomew and Rich, 2007). But the cause of the detachment and subsequent collapse of the wall is unknown. The break could be above an actual steeply dipping fault which extends downward into the subsurface strata; or the collapsed portion of the wall could be above strata which liquefied; or the break may be the head of a small shallow landslide which slid southward toward the Ashley River.

Regionally, paleo-sand blows are known to have occurred during and prior to the 1886 Charleston earthquake (e.g., Dutton, 1889; Talwani and Cox, 1985; Amick et al., 1990). Since 2000, numerous test pits have been dug on a grid across other parts of the town site as part of the ongoing archaeological work. One deeper excavation, based on a GPR survey, near the northwest corner but outside of the fort (north of point Z on Figure 6) encountered a pre-1886

Figure 9. Photograph looking east along possible N60E-trending fault (black line) across the eastern wall of the powder magazine with the southern side (right) tilted downward. Small black rectangle is 15 by 20 cm notebook.

Figure 10. Photograph looking east at shallow depression (labeled 2 on Figure 2), which is underlain by a linear negative magnetic anomaly (Figure 11) consistent with a possible clastic dike, in the southeastern part of the Marketplace. Small black rectangle is 15 by 20 cm notebook on east flank of depression.

sand blow (Talwani et al., 2009, 2010).

## Terrain Analysis

High resolution LiDAR data, covering the project area, were processed and analyzed to search for sand blows in a portion of the Marketplace. LiDAR data for Dorchester County were acquired in 2009 by South Carolina Geographic Information Systems (2011) and had a nominal 1.4 m point spacing, a Vertical Root Mean Square Error of 0.185 m, and a Horizontal (RMSE) error of 1.0 m. LiDAR points within the Marketplace locality were spaced between 0.5 -1.4 m. A Bare Earth Model (BEM) was created and converted into a Digital Elevation Model (DEM) for analytical purposes. Following Hesse (2010), a Local Relief Model (LRM) was applied to the DEM. The LRM technique has been employed in archaeological research to great effect to locate unobtrusive archaeological sites in a wide variety of settings. The LRM is produced by employing a low pass filter to the data and thereby makes shallow, low–relief features more visible after removal of landscape scale features (Hesse

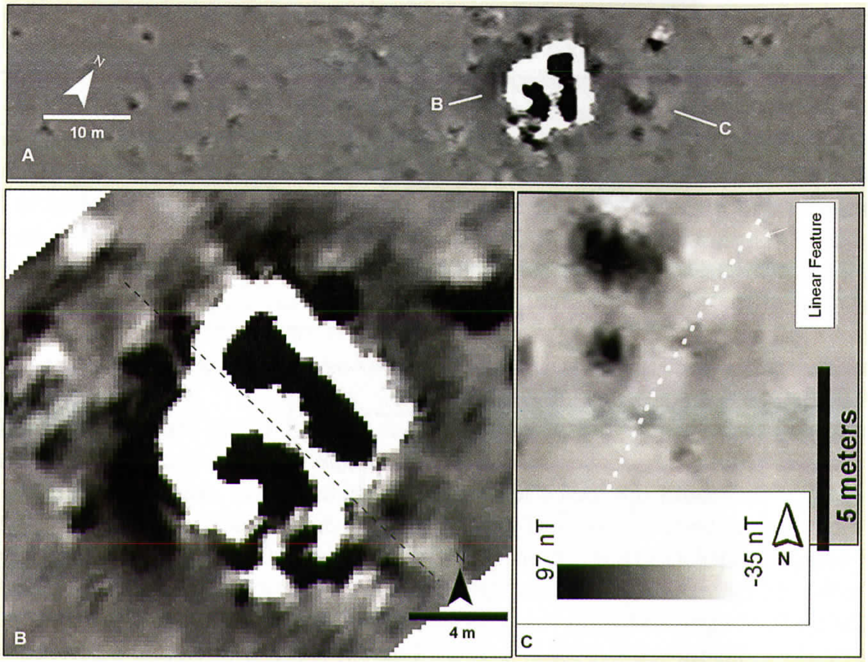

**Figure 11. Gradiometer survey of a portion of the Marketplace showing the entire 100 by 20 m survey block (A), enlargement of the remains of a probable kiln with dashed line indicating offset (B), and enlargement of area containing evidence for possible paleoseismites (C). Note the faint "halo" around the strong negative (white) anomaly (B). The "halo" represents the probable extent of the excavation for the kiln's foundation trenches.**

2010, p. 67).

The LRM isolates positive and negative differences in elevation and highlights small features across the land surface. Several small shallow depressions were recorded across the Marketplace using this technique. In this instance, these shallow depressions (negative values) indicate probable sand blows. The deepest of these shallow depressions (Figure 10) was selected as a target for a gradiometer survey.

Craters within the market place and within the fort, described above, are similar to sand-blow vents observed during the 1886 Charleston, SC earthquake (Dutton, 1889; Talwani, 1989), to those within the New Madrid Seismic Zone and elsewhere in the mid-continent (Cox et al., 2004), and to recent sand blows generated during the 2001 Gujarat, India, earthquake (Rajendran and Rajendran, 2003; Rydelek and Tuttle, 2004). Excavation of sand blows and age analysis of related deposits have established a chronology of strong paleoseismicity in the eastern U.S. over thousands of years (Amick et al., 1990; Cox et al., 2004, 2007; Munson et al., 1995, 1997; Obermeier et al., 1990, 2002, 2005; Talwani, 1989, 1996; Tuttle, 2001; Tuttle and Schweig, 1996; Tuttle et al., 1998, 2002, 2006).

## Features Identified On Preliminary Gradiometer Surveys

Gradiometer surveys have proven to be effective, nondestructive means of mapping both archaeological and geological features at the landscape scale (e.g., Kvamme 2003, 2006; Lockhart and Green, 2006; Mickelson, 2008; Weston, 2001). On some of these surveys (e.g., Lockhart and Green, 2006), paleoseismites (primarily clastic dikes) have also been imaged and confirmed by subsequent excavations (e.g., Lockhart and Green, 2006). Bartholomew et al. (2009b) used the Bartington gradiometer to map the active Lima Reservoir fault in the Centennial Valley, Montana. They relocated an old

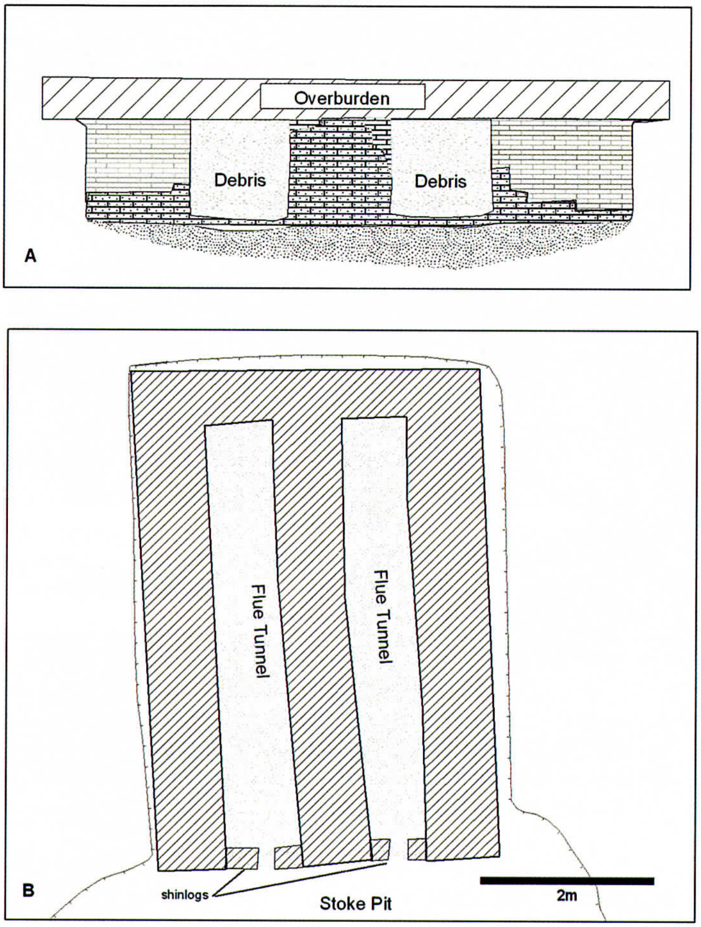

**Figure 12. Cross-section (A), and plan view (B) of a kiln excavated in Essex, England dating to around 1700 (modified after Drury, 1975, and Metz et al., 1998). This style of updraft brick kiln was typical of structures built both in Colonial America and England, although the size of the kiln could be highly variable because size was a function of the brick-maker's production target (Dobson, 1882). Kilns such as these were semi- subterranean, with the firebox, shinlogs (temperature regulators), and flue tunnels all built below ground surface. The floor of the Kiln was at or near ground surface and the above ground portion of the kiln could have been as much as 4-5m high. In the example illustrated here, the kiln had been robbed of some brick and the flue tunnels eventually filled with debris following abandonment.**

trench dug in 1986 (Bartholomew et al., 2002a) by tracing the main fault 30 meters from a new trench excavated in 2008 to the vicinity of the old trench. Thus the gradiometer survey is a potentially powerful tool for identifying faults and other paleoseismites within archaeological sites where excavations must be limited.

