Chapter 11

Long-Term Barrier Evolution Related to Variations in Underlying Geology and Land Use

SERDP Project Number: RC-1413

Coastal Barrier Module

Research Project CB-2

Lead Researcher:
Antonio B. Rodriguez

Supporting Researchers:
Stephen R. Fegley, Winnie Yu, Ethan Theuerkauf

University of North Carolina at Chapel Hill
Morehead City, NC
E-mail: abrodrig@email.unc.edu

May 10, 2013
Final
This report was prepared under contract to the U.S. Department of Defense (DoD) Strategic Environmental Research and Development Program (SERDP). The publication of this report does not indicate endorsement by DoD, nor should the contents be construed as reflecting the official policy or position of DoD. References herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, do not necessarily constitute or imply its endorsement, recommendation, or favoring by DoD.
# Table of Contents

List of Acronyms ....................................................................................................................... 11-v
Abstract ...................................................................................................................................... 11-1
Objectives .................................................................................................................................. 11-2
Background ................................................................................................................................ 11-2
   Study Area ............................................................................................................................... 11-4
Materials and Methods ............................................................................................................... 11-7
   Seismic and side-scan sonar data ................................................................................... 11-7
   Coring ..................................................................................................................................... 11-8
   Radiocarbon Dating ....................................................................................................... 11-9
   Mapping Shoreline Changes .......................................................................................... 11-9
Results and Discussion ............................................................................................................ 11-12
   Nearshore Framework Geology ................................................................................... 11-12
   Depositional Environments and Lithologic Facies ...................................................... 11-14
   Stratigraphy .................................................................................................................. 11-20
   Timing of Washover Fan Emplacement ........................................................................... 11-23
   Shoreline Movement at Decadal to Yearly Time Scales ................................................... 11-24
   Along-shore variability in rates of shoreline movement ............................................... 11-24
   Impacts of Changes in Storminess and the Rate of SLR on Island Evolution .......... 11-27
Conclusions and Implications for Future Research ................................................................. 11-30
Literature Cited ........................................................................................................................ 11-32
Appendix 11-A: Onslow Beach Cross Sections .................................................................... 11-A-1
Appendix 11-B: List of Scientific Publications ..................................................................... 11-B-1
Appendix 11-C: List of Students ........................................................................................... 11-C-1
List of Figures

11-1. Regional Study Area Map................................................................. 11-5
11-2. Decadal-Scale Trends in Shoreline Position........................................... 11-6
11-3. The bathymetry map of the nearshore area of Onslow Beach shows high-relief features located offshore of the headland at the same location where Riggs et al. (1995) recognized outcropping rock limestone. ......................................................... 11-6
11-4. MCBCL use zones on Onslow Beach, NC ............................................. 11-7
11-5. Seismic and side-scan sonar trackline map of area offshore Onslow Beach, NC. ....... 11-8
11-6. Core-transect locations .................................................................... 11-9
11-7. Mapping shoreline movement ......................................................... 11-11
11-8. Sea-floor bottom types ................................................................. 11-13
11-9. Sand-thickness map ...................................................................... 11-14
11-10. Lithofacies of depositional environments on Onslow Beach, NC .......... 11-16
11-11. Proximal washover fan facies .......................................................... 11-18
11-12. Distal washover fan facies ............................................................... 11-18
11-13. Fence diagram ............................................................................. 11-21
11-14. Decadal and annual rates of shoreline movement along the various zones on Onslow Beach, NC ................................................................. 11-25
11-15. Record of washover fans along Onslow Beach, NC .......................... 11-28

List of Tables

11-1. Radiocarbon data and sample information .................................. 11-10
# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>degrees Celsius</td>
</tr>
<tr>
<td>µm</td>
<td>micrometer</td>
</tr>
<tr>
<td>Φ</td>
<td>phi</td>
</tr>
<tr>
<td>3-D</td>
<td>three dimensional</td>
</tr>
<tr>
<td>A.D.</td>
<td>Anno Domini</td>
</tr>
<tr>
<td>AMS</td>
<td>Accelerator Mass Spectrometry</td>
</tr>
<tr>
<td>BP</td>
<td>Before present (1950)</td>
</tr>
<tr>
<td>cal yr BP</td>
<td>calibrated years before present</td>
</tr>
<tr>
<td>cm</td>
<td>centimeter</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>DoD</td>
<td>U.S. Department of Defense</td>
</tr>
<tr>
<td>ICW</td>
<td>Intracoastal Waterway</td>
</tr>
<tr>
<td>kHz</td>
<td>kilohertz</td>
</tr>
<tr>
<td>km</td>
<td>kilometer</td>
</tr>
<tr>
<td>km/h</td>
<td>kilometers per hour</td>
</tr>
<tr>
<td>LiDAR</td>
<td>light detection and ranging</td>
</tr>
<tr>
<td>m</td>
<td>meter</td>
</tr>
<tr>
<td>m²</td>
<td>square meter</td>
</tr>
<tr>
<td>m/s</td>
<td>meters per second</td>
</tr>
<tr>
<td>m/yr</td>
<td>meters per year</td>
</tr>
<tr>
<td>mm/yr</td>
<td>millimeters per year</td>
</tr>
<tr>
<td>MCBCL</td>
<td>Marine Corps Base Camp Lejeune</td>
</tr>
<tr>
<td>MWP</td>
<td>Medieval Warm Period</td>
</tr>
<tr>
<td>NAVD88</td>
<td>North American Vertical Datum of 1988</td>
</tr>
<tr>
<td>NCDCM</td>
<td>North Carolina Division of Coastal Management</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>RTK-GPS</td>
<td>real-time kinematic global positioning system</td>
</tr>
<tr>
<td>SEGSA</td>
<td>Southeastern Section of the Geological Society of America</td>
</tr>
<tr>
<td>SERDP</td>
<td>Strategic Environmental Research and Development Program</td>
</tr>
<tr>
<td>SLR</td>
<td>sea level rise</td>
</tr>
</tbody>
</table>
Abstract

Onslow Beach is an important asset to Marine Corps Base Camp Lejeune (MCBCL) being the primary Atlantic Ocean location where amphibious military training takes place and also a popular spot for military-staff and family recreation. The future sustainability and effective management of that resource depends on a better understanding of the evolution of the barrier in terms of shoreline movement and landscape changes. The main objective of this study is to examine the evolution of Onslow Beach over millennial to yearly time scales to help better manage future landscape changes that may occur in response to changes in storminess and sea level rise (SLR). Shoreline displacements at decadal and yearly time scales were measured from aerial photography and terrestrial laser scanning, respectively and the evolution of the barrier at millennial to centennial time scales was reconstructed from sediment cores and radiocarbon data. Those data show that Onslow Beach is a transgressive barrier island that moved from approximately 300 m seaward of its present location approximately 200 Anno Domini (A.D.) to its present position during the late Holocene principally through overwash processes and washover fan formation. The oldest washover fan deposits preserved in the stratigraphy of the island are approximately 200 A.D. and at that time an open-water lagoon separated Onslow Beach from the mainland. At approximately 1850 A.D., the number and landward extent of washover fans increased sharply along the entire island. This corresponds to an increase in the rate of SLR to 3.2 mm/yr and a low number of annual tropical cyclones in the Atlantic Ocean. The increase in number and landward extent of washover fans at 1850 A.D. also implies that the rate of island transgression increased. The increase in the rate of SLR likely lowered the elevation of the island principally through erosion of the dunes, and made the island more vulnerable to overwash. These data suggest that Onslow Beach is extremely sensitive to increases in the rate of SLR, which cause an immediate decrease in the elevation of the island and its resistance to overwash. This sensitivity is likely the result of the island being sediment starved, a product of its framework geology (limestone outcropping near the shoreface) and its location at the center of a coastal embayment. Military training activities have little impact on island evolution because the decadal record of shoreline movement and the geological record of island evolution show that the military training zone has been vulnerable to overwash and experienced high rates of shoreline retreat since at least 1850 A.D., long before MCBCL existed. High rates of shoreline retreat at the military training zone are due to the low sediment supply there as compared to the northeastern part of the island where nearshore sand thicknesses are greater. Yearly rates of shoreline retreat at the military training zone, measured November 2007–September 2011, are up to four times higher than the decadal rates, but some of that difference is likely due to different measurement methodology (aerial photos versus laser scanning). The yearly and decadal rates of shoreline movement documented in this study should be used by MCBCL for making management decisions at those respective time scales; however, some of those rates include high variability indicating that the long-term trend should not be projected into the future.