A survey (Figure 11A) was done over part of the Marketplace where the 0.5-meter-deep circular depression with a 3-meter diameter (Figure 10) is present at C. Several other depressions of similar size are also present, but were not surveyed, in other parts of the marketplace. The market place was cleared and leveled during its occupation and kept clear and probably farmed long after the town was abandoned. No small mounds are adjacent to these depressions, thus the depressions are not likely to have been caused by uprooting of large trees. We surveyed this depression because we suspected that it might be a sand blow related to the 1886 earthquake. It, of course, contains a thicker accumulation of organic material near its center, resulting in higher magnetic readings (Kvamme, 2006; Bevan, 1998). But, the striking feature (Figure 11C) is the linear, segmented band of locally reduced magnetism which lies beneath the depression and which is consistent with a high sand content. Although only a portion of this feature has been surveyed, it is not likely to be manmade. We tentatively interpret this band as a possible clastic dike which fed the possible sand blow.

Another survey (Figure 11B) was over a feature originally thought to be a buried well in the market place (B on Figure 11A), based on a GPR profile. The ground surface is flat, thus no mound marks this structure like the typical partially exposed foundations observed around the town site. However, this feature (Figure 11B) is approximately 7 x 9 meters, which is more consistent, in size, with it being a colonial structure built above ground rather than a well. However, it differs significantly from the expected shape of colonial structures in several respects. First, it appears to be subdivided into two elongate rectangular features, with significant damage to the western and central walls. The structure is consistent with descriptions of English style (e.g., Dobson, 1882; Drury, 1975) brick kilns (Figure 12) and is similar to those built at Jamestown, Virginia, and elsewhere in colonial America (Metz et al., 1998). Such kilns were built at the colonial town sites, were kept continuously burning (sometimes termed "firing") until an entire batch of bricks was fired, and then were abandoned or rebuilt before the next batch of bricks was processed (e.g. Metz et al., 1998). Thus, we interpret this structure to most likely be the first brick kiln (with two flue tunnels) built at Dorchester which, after its use, was buried to make a large Marketplace.

The most striking aspect of the structure is that the NE-SW-trending walls are offset ~0.25-

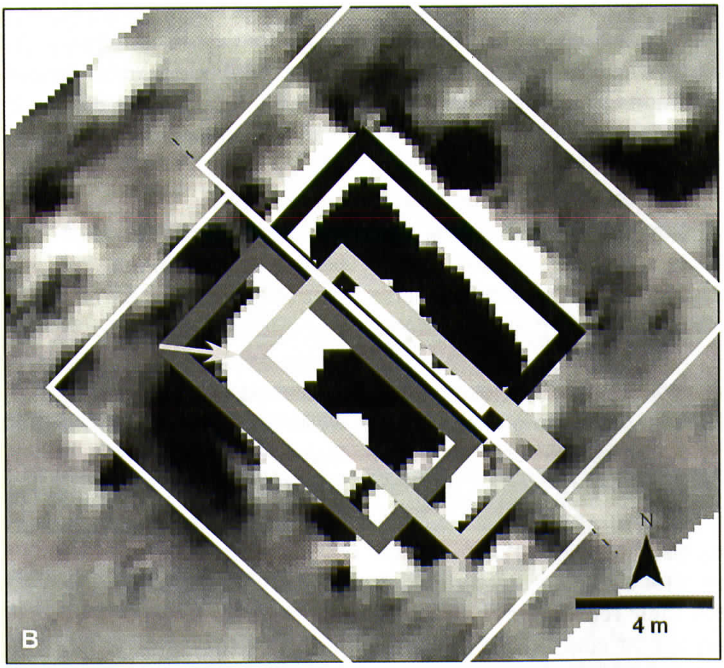

Figure 13. Interpretive diagram showing left-lateral offset of kiln sections (dark gray rectangles) and excavated band (white rectangles) around them, along a possible N45W-trending fault. The more deformed western section (light gray rectangle) appears to have been displaced, from its likely original position where it was aligned adjacent to the eastern section (darker gray rectangles), along a S84E-vector (gray arrow) into the eastern section.

0.5-meters by a linear feature which we tentatively interpret as a fault with a component of left lateral slip. Colonial houses, out-buildings, and kilns were normally built as simple rectangular structures (Kornwolf, 2002) lacking such offset features. This suspected fault trends ~235°-315° which is *favorably oriented* (e.g., Sibson, 1990) to one (339°) of the two fault-plane solutions for the causative fault determined from fracture data in the fort's walls (Bartholomew and Rich, 2007). It is also subparallel to the $JR_2$ fracture trend (330°), which is known to have Jurassic surfaces that were subsequently reactivated as faults during the Cenozoic (Bartholomew et al., 2007, 2009). The fault is not simply a left-lateral strike-slip fault, it also has a significant component of reverse displacement as well, as evidenced by how the structure was compressed in a direction perpendicular to the fault (Figure 13). By assuming that the east half and the west half of the structure were originally aligned (darker gray rectangles on Figure 13), then an approximate slip vector and horizontal component of the surface displacement can be determined from the corners of the southwestern portion in its inferred original location to its approximate present location (light gray rectangle on Figure 13). The surface displacement is ~1-2m along a 96°-274°-trending slip vector. Bartholomew and Rich (2007) noted that one cluster of slip-vectors reported by Madabhushi and Talwani (1993) is 274°@38° on both oblique reverse and oblique left-lateral fault-plane solutions. Thus, we infer that the surface rupture which displaced the kiln was along an oblique reverse fault with a strike of ~235°-315°, a slip-vector of 96°-274°, and a horizontal component of displacement of ~1-2m. Dura-Gomaz and Talwani (2009) showed two representative fault-plane solutions: one for an ~pure dip-slip reverse fault and one for an ~ pure strike-slip fault (Figure 3). Both their representative reverse fault and the ellipse of concentrated modern seismicity documented by them (Figure 3) are subparallel to the trend of the Dorchester fault inferred to be the causative fault of the Charleston earthquake by Bartholomew and Rich (2007). This is based on their analysis of fractures in the tabby walls of Fort Dorchester. Their representative strike-slip fault-plane solution has a left-lateral plane with an orientation of 105°, 80° and would have had a slip-vector which trends subparallel to the oblique reverse fault which offset the kiln chambers. These and other fault-plane solutions (e.g., Madabhushi and Talwani, 1993; Dura-Gomaz and Talwani, 2009) have similarly oriented P-axes ($SH_{MAX}$) (~65+/-5), but differ in fault-type (reverse versus strike-slip) due to inversion of $Sh_{min}$ and $S_v$ as the least principal stress axis suggesting that $Sh_{min}$ and $S_v$ are ~equal within the shallow crust where the modern seismicity is concentrated.

## CONCLUSIONS

Colonial Dorchester was occupied, abandoned, scavenged, and rebuilt three times before being left for good in 1820. Occupations were at: 1697-1752/6; ca.1758-1760; and ca.1776-1820. Final degradation was caused by being near the epicenter of the great 31 August 1886 Charleston earthquake. Although the toppled brick bell tower of the old church was repaired long after the quake, little restoration work was done before the site became a historic State Park in 1960. Thus, evidence it contains concerning the 1886 and earlier earthquakes, as well as its three periods of occupation, remains buried. Archaeological excavations in the fort, systematic test pits across the town site, and our preliminary gradiometer surveys provide tantalizing evidence about the Charleston earthquake and an earlier earthquake. On one survey, we have identified one probable oblique reverse fault juxtaposing two halves of a colonial brick kiln. On another, we have identified a possible clastic dike beneath a shallow depression which may represent a sand-blow vent. Thus, our preliminary gradiometer surveys indicate that we can map both geological and archaeological features without disturbing the integrity of the town site. This permits us to accurately select potential targets for future excavations.