Keywords: Barrier island, transgression, washover fan, sea level rise, beach, overwash, Medieval Warm Period, Little Ice Age, beach erosion, salt marsh, peat
Objectives

The North Carolina Division of Coastal Management’s long-term average erosion rates for Onslow Beach (1938–1992) show significant along-beach variability. Erosion of Onslow Beach impacts Marine Corps Base Camp Lejeune (MCBCL) amphibious training and recreation and habitat distribution and quality, making management challenging. The main objectives of this research are to

1. Determine the principle drivers of along-beach variations in erosion rates by comparing the historical rates of shoreline erosion with anthropogenic activities and the underlying geology.

2. Place the short-term (yearly) geomorphic evolution of the island, derived from the monitoring data, in context with the historical (100 years) and geological (thousands of years) geomorphic evolution.

3. To provide a model that can be used to predict short-term (yearly to decadal) morphologic changes (shoreline migration).

4. To test H1: Erosional “hot spots”, identified as localized areas with higher than average coastal retreat rates, are not a result of anthropogenic activities and H2: Onslow Beach is sediment starved due to a lack of unconsolidated material located seaward of the shoreface and insufficient amount of sediment transported to the area by longshore drift and a low rate of production of new sediment through bioerosion of limestone outcrops.

Background

Sustaining the value of environmental and mission-related assets while conducting shoreline management requires a better understanding of the short- and long-term rates of coastal change, which will help differentiate between geologic, hydrodynamic, and anthropogenic forcing mechanisms. The coastal barrier ecosystem is organized directly and indirectly by the physical dynamics of ocean forcing and sediment transport. Physical processes operating in the nearshore vary in magnitude on time scales ranging from hours (coastal storms) and months (seasonal weather patterns) to decades (climate and associated sea level change). The morphological response of the coastal barrier ecosystem to these perturbations is poorly understood, but is critically needed for better shoreline management.

Ocean shorelines retreat at different rates in response to rising sea level due to many factors, including variations in framework geology (antecedent topography and lithology), sediment supply, shoreface hydrodynamics, and storminess. The significant variability in shoreline position and morphology that exists along many coasts at spatial scales of 10–100 km is a reflection of their different rates of retreat and implies differences in coastal evolution at centennial to millennial time scales. The Carolina Capes, including Cape Fear, Cape Lookout, and Cape Hatteras (Figure 11-1), likely transgressed landward at a slower rate than the adjacent embayments (Onslow Bay, Raleigh Bay) in response to sea level rise (SLR) from the last glacial maximum (approximately 20,000 years ago) to present. This is because the continental shelf break, which is where the shoreline was located during the early deglaciation, does not mimic the cape-embayment-morphology of the modern shoreline. Understanding the regional controls on coastal evolution and the responses of coastal environments to changing processes at geological
time scales is important due to imminent accelerated SLR and predicted increased storminess and their associated impacts on coastal systems (Donnelly et al., 2004; Scott et al., 2003).

As sea level rises over geologic time scales, waves are generally assumed to erode headlands and straighten a coastline; however, the Carolina Capes are still prominent features along the southeastern U.S. coastline. Ashton et al. (2001) challenged that notion using a numerical model to demonstrate that waves with large angles between their crests and the coast (high-angle waves) can develop coastal perturbations that resemble the Carolina Capes (Cape Fear, Cape Lookout, Cape Hatteras; Figure 11-1). The high-angle wave energy makes the cape flanks more stable than the central embayments (e.g., Cape Lookout and Onslow Bay; Ashton and Murray, 2006). Model predictions compared well with the wave-climate variability that exists along the Carolina Capes (Ashton and Murray, 2006) and with field data that show the slow (approximately 5,000 years) degradation (capture) of a former Carolina Cape in Raleigh Bay (Thieler and Ashton, 2011). It takes approximately 50,000 years to produce perturbations of a similar scale as the Carolina Capes from high-angle waves impacting a straight coastline, which is much longer than the less than 9,000 years that the continental shelf was flooded after the last glacial maximum (Ashton et al., 2001; Thieler and Ashton, 2011). This discrepancy implies coastal modification over multiple sea-level cycles and likely influence of pre-existing capes on coastal evolution during the last episode of SLR on the continental shelf (approximately 9,000 years ago; Ashton and Murray, 2006). Many researchers have demonstrated the strong influence of variations in the elevation and lithology of the pre-Holocene antecedent topography that formed during previous sea-level cycles on the evolution of coastal systems (Belknap and Kraft, 1985; Kraft 1971; Pierce and Colquhoun, 1970; Rodriguez et al., 2004; Wilkinson and Basse, 1978).