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# LATE PLEISTOCENE AND HOLOCENE VEGETATION CHANGES IN THE SANDHILLS, FORT JACKSON, SOUTH CAROLINA

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## ABSTRACT

**A small streamhead pocosin wetland at Fort Jackson, South Carolina, preserves a history of late Pleistocene and Holocene plant communities in an upland habitat of the Sandhills of the upper Coastal Plain. During the late Pleistocene, the assemblage of *Pinus* (pine, including *P. banksiana* [jack pine], *Picea* (spruce), and Asteroideae (a subfamily of Asteraceae, the sunflower family) signals a cold, dry climate. *Quercus* (oak) was sparse; *Liquidambar* (sweetgum) and *Nyssa* (tupelo) were absent. During the Holocene, pine dominated except for an interval of oak dominance beginning after 9,520 cal yr BP and ending around 7,400 cal yr BP. Sediment characteristics suggest higher or more intense precipitation in the earlier segments of the Holocene record. Evidence from the pollen record is equivocal. Higher proportions of *Nyssa* (probably *N. biflora*, an obligate wetland species, or *N. sylvatica*, a facultative wetland species, or both) during the oak interval dominance could indicate expansion of the wetland, reduced fire fre-**

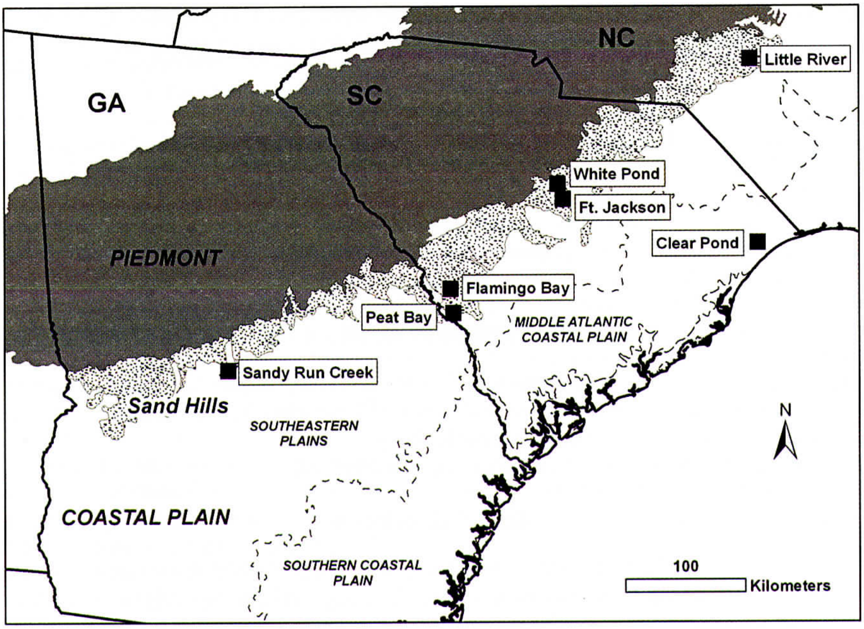

**Figure 1. Location of Fort Jackson and other southeastern wetlands discussed in this study. Boundaries for Piedmont, Coastal Plain, and Sandhills are based on US EPA ecoregions (US EPA, 2010). The Coastal Plain includes the Southeastern Plains, Middle Atlantic Coastal Plain, and Southern Coastal Plain (all Level III ecoregions). The Sandhills (Level IV) lies within the Southeastern Plains.**

**quency, or decreased pollen contributions from other sources, such as pine in the uplands. The rapid transition back to pine dominance was accompanied by decreases in *Nyssa* and *Fagus* (beech, prominent only in the uppermost sample of the mid-Holocene oak interval) and an increase in Gramineae (grasses), suggesting an increase in fire frequency or intensity, a decrease in moisture, or both. Asynchronies in the oak-pine transition across the Coastal Plain suggest that it is a poor proxy for Holocene climate change. The asynchronies may be in part a consequence of the importance of fire in shaping these communities.**

## INTRODUCTION

The general outline of late Pleistocene and Holocene vegetation change is well-understood for the Coastal Plain of Southeastern North America, but many details remain obscure, particularly for vegetation during the Holocene, due in large part to a paucity of records and poor chronologic resolution for the transitions (e.g., Watts et al., 1996; LaMoreaux et al., 2009).

Climate was evidently cool and dry during the last glacial maximum (Watts et al., 1996). Typically, the pollen records of the last glacial maximum indicate dominance by pines, including jack pine (*Pinus banksiana*), with a presence of spruce (*Picea*). Warming climate at the end of the Pleistocene is typically marked by increases in abundances of hardwoods.

A key component of Holocene changes is the shift in dominance by oak (*Quercus*) during the early Holocene to dominance by pine during the mid- to late Holocene. Among locations in the Coastal Plain of Georgia and the Carolinas (Figure 1), the times for the transition range from around 8,900 cal yr BP (converted [see Methods] from reported age of 8,000 radiocarbon yr BP) at Clear Pond on the lower Coastal Plain of South Carolina (Watts et al., 1996), around 7,800 cal yr BP (converted from reported age of 7,000 radiocarbon yr BP) at White Pond in the Sandhills of South Carolina (Watts, 1980), after 6,100 cal yr BP (5,300 radiocarbon yr BP) in a

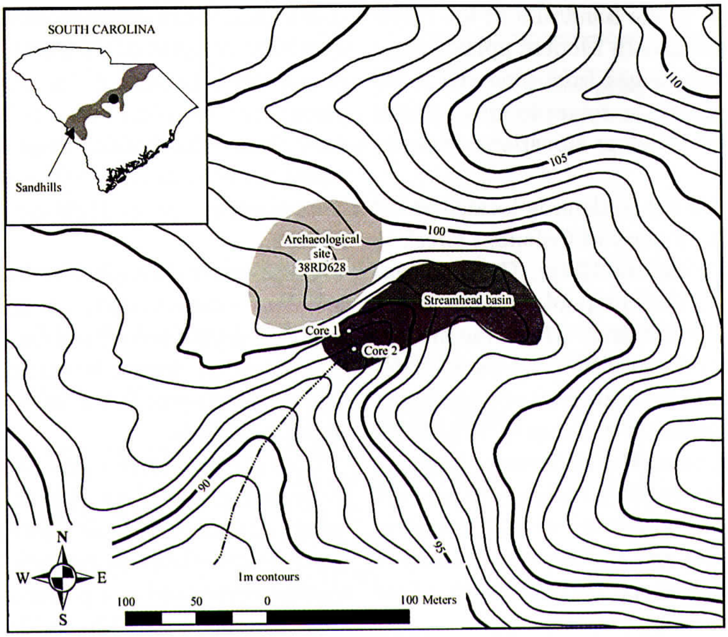

**Figure 2. Map of Fort Jackson wetland.**

paleochannel of the Little River in the Sandhills of North Carolina (Goman and Leigh, 2004), and around 4,500 cal yr BP (4,000 radiocarbon yr BP) at Sandy Run Creek in the upper Coastal Plain of Georgia (LaMoreaux et al., 2009) and at several other locations (not shown) in southern Georgia (Seielstad, 1994; Brook, 1996; LaMoreaux, 1999). Transitions from oak to pine dominance occurred around 7,800 cal yr BP (converted from reported age of 7,000 radiocarbon yr BP) at three lakes (not shown) in southern Georgia and northern Florida and around 5,700 cal yr BP (converted from reported age of 5,000 radiocarbon yr BP) at lakes in peninsular Florida (Watts et al., 1996).

The early Holocene vegetation shifts from oak to pine dominance have been associated with both increased precipitation (e.g., Watts, 1980) and decreased precipitation (e.g., Goman and Leigh, 2004; LaMoreaux et al., 2009) and increased fire, due either to drier climate or to human activity (LaMoreaux et al., 2009). Otvos (2005) argued for drier early Holocene conditions based on records of sand dune activity along the Gulf of Mexico. In contrast, Leigh (2006) argued from patterns of decreasing size of stream meanders during the Holocene that stream discharge was higher during the early Holocene than at present.

Understanding the variation in timing of vegetation shifts and resolving the contradictory inferences about climate are obviously important for understanding how regional climates respond to global processes, as well as for reconstructing prehistoric landscapes and resources for human activity.

Here we present results of pollen analysis of a sediment core from a streamhead pocosin wetland associated with an archaeological site at Fort Jackson, in the Sandhills near Columbia, South Carolina (Figure 1). In comparisons with other pollen records from the region, we focus particularly on the shift from oak to pine dominance, which occurred abruptly at Fort Jackson during the mid-Holocene. We review the chronologies of these transitions, and we consider the evidence for changes in climate and for changes in fire regimes, which may have more strongly localized or habitat-specific effects on vegetation.

## Site characteristics

Fort Jackson is situated near Columbia,

South Carolina, in the Sandhills of the upper Coastal Plain (Figure 2). Modern upland vegetation of the area ranges from pine and scrub oak communities on the ridges to mesic mixed hardwood forest at lower elevations (Nelson, 1986).

The small (0.9 ha) wetland is located at the head of a small tributary of Colonel's Creek, a tributary of the Wateree River. The core was collected from a shallow pool of water at the lower end of the wetland, where the stream emerges. In occasional visits over the past decade, we did not observe absence of water in the pool. The wetland is a densely vegetated streamhead pocosin. The understory includes fetterbush (*Lyonia lucida*), redbay (*Persea borbonia*), blueberry (*Vaccinium* spp.), bamboo vine (*Smilax* spp.), and grasses; the overstory is mainly oak (*Quercus* spp.) and red maple (*Acer rubrum*) with a few pines (*Pinus* spp.).

The wetland is downslope of an archaeological site that was occupied at intervals throughout the Holocene. Site 38RD628 was initially recorded by Roberts et al. (1992) during a standard survey conducted in 1991 under the auspices of the U.S. Army Corps of Engineers, Savannah District. More extensive investigations were conducted by Clement et al. (2005).

## METHODS

### Field and laboratory

Cores 1 and 2 were taken on 13 June 2001 from the central area of the wetland where standing water was present (Figure 2). Three-inch (7.6 cm) diameter aluminum tubing was driven into the substrate with a slide hammer, then retrieved with a winch mounted on a bipod. Core 1 was the longer of the two cores (133 cm). The core was opened by making shallow longitudinal cuts through the tubing on opposite sides with a circular saw. The core contents were then sliced lengthwise with a potter's wire, allowing the sediment to be laid open for observation and sampling.

The presence of recent roots in most strata suggested that dates of bulk sediment would yield misleading results. To obtain charcoal for accelerator mass spectroscopy (AMS) dates, approximately 1 cc of sediment was placed in a clean Petri dish where it was carefully disaggregated. Charcoal pieces were collected with forceps, rinsed with distilled water, and air-dried in small covered dishes. All radiocarbon dates were determined by Beta Analytic, Miami, Florida.

Close-interval samples for analysis of pollen, sediment texture, and loss-on-ignition were collected at depths corresponding to the radiocarbon dates, at depths immediately above or below stratigraphic boundaries, and from some additional depths.

Loss on ignition analysis was accomplished by heating at 430°C for 24 hours using the procedure of Gale and Hoare (1991). Organic carbon was calculated as percent weight loss on ignition (expressed as a percentage of dry sediment weight) divided by 2.13 (Dean, 1974). The remaining clastic sediment was dispersed with sodium hexametaphosphate in an ultrasonic bath. The <20-µm fraction was removed by repeatedly suspending and decanting the fines after the appropriate settling time. Remaining sediment was separated into sand and coarse silt fractions using a 62.5-µm screen.

For palynological analysis, processing was minimized in order to recover as much microfossil material as possible. Each sample (approximately 2 cc) was sieved through a 212-µm screen. The >212-µm fractions, which contained macrofossils, were washed into small vials and preserved with a few drops of 10% HCl. Those samples remain under refrigeration at Georgia Southern University, pending analysis. The <212-µm fractions, which contained pollen and other microfossils, were treated according to methods described in Traverse (1988) for the processing of organic-rich sediments. Residues were mixed with a 50:50 blend of glycerine jelly and water, and slides were prepared for microscope analysis.

Slides were scanned for presence and absence of pollen and spores. On slides that had sufficient numbers for counting, at least 300 palynomorphs of identifiable type were tallied (Rich et al., 2000). Counts of broken pine pollen grains were combined to give whole grain

Table 1. Stratigraphic zones of Fort Jackson Core 1.

| Zone | Depth (cm)* | Munsell color | Comments |
|---|---|---|---|
| 4c | 0-20 | 2.5 YR 2.5/1<br>reddish black | loose peaty material, macroscopic plant parts |
| 4b | 20-30 | 5 YR 2.5/1<br>black | |
| 4a | 30-43 | 5 YR 2.5/1<br>black | |
| 3b | 43-(77-80) | 5 YR 2.5/1<br>black | sand stringers |
| 3a | (77-80)-(88-89.5) | 5 YR 2.5/2<br>dark reddish brown | more sand stringers than above |
| 2b | (88-89.5)-(94-96) | 10 YR 3/2<br>very dark grayish brown | |
| 2a | (94-96)-(100-102) | 10 YR 3/2<br>very dark grayish brown | |
| 1e | (100-102)-109 | 5 YR 7/2<br>pinkish gray | |
| 1d | 109-112.5 | 7.5 YR 4/2<br>brown | |
| 1c | 112.5-(114.5-116) | 5 YR 7/2<br>pinkish gray | |
| 1b | (114.5-116)-(117.5-121.5) | 10 YR 3/3<br>dark brown | |
| 1a | (117.5-121.5)-135 | 10 YR 6/2<br>light brownish gray | |

*Values in parentheses give depths on left and right sides of core

equivalents. General characteristics of the residues were noted. Some contained algal remains, others contained diverse tissue fragments, and nearly all of them bore minute bits of charcoal.

### Data analysis

Statistical analyses, including principal components analysis, were performed in S-Plus (Insightful Corp., Seattle, WA).

Radiocarbon ages from this study and from some published reports were converted to calendar ages using CALIB 6.0.2 (Stuiver et al., 2010) with the IntCal09 calibration curve. We report the median probability of the calibrated age.

## RESULTS

### Sediment characteristics and radiocarbon ages

Four stratigraphic zones were identified, based mainly on sediment texture and color (Figures 3 and 4, Table 1). Stratigraphic boundaries within and between these zones were abrupt and straight, suggesting erosional unconformities. The radiocarbon ages (Table 2, Figure 3) show temporal gaps. These gaps are largely associated with the apparent erosional unconformities and with textural changes in the sediment, indicating significant changes in the depositional environments.

Charcoal was present in all strata. The fragments were smaller and had a more degraded appearance in the lighter-colored strata, including Zones 1a, 1c, and 1e.

Zone 1 consisted mainly of loamy sand and sandy loam. It comprised three layers of lighter color (Zones 1a, 1c, and 1e) alternating with layers of dark color (Zones 1b and 1d), likely representing buried surface horizons. Charcoal sufficient for radiocarbon analysis was present only in the darker layers. The early Holocene ages for material from Zones 1b and 1d are in-

**Table 2. Radiocarbon ages for Fort Jackson Core 1. Calendar ages were calculated using CALIB 6.0.2 (see Methods); medians were rounded to nearest decade.**

| Zone | Depth (cm) | Beta Analytic | Conventional radiocarbon age ± 1 sigma | Calibrated calendar age | | Material |
|---|---|---|---|---|---|---|
| | | | | Median | 2-sigma range (probability) | |
| 4c | 20.5-21.5 | Beta-170355 | 1,470 ± 40 BP | 1,360 cal yr BP | 1,295-1,416 cal yr BP (0.99)<br>1,469-1,483 cal yr BP (0.01) | ~12 pieces of charcoal |
| 4c | 28.5-29.5 | Beta-170356 | 2,910 ± 40 BP | 3,060 cal yr BP | 2,946-3,209 cal yr BP | many pieces of charcoal |
| 4a | 31-31.5 | Beta-206279 | 3,200 ± 40 BP | 3,420 cal yr BP | 3,349-3,484 cal yr BP (0.975)<br>3,531-3,553 cal yr BP (0.025) | many pieces of charcoal |
| 4a | 43 | Beta-170352 | 6,420 ± 40 BP | 7,360 cal yr BP | 7,274-7,422 cal yr BP | many pieces of charcoal |
| 3b | 55.5 | Beta-167594 | 6,520 +/- 40 BP | 7,440 cal yr BP | 7,325-7,399 cal yr BP (0.197)<br>7,411-7,507 cal yr BP (0.798)<br>7,548-7,551 cal yr BP (0.005) | 1 piece of charcoal |
| 3b | 64.5-65.5 | Beta-170357 | 5,840 ± 40 BP | 6,660 cal yr BP | 6,508-6,511 cal yr BP (0.003)<br>6,533-6,745 cal yr BP (0.997) | many pieces of charcoal |
| 3b | 77 | Beta-170353 | 6,600 ± 40 BP | 7,500 cal yr BP | 7,433-7,524 cal yr BP (0.74)<br>7,528-7,566 cal yr BP (0.26) | 1 piece of charcoal |
| 3a | 81-82 | Beta-206280 | 8,870 ± 40 BP | 10,020 cal yr BP | 9,780-9,850 cal yr BP (0.08)<br>9,860-9,878 cal yr BP (0.02)<br>9,884-10,173 cal yr BP (0.90) | 1 piece of charcoal |
| 3a | 87-88.5 | Beta-170358 | 8,470 ± 40 BP | 9,500 cal yr BP | 9,439-9,533 cal yr BP | 1 piece of charcoal |
| 2b | 92.5 | Beta-167595 | 17,420 ± 60 BP | 20,750 cal yr BP | 20,380-21,186 cal yr BP | 1 disintegrating piece of charcoal |
| 2a | 97-98 | Beta-170359 | 18,120 ± 100 BP | 21,650 cal yr BP | 21,338-22,082 cal yr BP | 1 piece of charcoal |
| 1d | 109-111 | Beta-170354 | 9,210 ±50 BP | 10,370 cal yr BP | 10,248-10,505 cal yr BP | many pieces of charcoal |
| 1b | 116-117 | Beta-170360 | 11,770 ± 50 BP | 13,620 cal yr BP | 13,442-13,771 cal yr BP | 1 piece of charcoal |

consistent with Pleistocene ages for Zone 2, which lies stratigraphically above it. Possible explanations include: 1) contamination by material from overlying strata during the retrieval, cutting, or processing of the core; 2) contamination by post-depositional insertion of material; 3) reworking and redepositing of older material from other parts of the basin; 4) deposition into an undercut bank beneath the older material. Because the stratigraphic boundaries appear to be sharp, without evidence of smearing in the parts of the core that were sampled, we do not favor the contamination hypotheses.

Zone 2 consisted of sandy loam. The radiocarbon dates indicate Pleistocene ages around the time of the last glacial maximum.