Storms can produce profound morphologic changes to a barrier island over a short period. Changes in storm climate (i.e., storminess; storm frequency and magnitude) over decadal time scales also strongly affect barrier morphology, which is compounded with SLR. Storms accelerate longshore transport, remove sediment from the shoreface, and deposit sediment in backbarrier environments by producing washover fans and/or flood-tidal deltas, which create rapid changes to the morphology of a coastline. Although individual storms occur on short time-scales (days to weeks) and are not commonly integrated into long-term shoreline-change models (Valvo et al., 2006), changes in the storm climate occurs across centennial to millennial time scales and should be considered. Mann et al. (2009) showed an increase in hurricane landfall along the U.S. Atlantic Coast during the Medieval Warm Period (MWP) at approximately 1,000 cal yr BP. During the Little Ice Age at approximately 400 cal yr BP there is also evidence of increased storminess (nor’easters) impacting the U.S. Atlantic coastline (Mallinson et al., 2011). Slott et al. (2006) simulated coastline changes over 200 years of evolution of the Carolina Capes with a wave climate that is similar to increased tropical and extra-tropical storm conditions. Those scenarios of increased storminess show accretion near the capes and erosion at the embayments occurring at rates several times higher than rates simulated without the change in storm climate (Slott et al., 2006). Although that model’s output corresponds with historic rates of shoreline movement when input parameters match the recent wave climate (Slott et al., 2006), results from increased storminess have not been empirically tested.

Barrier islands located at the maximum curvature of a coastal embayment, similar to Onslow Beach, are predicted to have transgressed more rapidly during the Holocene and experienced
increased rates of erosion during stormy periods than barrier islands located along cape flanks, similar to Bogue Banks (Ashton and Murray, 2006; Slott et al., 2006). Both of these predictions can be tested along Onslow Bay, which experienced variations in storminess during the Holocene (Mallinson et al., 2011; Mann et al., 2009). Anthropogenic stressors such as dredging, construction, landing craft deployment, amphibious training, and munitions practice further impact the morphology of the coastal barrier at yearly to decadal time scales and play a large role in regulating rates of change. It is necessary to place short-term morphologic changes, measured directly, in context with the long-term evolution, derived from the geologic record, to differentiate between background and anthropogenic stressors. Additionally, it has been demonstrated that shorelines can exhibit non-linear rates of retreat in response to variations in underlying geology at century and decadal time scales (Browder and McNinch, 2006; Rodriguez et al., 2004).

Study Area

Onslow Beach is a northeast-southwest trending barrier island located at Marine Corps Base Camp Lejeune (MCBCL) in southeast North Carolina (Figure 11-1). It is a wave-dominated barrier with a mean wave height of 0.91 m and tidal range of 1.2 m based on National Oceanic and Atmospheric Administration’s (NOAA’s) tide gauge at Wrightsville Beach, NC (Station ID 8658163, located 60 km southwest of Onslow Beach). This 12 km–long barrier fronts saltmarsh with sinuous tidal channels and is bounded by the New River Inlet to the southwest and Browns Inlet to the northeast. The Intracoastal Waterway (ICW) extends through the backbarrier marsh. The shoreline of Onslow Beach is sinusoidal with a central headland separating two embayments (Figure 11-1). The morphology of the island also varies along its length. The northeastern arcuate section has a wide beach (approximately 80-m wide) with multiple well-developed dune ridges (7–9 m in height). Landward of the dune ridges a narrow (less than 100–m wide) maritime forest abuts the backbarrier saltmarsh. This northeastern section of the barrier has low net decadal rates of accretion of approximately 0.25 m/yr (Figure 11-2; Rodriguez et al., 2012). The central headland area has a narrow beach (approximately 20-m wide) with a single discontinuous dune ridge less than 4 m in height. Numerous washover fans extend less than 100 m across the dunes and the vegetation is dominated by shrub thickets, but dead standing and fallen trees are frequently observed. The beach widens significantly along the southwestern embayment from 20 m in the northeast to 80 m in the southwest. The discontinuous dunes are less than 2 m in height and washover fans can be extensive (250-m wide) and extend across backbarrier marshes. This southwestern part of Onslow Beach has a net erosion rate of approximately 2 m/yr and erosion rates decrease toward the headland where shoreline position is highly variable through time (Figure 11-2; Rodriguez et al., 2012). The variable morphology of Onslow Beach reflects its central location within Onslow Bay because it defines the border between the high-elevation regressive islands with multiple beach ridges to the north and the low-elevation, narrow transgressive islands to the south (Cleary et al., 1996).
Figure 11-1. Regional Study Area Map.