Zone 3 consisted mainly of sand and loamy sand. The radiocarbon dates indicate an early Holocene age for Zone 3a and a mid-Holocene age for Zone 3b. Deposition in Zone 3b appears

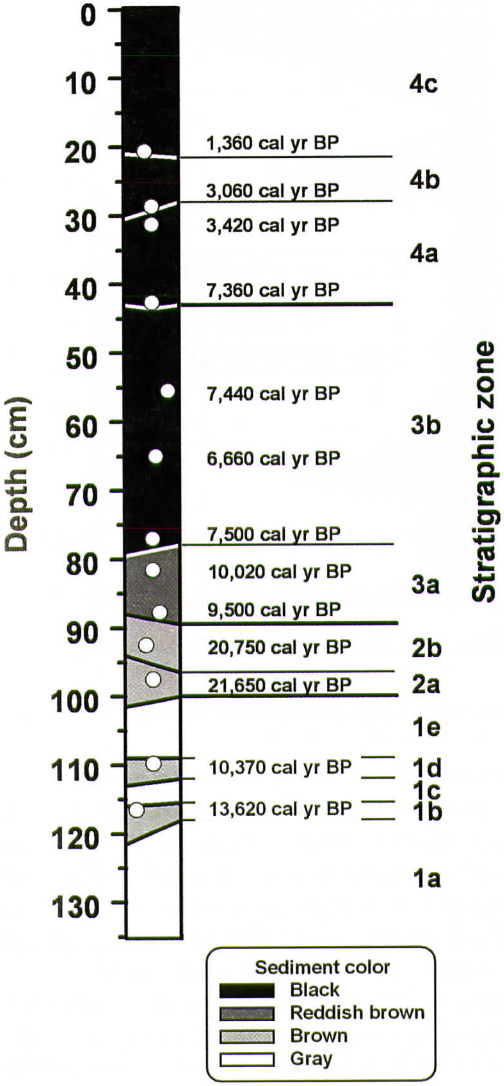

**Figure 3. Stratigraphy and radiocarbon samples from Core 1. Positions of radiocarbon samples are shown by filled circles; all were collected between, and usually adjacent to, stratigraphic boundaries.**

to have been rapid (note the steep slope of the curve in Figure 4)--an inference consistent with the presence of sand stringers. If deposition in Zone 3a, which also contained sand stringers, was similarly rapid, the boundary between Zones 3a and 3b likely represents an erosional unconformity. The gaps in radiocarbon ages above and below the boundary support this interpretation.

Zone 4 consisted mainly of peat over sand and clay. Sand was present throughout this zone, and was more abundant at depth. The radiocarbon dates indicate mid- to late Holocene age for the sediments. Because the age of material from the base of 4a is similar to the age of material in 3b, we infer that the stratigraphic boundary between 4a and 3b represents a distinct, rapid change in depositional environment.

## Pollen

Three hundred or more pollen grains and spores were recovered from all but one of the samples. For that sample after (104 cm), a residue-bearing slide was scanned, and taxa were recorded if present. Preservation was good, except that many of the bisaccate pollen grains (from pine and related conifers) were damaged.

Fifty-nine taxa of pollen and spores were identified, including 24 taxa of herbs, 14 taxa of shrubs, one vine (*Vitis*), and 20 taxa of trees (Figures 5 and 6, Table 3). Identities of two herbs (*Equisetum* and Brassicaceae) and one tree (*Liriodendron*) were questionable. All pollen and spores were included in the pollen totals. With the exception of *Sphagnum* (7% maximum in any sample), the aquatic taxa conventionally excluded from the pollen totals were present in negligible amounts.

Two taxa of algae were encountered, the zygospore *Ovoidites* (Rich et al., 1982) and the putative algal cyst *Pseudoschizaea* (Rich and Pirkle, 1994). *Ovoidites* was present in one sample, while *Pseudoschizaea* appeared in several samples in very small numbers. Algal remains were not included in the pollen totals.

Only *Pinus*, *Quercus*, *Nyssa*, and *Myrica* exceeded 10% of the pollen count in any sample (Figures 5 and 6). About two-thirds (39 of 59) of the taxa appeared in only minor amounts (Table 3).

## Distributions of taxa

Among the trees and shrubs (Figure 5), *Pinus* (pine) was generally abundant except in Zone 3b. It reached its highest concentrations in Zone 2. At 98 cm, 10% of the pollen total was *P. banksiana* (jack pine). *Picea* (spruce) appeared

Table 3. Minor taxa (2% maximum in any sample) from Fort Jackson Core 1.

| | | Trees, shrubs, and vines | | | | | | | | | | | | | | | | | | | | | Herbs and grasses | | | | | | | | | | | | | Ferns and fern allies | | | Aquatics | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zone | Depth (cm) | *Acer* | *Carya* | *Castanea* | *Celtis* | *Cornus* | Cyrillaceae | Ericaceae | *Fraxinus* | *Gordonia* | *Itea* | *Juglans* | *Liriodendron* | *Ostrya/Carpinus* | *Platanus* | *Rhus* | *Sambucus* | Taxod./Cupress./Tax. | *Tsuga* | *Ulmus* | *Viburnum* | *Vitis* | *Ambrosia* | Brassicaceae | Chenop./Amaranth. | Cyperaceae | *Decodon* | Fabaceae | *Iva* | Liliaceae | *Polygonella* | *Polygonum* | *Sabatia* | Umbelliferae | *Urtica* | *Equisetum* | *Pteridium* | *Selaginella* | *Sagittaria* | *Typha/Sparganium* |
| 4c | 0-5 | ● | ● | | ● | | ● | ● | | | | | ● | | | | | ● | | | | | ● | | ● | ● | | ● | | ● | | | | | | ● | | | ● | |
| 4c | 12-13 | ● | ● | ● | | | ● | ● | | | | | | | | | | ● | ● | ● | | | ● | ● | ● | ● | ● | | | ● | | | | | | | | | ● | |
| 4c | 20-21 | ● | ● | ● | | | ● | ● | ● | ● | ● | | ● | | | | | ● | ● | | | | | ● | | ● | | | | | | ● | | | ● | ● | ● | | | |
| 4b | 29 | | ● | ● | | | | | ● | | ● | | | ● | | | | ● | | | | ● | | | | ● | | | | ● | | | | | | | | | | |
| 4a | 36 | | ● | | | | ● | | | | ● | ● | | | | ● | | ● | | ● | | | | | | ● | | | | ● | | | | | | | | | | |
| 4a | 43 | ● | ● | ● | | | ● | | | | ● | | | | ● | | ● | ● | | | | ● | | | | | | | | ● | | | | ● | | | | | | |
| 3b | 49 | | ● | | | | ● | ● | | | ● | | | ● | | | | | | ● | | ● | ● | | | ● | ● | | | | | | | | | | | | | |
| 3b | 55 | | ● | | | | ● | ● | ● | | | | | | | | | | | ● | | | ● | | | ● | | | | ● | | | | | | | | | | |
| 3b | 64-65 | ● | ● | | | | | | ● | | ● | | | | ● | | | | | | | ● | ● | | | ● | | | | | | | | | | | | | ● | |
| 3b | 77 | ● | ● | ● | | | | ● | ● | | ● | ● | | | ● | | | ● | | ● | | ● | ● | | | | | | | ● | | | ● | | | | | | | |
| 3a | 87-88 | | ● | | | | ● | ● | | | | | | | ● | | | ● | | ● | | ● | ● | | | | | | | ● | | | | | | | | | | |
| 2b | 92 | | ● | ● | | | | ● | | | | | | | | | | | | | ● | | ● | ● | | | | | | | ● | | | | | | | | | |
| 2a | 98 | | | | | ● | | ● | | | | | | | | | | | | | | | ● | ● | | ● | | | | | ● | ● | | | | | | ● | | |
| 1e | 104 | | | | | | | | | | | | | | | | | | | | | | | T | | | | | | | T | T | | | | | | | | T |
| 1d | 110 | | ● | ● | | ● | | ● | | | | | | ● | ● | | | | | | | | | ● | | ● | | | ● | | | ● | | | | | | | | |
| 1b | 116-117 | | ● | ● | | ● | | ● | ● | | ● | | | | ● | ● | | ● | | | | ● | ● | | | ● | | | ● | | | ● | | ● | | | | | | |