(A) Onslow Beach is located in the center of Onslow Bay, NC. (B) Map showing changes in elevation along the island and the locations of the 15 focus sites. (C) Oblique aerial photo looking towards the southwest shows the sinusoidal morphology of the island. (D) At the headland, consolidated and oxidized gravelly sand is outcropping on the beachface.

The central headland is produced by a submarine rock ridge that intersects Onslow Beach (Figure 11-3; Riggs et al., 1995). The rock ridge is composed of the Oligocene Silverdale Formation, a sandy, molluscan-mold limestone unit (Harris et al., 2000). The Quaternary sediment layer is thin and patchy offshore of southern and central Onslow Beach, where more
than 50% of the inner shelf is exposed limestone (Johnston, 1998) and Riggs et al. (1995) labeled the Onslow Beach as being “sediment starved.”

**Figure 11-2. Decadal-Scale Trends in Shoreline Position.**

The shoreline shape curve was derived from measuring the maximum distance between the 2008 digitized shoreline and the best-fit line through the points that define the shoreline positions in 1938, 1956, 1979, 1989, 1998, 2006, and 2008. Positive values are where the 2008 shoreline is seaward of the best-fit line. Rates of shoreline movement and r-squared values are based on Benton et al. (2004). Notice that the along-shore distance of 0 m is very close to Focus Site 1.

**Figure 11-3. The bathymetry map of the nearshore area of Onslow Beach shows high-relief features located offshore of the headland at the same location where Riggs et al. (1995) recognized outcropping rock limestone.**

The washover fans in the central and southwestern parts of Onslow Beach indicate storms are an important driver of geomorphologic change on the island. Historical records show 35 hurricanes passed within 120 km of Onslow Beach from 1857 A.D. to 2011, six of which were Category 3 or higher (wind speeds ≤178 km/h; csc.noaa.gov/hurricanes [NOAA, 2012]). Hurricane Fran (Category 3) made landfall in September 1996 and transported $199 \pm 88 \times 10^3$ m$^3$ of sand across the backbarrier environments forming an extensive washover fan at the southwestern end of
Onslow Beach (Foxgrover, 2009). Hurricane Bertha (Category 3) made landfall 2 months prior and likely contributed to the significant overwash of the island during Hurricane Fran by eroding the dunes. After Hurricane Fran, Hurricane Irene (Category 1, wind speeds ≤119 km/h) was the next large storm to cause significant overwash at Onslow Beach. That storm made landfall in August 2011 at Cape Lookout, NC, 70 km northeast of the study area (Figure 11-1), and formed washover terraces and fans along the southwestern and central parts of Onslow Beach.

The MCBCL created four spatially explicit use zones along Onslow Beach (Figure 11-4). The southwestern part of the island is used primarily by off-road recreation vehicles. People drive to this end of the island mainly to access fishing spots near the inlet. The central part of the island is used for military training and the main disturbance is large vehicles and equipment creating ruts in the beach. An access road (unpaved) behind the dune line is maintained. Egress points connect the road to the beach and are situated at natural breaks in the dune line that were formed by storms. Northeast of the training zone is the recreational part of the beach where the main impact is from foot traffic. The northeastern end of the island serves as a buffer zone between Onslow Beach and adjacent Browns Island, which is an impact area that is used in ordnance testing and is restricted from foot and vehicular traffic.

Materials and Methods

The broad time-scales included in this study require using a variety of diverse methods. The geologic history of the island was reconstructed based on identifying depositional environments and mapping their distribution from sediment cores and geophysical data. Depositional environments were placed in a chronostratigraphic framework by radiocarbon dating shells and wood subsampled from the cores. Shoreline movements at decadal and yearly time scales were measured from aerial photos and laser scanning, respectively.

Seismic and side-scan sonar data

Seismic and side-scan sonar data (approximately 50 km) were collected at the same time along the shoreface of Onslow Beach to map the sand thickness and the sea floor bottom type (sand, peat, or rock), respectively (Figure 11-5). These data were collected at high-tide so that acoustic facies interpretations of the intertidal and shallow subtidal areas could be verified with observations made at low tide from the shore. Seismic data were collected using an EdgeTech
SB-216S chirper set at 2–12 kHz and triggered every 0.25 seconds. Side-scan sonar data were collected using an EdgeTech 4200-Full Spectrum system set at 410 kHz, which has an across-track resolution of 2 cm. Side-scan sonar data are displayed with areas of high acoustic backscatter as dark to black-colored and low acoustic backscatter as light to white colored. All marine seismic data sets were interpreted using Chesapeake Technology, Inc. SonarWiz software and maps were generated using Surfer 9.0. A velocity of 1,500 m/s was used to convert the two-way travel time to depth.