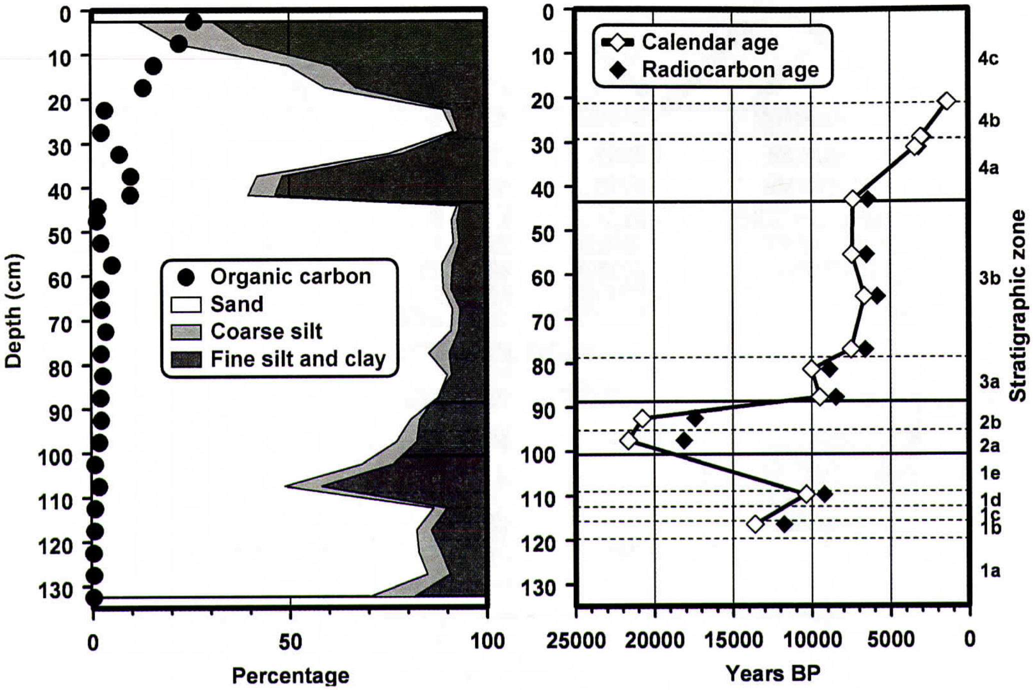

**Figure 4. Sediment composition and radiocarbon ages for Core 1.**

only between 92-110 cm (Zone 2 and the upper two strata of Zone 1); at 98 cm, it constituted 6% of the pollen total. Other conifers were sparse. The Taxodiaceae-Cupressaceae-Taxaceae (families including cypress, red cedar, and Atlantic white cedar) were present in all samples from Zone 4 and a few other samples from Zones 1 and 3. *Tsuga* (hemlock) was present in two samples from Zone 4c; it is presently known only from the mountains of western South Carolina.

*Quercus* (oak) was abundant throughout the core except in Zone 2. Oak was more abundant than pine only in Zone 3b.

*Nyssa* (tupelo) was present in Zones 1, 3, and 4, but absent from Zone 2. It made up the greatest percentage of the total pollen in Zone 3b. The three common species of the modern Coastal Plain prefer different habitats (USDA, NRCS, 2009). *N. sylvatica* (blackgum) is a facultative wetland species and is common in upland habitats of the Sandhills (Barry, 1980). *N. biflora* (swamp tupelo) and *N. aquatica* (water tupelo) are obligate wetland species. *N. biflora* is common in nonalluvial swamps, including streamhead pocosins (Nelson, 1986) and shallow ponds; *N. aquatica* is typically found in river swamps (Brown and Kirkman, 1990). The geomorphic setting and ecological context suggest that the *Nyssa* species are *N. biflora, N. sylvatica*, or both.

*Myrica* (the common wax myrtle of southern wetlands, but including bayberry and sweet fern, which are more common to northern wetlands) occurred throughout the core. *Myrica* occurs in a range of moist to mesic habitats. It was most abundant in Zone 3.

*Liquidambar* (sweetgum), a common facultative wetland tree of the modern southeast (USDA, NRCS, 2009), was consistently present in Zones 1 (except the poorly preserved sample from Zone 1e), 3, and 4, but absent from Zone 2.

A more typically temperate forest tree, *Fagus* (beech), also followed this general pattern; its maximum abundance occurred in Zone 3. Beech has not been observed in the modern flora of Fort Jackson (B. Pittman, South Carolina Department of Natural Resources, and J. Nelson, University of South Carolina Herbarium, personal communication, 2009), although it

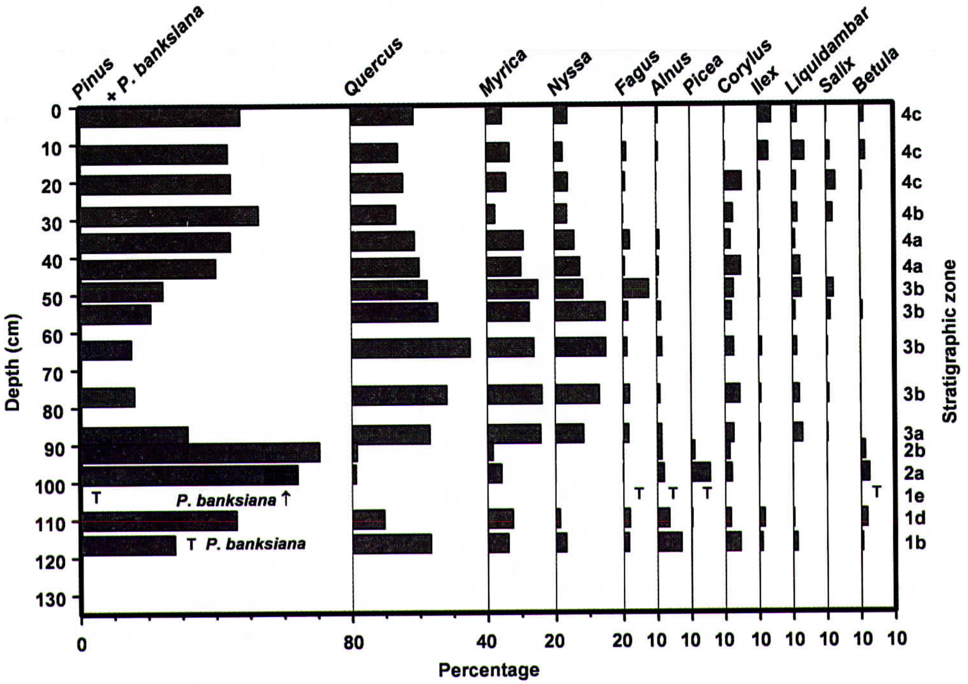

**Figure 5. Abundances of tree and shrub pollen. Percentages are calculated relative to sum of all taxa. Minor taxa (2% maximum abundance) are listed in Table 3. T indicates trace.**

does occur along the bluffs of the Wateree River. *Carya* (hickory) was present but sparse nearly throughout the core.

Among the herbs and grasses (Figure 6), Asteroideae (a subfamily of the Asteraceae, the sunflower family), all with conspicuous long spines suggesting that they are insect-pollinated, were most abundant in Zones 1 and 2. (*Ambrosia*, among the minor taxa in Table 3, also belongs to the Asteroideae, but it is wind-pollinated.) Gramineae (grasses) were most abundant in lower strata of Zone 4.

Fern spores, particularly those assignable to *Woodwardia* (chain fern) and *Osmunda* (including cinnamon, interrupted, and royal ferns) were fairly abundant except in Zone 2. Both genera are common in modern southeastern wetlands. The *Woodwardia* are obligate wetland species in this region, and the *Osmunda* are obligate or facultative, depending on species (USDA, NRCS, 2009).

## Assemblages

In the principal components analysis of pollen composition, the first two components accounted for 87% and 4% of the total variance among samples (Figure 7). In the biplot, the samples of Zone 4 form one cluster; the samples of Zones 3 and 1b form another. The samples from Zones 2 and 1d are not similar to other samples. Pine and oak loaded most heavily on the first component, with smaller contributions from *Nyssa* and *Myrica*. Oak loaded most heavily on the second component. Other taxa made only very small contributions to either component.

Broad-leaved woody taxa, including trees, shrubs, and vines, were more numerous in Zones 1, 3, and 4 (13 to 19 taxa, n= 13 samples, excluding the poorly preserved sample from Zone 1e) than in Zone 2 (7 and 9 taxa, n=2 samples). This difference is significant (Wilcoxon rank sum test, p=0.03).

## INTERPRETATION

The strong associations between the sediment zones and pollen assemblages indicate

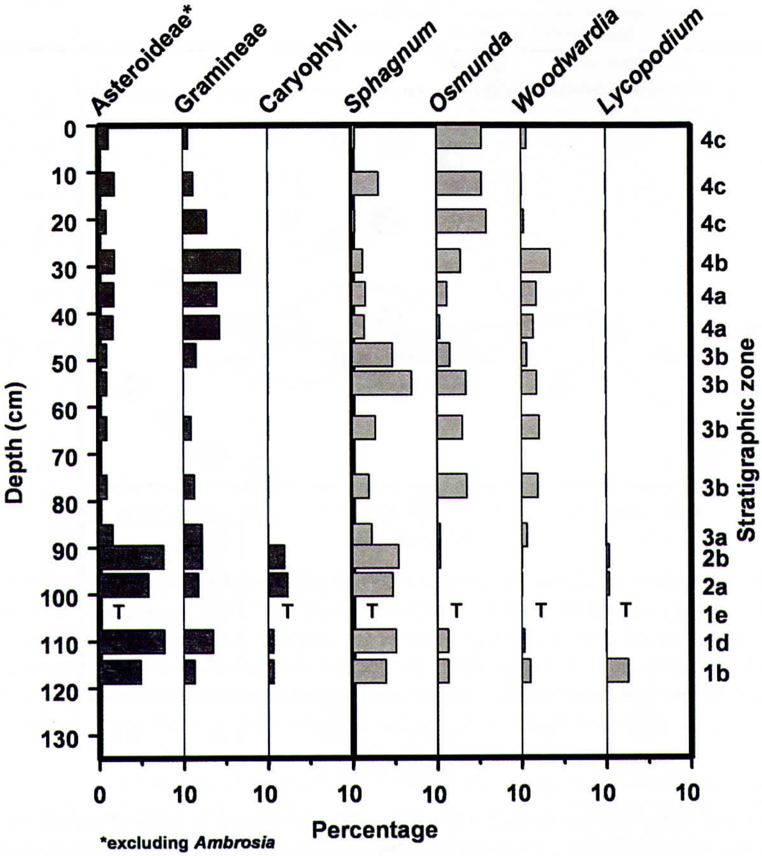

**Figure 6. Abundances of herb and grass pollen and spores of ferns and fern allies. Herbs and grasses are shown in left section; ferns and fern allies, in right section. Minor taxa (2% maximum abundance) are listed in Table 3. T indicates trace.**

that changes in plant communities occurred with changes in the depositional environments.

## Zone 1

If the samples were preserved in proper stratigraphic sequence, they would have been emplaced before the last glacial maximum. Alternatively, and probably more likely, the zone represents a stratigraphic inversion and dates to the deglacial through early Holocene. Pine dominated the assemblages. Mild climate is indicated by *Nyssa* and sweetgum. The appearance of spruce in the upper samples suggests cooler intervals. The relative abundances of Asteroideae and grasses indicate open habitats. The alternation of light and dark bands suggest periods of surface stability alternating with periods of more rapid deposition.

## Zone 2

The radiocarbon ages place these samples near the time of the last glacial maximum. The climate was cold, as illustrated by the presence of spruce in both samples and by the relative abundance of jack pine in the lower sample. Oak was sparse. Sweetgum and *Nyssa*, both associated with warm climates, were absent. Beech, *Ilex* (holly), and *Salix* (willow) also were absent. The dryness of the environment is inferred from the presence of the herb *Polygonella,* which characteristically lives on dry, sandy soils (Gleason and Cronquist, 1963; Watts, 1980; Rich et al., 2002). This inference is supported by the presence of Caryophyllaceae

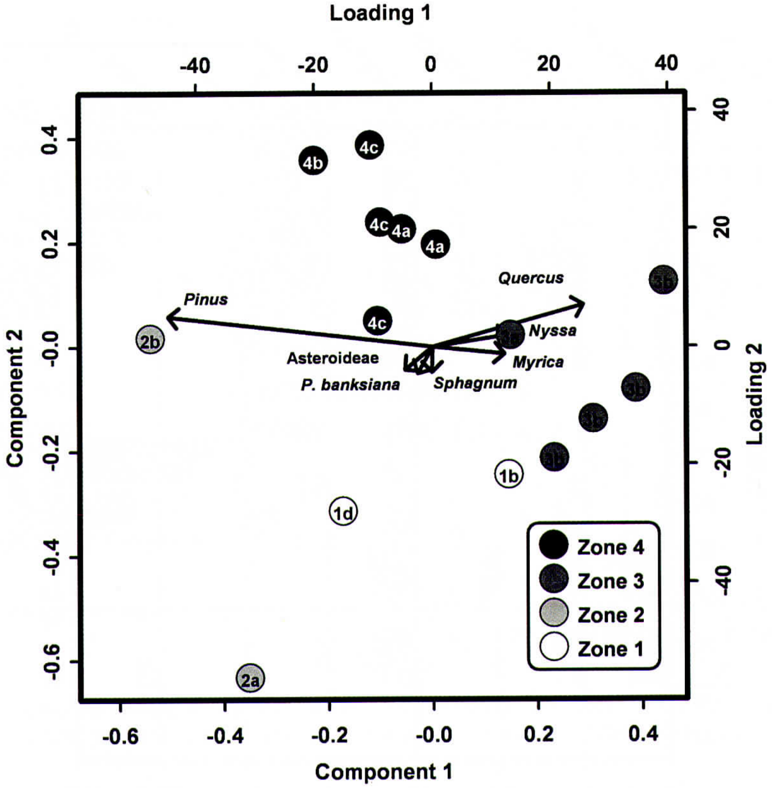

**Figure 7. Principal components analysis of pollen composition. Scores of pollen samples for the first two principal components are shown by filled circles. Arrows indicate the strength and direction of the loadings, which measure importance, of taxa on the first two principal components. All 59 taxa of pollen and spores were included in the analysis; loadings are shown for the most influential taxa.**

(pink family); most members of this family live on rocky slopes, or on dry sandy or gravelly soil (Gleason and Cronquist, 1963).

## Zone 3

The samples of Zone 3 represent intervals during the early and mid-Holocene. The sand content and presence of sand stringers suggest high mobility of sediments during these preserved intervals. The climate was warmer, as indicated by typical warm temperate trees and shrubs, such as *Nyssa*, *Myrica*, and sweetgum throughout the zone. Dominance shifted from pine to oak at some time between the early Holocene (Zone 3a: 9,500 and 10,020 cal yr BP) and mid-Holocene (Zone 3b: ages of 7,500, 6,660, and 7,440 cal yr BP; the middle value may be erroneously low) samples. However, composition of the assemblages remained otherwise fairly similar.

The greater abundances of hardwoods in the oak interval suggest lower fire frequency or intensity or higher precipitation or both. In modern forests of the Coastal Plain, pines are tolerant of fire but intolerant of shade. Maintenance of the pine forest depends on fire or large-scale other disturbances to suppress hardwoods, such as oaks, and to create openings for recruits (e.g., Gillam and Platt, 1999). In the streamhead pocosin, fire may also "limit dominance of canopy species," mainly hardwoods (Nelson, 1986). Oak in Zone 3b was accompanied by an abundance of *Nyssa*, from the streamhead pocosin (*N. biflora*) or from the uplands (*N. sylvatica*).

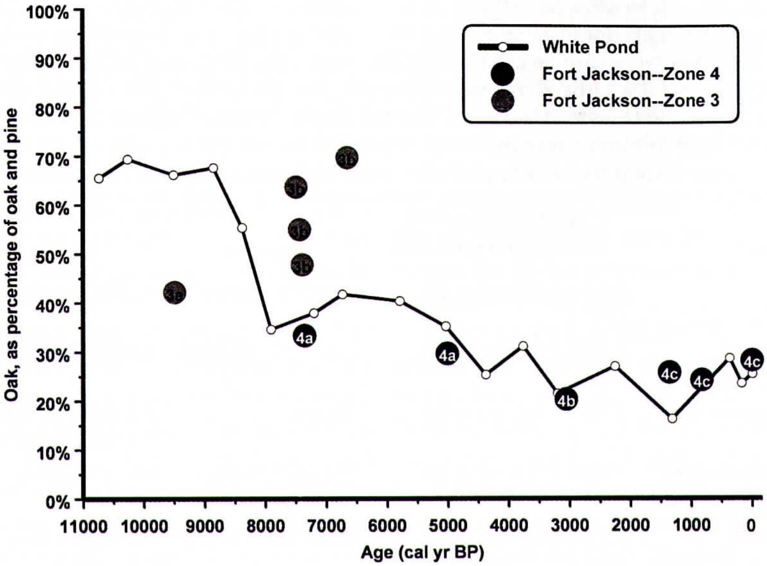

**Figure 8. Holocene shifts between oak and pine dominance at Fort Jackson and White Pond. Data for White Pond were obtained from the North American Pollen Database (Watts, 2000). We followed Watts' method of linear interpolation for assigning ages to the White Pond samples, but substituted calendar age (Table 4) for the radiocarbon age at 404 cm. Ages for Fort Jackson pollen samples were based on dates at corresponding depths from Table 2 (7 samples), linear interpolation (3 samples), or assumption of modern origin (uppermost sample).**

Higher precipitation would tend to promote expansion of hydric vegetation in the immediate vicinity of the wetland and mesic vegetation in surrounding areas. The relative increases in *Nyssa* and *Myrica* could thus indicate higher precipitation. However, they could also simply reflect reduced fire frequency or decreased pollen contributions from other sources.

Reduced fire frequency during this interval, or moister conditions, or both, may have also permitted expansion of beech, which is intolerant of fire (Coladonato, 1991) into mesic habitats at lower elevations.

## Zone 4

The samples of Zone 4 represent intervals during mid-Holocene to modern times. Pine was dominant throughout the zone. Because the age obtained at the base of this zone (7,360 cal yr BP) does not differ substantially from the ages immediately below, we infer that the return to pine dominance was rapid.

Changes associated with the return to pine dominance suggest a decrease in precipitation, at least during the initial phase. In Zones 4a and 4b, lower sand content of the sediment supports the idea that there was less disturbance or runoff, and the abundance of grasses indicates a more open habitat. *Nyssa* and *Myrica* declined, possibly in response to fire or contraction of the wetland. Beech also declined, perhaps retreating toward its modern local distribution along the bluffs of the Wateree River. In Zone 4c, the fern *Osmunda* largely replaced the other herbaceous taxa. Pine dominance persisted into the present, but changes in the sediments, as well as in the pollen associations, indicate further variation in the environment.

## DISCUSSION

The pollen record from the Fort Jackson wetland preserves a record of vegetation changes in a small streamhead pocosin wetland surrounded by xeric uplands. White Pond, a 30-ha lacustrine wetland, lies near the Fort Jackson wetland at a similar elevation. The 200-ha basin sur-

**Table 4. Holocene oak to pine transitions in southeastern pollen records. Transition interval is the time span over which dominance shifted from oak to pine. For Clear Pond and White Pond, the radiocarbon ages were converted to calendar ages (see Methods) before interpolation. For Sandy Run Creek and the Little River paleochannel, sample depths and relative abundances of oak and pine pollen were estimated from the published pollen diagrams; calendar ages were used as given. Ages in transition interval are rounded to nearest hundred years. After the transition interval, pine dominance continued into modern times at each of these sites.**

| Site | Transition interval (n of pollen samples) | Basis for chronology | |
|---|---|---|---|
| | | Method | Ages (cal yr BP) |
| Clear Pond<br>(Hussey, 1993, 2000) | 9,400-8,800 cal yr BP<br>(n=10) | Linear interpolation | 13,360, 9,470, 7,800 cal yr BP |
| White Pond<br>(Watts, 1980, 2000) | 8,900-7,900 cal yr BP<br>(n=3) | Linear interpolation | 10,930, 280 cal yr BP |
| Fort Jackson streamhead<br>(this study) | 7,500-7,400 cal yr BP<br>(n=5) | Range | 7,500, 7,440, 7,360 cal yr BP<br>(6,660 cal yr BP excluded) |
| Little River paleochannel<br>(Goman and Leigh, 2004) | 5,800-4,300 cal yr BP<br>(n=2) | Linear interpolation | 6,010, 1,860 cal yr BP |
| Sandy Run Creek<br>(LaMoreaux et al., 2009) | 4,500-3,600 cal yr BP<br>(n=4) | Linear interpolation | 4,610, 925 cal yr BP |

rounding White Pond is situated on a sandy interfluve at the head of four small watersheds (Elgin 7.5 minute quadrangle map, SC DNR, 2007)

The late Pleistocene assemblages were similar between the Fort Jackson and White Pond (Watts, 1980, 2000). The *Pinus*/*Picea*/Herb zone (22,780-15,310 cal yr BP; published radiocarbon ages converted to calendar ages) at White Pond corresponds to Zone 2, and possibly the upper portion of Zone 1, at Fort Jackson. Pines, including forms identified with jack pine, dominated the terrestrial pollen at both wetlands; spruce was present. Oak and other hardwoods were sparse, and warm-climate species such as sweetgum and *Nyssa* were absent. Abundances of herbs and grasses at both sites indicate open habitat. The *Fagus-Carya* zone (15,310-10,930 cal yr BP) at White Pond is probably absent at Fort Jackson, although it is possibly present as a stratigraphic inversion in Zone 1.

The Holocene at White Pond is represented by a *Pinus-Liquidambar* zone (10,930 cal yr BP to present), which corresponds to Zones 3 and 4 at Fort Jackson. Oak dominated at White Pond during the Pleistocene-Holocene transition and the early Holocene (Figure 8). There is a single, pine-dominated sample from the early Holocene (Zone 3a) at Fort Jackson; oak dominated the interval contained in Zone 3b. The interpolated age for the end of the oak-pine transition at White Pond, 7,900 cal yr BP (Table 4), precedes the age for the end of the oak-pine transition at Fort Jackson by 500 yr. However, given the very long span (more than 10,000 cal yr) for the interpolation at White Pond, along with the potential for variation in sedimentation rates (Watts, 1980), it is plausible that these transition times coincided. Given the gaps in the record at Fort Jackson, it is also plausible that additional shifts between oak and pine dominance occurred at Fort Jackson during the early to mid-Holocene, as well as later. The lack of obvious asynchrony between the preserved transition at Fort Jackson and the transition at White Pond may be simply fortuitous.

Watts (1980) hypothesized that the shift from oak to pine at White Pond, as well as elsewhere in the southeast, reflected a shift from a drier to a moister climate. At Fort Jackson, in contrast, sediment characteristics suggest higher or more intense precipitation in the earlier segments of the Holocene record (Zones 3a and 3b). Evidence from the pollen record, however, is equivocal. The shift from oak to pine in the uplands probably required fire or other disturbance; modern pine-dominated communities in the region require such disturbances to suppress broad-leafed competitors and to create openings for recruitment (Gilliam and Platt, 1999). Because the wetland is small, its vegetation would be vulnerable to fire in the adjacent dry uplands. The relative changes in hydric or mesic woody vegetation, including *Nyssa*, which could indicate changes in size of the wetland, might be equally well explained by shifts in the fire regime.

Strong linkages between anthropogenic fire and shifts in forest composition have been established in other parts of eastern North America (e.g., Dey and Guyette, 2000). Human activity intensified during the Late Archaic and Woodland periods at the archaeological site above the wetland at Fort Jackson. The site was occupied ephemerally, evidently serving as a hunting camp for upland game procurement (Clement et al., 2005). The chronological resolution of the archaeological record does not support tight linkages to the palaeoenvironmental record at the wetland, but it is plausible that native American use of fire promoted expansion of pine.

To compare timing of the oak to pine transition at Fort Jackson with additional records for the region, we converted radiocarbon ages to calendar ages, if necessary, and then interpolated boundaries for the time interval during which the transition occurred (Table 4). The oak-pine transition at Clear Pond appears to pre-date the transition at Fort Jackson by at least a thousand years, and the transitions at Sandy Run Creek and the Little River paleochannel appear to post-date it by 1,500-2,500 years or more.

At both Sandy Run Creek and the Little River paleochannel, oak was consistently dominant during the early Holocene. At both sites, based on lithostratigraphic evidence, a wetter and stormier early to mid-Holocene climate was inferred, with the transitions occurring about 6,100 cal yr BP at the Little River paleochannel (Goman and Leigh, 2004) and about 4,500 cal yr BP at Sandy Run Creek (LaMoreaux et al., 2009). The substantial difference in timing of these transitions suggests that local conditions mediated responses to the broad climatic shifts. In any case, changes in pollen composition occurred after the lithostratigraphic changes at both sites (Table 4). The shift from oak- to pine-dominance occurred between 5,800 and 4,300 cal yr BP at the Little River paleochannel (two pollen samples only); it occurred gradually between 4,500 and 3,600 cal yr BP at Sandy Run Creek (four pollen samples). At Sandy Run Creek, the shift was also associated with greater abundance of charcoal.

Other records from the Sandhills indicate further environmental changes during the mid- to late Holocene. At Peat Bay, a wetland on a Pleistocene terrace of the Savannah River, diatom assemblages indicated a shift from an oxbow-like habitat to an open water pond around 5,400 cal yr BP and then to a temporary pond around 4,000 cal yr BP (Gaiser et al., 2001; radiocarbon ages converted to cal yr BP; despite its name, the wetland is not a Carolina bay). A moister climate was inferred for the open water pond; a drier climate, for the temporary pond. At Flamingo Bay, a Carolina bay in the uplands near Peat Bay, a basal date from organically enriched sediment suggests a shift in hydrologic conditions around 5,200 cal yr BP (Brooks et al., 1996; age converted to cal yr BP). Because the sample included material from an 11-cm section, the age should be interpreted as a minimum age. The preserved organics arguably reflect climatic conditions supporting longer periods of inundation in the basin. The fossil diatom record at Peat Bay, as well as sedimentary evidence for later episodes of paludification at Flamingo Bay (Gaiser, 1997), indicates that hydrologic conditions did not remain stable after around 4,000 cal yr BP. Other evidence for later Holocene variation includes an episode of sand rim emplacement at Big Bay around 2.2 ka BP (Brooks et al., 2010; Big Bay is 40 km SSE of Fort Jackson).

Despite the indications of further variations in climate after around 4,000 cal yr BP, pine remained dominant in essentially all vegetation records for the Sand Hills and the Coastal Plain during the late Holocene (Table 4; also, Seielstad, 1994; Brook 1996; LaMoreaux, 1999; other records reviewed by Watts et al., 1996). One possibility is that these later variations were in-substantial, relative to the earlier changes in climate. Another possibility is that they simply didn't have much effect on fire regimes.

## CONCLUSIONS

The pollen record from the Fort Jackson wetland indicates that the early Holocene landscape of the Sandhills was not uniformly dominated by oak. Comparisons with other pollen records also show that oak-pine transitions were not synchronous, even within the Sandhills portion of the Coastal Plain.

We suggest that the oak-pine transition may be a poor proxy for Holocene climate change in the Coastal Plain. The asynchronies may be in part a consequence of the importance of fire in shaping these communities. Climate will affect fire frequency and intensity. But the occurrence of fire also has a random component, especially at the spatial scale relevant to some of the smaller wetlands, as well as a possible prehistoric anthropogenic component. A clearer assessment of response to climate and other influences will benefit greatly from the examination of a larger number and variety of sites, with tighter chronologic and stratigraphic controls.

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