Figure 11-5. Seismic and side-scan sonar trackline map of area offshore Onslow Beach, NC.

Coring

To determine the stratigraphy of Onslow Beach, we collected 43 cores from 11 transects in the barrier and adjacent environments. The cores make up one shore-parallel, two backbarrier and eight cross-island transects separated by an average of 1.2 km (Figure 11-6). Transect locations were selected based on accessibility, spacing, and presence of relevant geomorphic features like the locations of embayments, the headland and washover fans. Many transects were sampled near sandy paths leading to the ICW from the main paved road that runs along the central part of the island. The northeastern end of Onslow Beach has restricted access because it acts as a buffer between the recreational part of the beach and an area that receives live fire and may contain unexploded ordnance; therefore, we could not collect cores from this portion of the island.

Most of the cores were obtained using the standard vibracoring method (Lanesky et al., 1979), which retrieved cores 0.62 m to 3.94 m in length. The vibracorer had difficulty penetrating through the upper dry sediment, requiring hand auguring to the water table (the upper ~100 cm) at most of the sites. The augured sediment was logged in the field and the depth of the hole was recorded before vibracoring. The washover fan that formed during Hurricane Irene was sampled on September 1, 2011, 5 days after the storm, with four cores ranging 43–65 cm in length (F2wash). These short cores were collected by pounding aluminum pipe into the ground with a sledgehammer. The locations and elevations of the cores, as well as topographic profiles crossing the barrier at the eleven transects, were surveyed with a Trimble R8/5800 real-time kinematic global positioning system (RTK-GPS) unit. Average horizontal and vertical precisions were 0.015 m and 0.020 m, respectively.
The cores were split length-wise, photographed, described (color descriptions based on the Munsell color chart), and subsampled. Interpretations of depositional environments relied on constraining lithologies, sedimentary structures, and macrofossil assemblages. Approximately 370 subsamples were taken from the cores for grain size analyses. A 2,000-µm sieve was used to determine the greater than 2,000-µm fraction and a Cilas laser particle-size analyzer for the 2,000-µm to 0.04-µm component (see manufacturer’s specifications).

The organic matter content of approximately 300 subsamples from the cores was measured using the loss on ignition method (Heiri et al., 2001). Subsamples were collected at 15-cm intervals or at 1- or 2-cm intervals for high-resolution analyses of the modern marsh sediment. After drying the samples overnight at 110°C, they were burned at 550°C in a muffle furnace for 5 hours. Percent organic matter was calculated from the measured dry masses before and after the burning stage.

**Radiocarbon Dating**

Shell and organic material from the cores were selected for accelerator mass spectrometry radiocarbon dating. Articulated bivalves, large pieces of wood, and plant seeds were preferentially chosen over bulk organic samples, small wood fragments and unpaired valves to minimize the adverse effects of reworking on developing an accurate chronostratigraphy. Radiocarbon analysis of 18 samples was performed by Woods Hole Oceanographic Institution and Beta Analytic (for details on methodology used, see www.whoi.edu/nosams). Ages in this study are reported as calibrated years before present (1950) or A.D. at two standard deviations obtained by using the CALIB 6.0 program (Stuiver and Reimer, 1993; Table 11-1).

**Mapping Shoreline Changes**

Shoreline changes were measured at 15 focus sites selected to represent the diverse morphologies along Onslow Beach (Figure 11-1). Topographic data were collected using a Riegl three-dimensional (3-D) LMSZ210ii Terrestrial Laser Scanner. The scanner was mounted onto a truck and rotated 360 degrees while collecting approximately 2 million spatial (x, y, and z) data points from laser returns. RTK-GPS surveyed reflectors, positioned within the scan area, were used to reference the data points to a global coordinate system Universal Transverse Mercator (Theuerkauf and Rodriguez, 2012). Two scan positions were occupied at each focus site, resulting in approximately 200 m of coverage along the beach (approximately 4-million points per site per survey). Beach surveying was restricted to 2 hours before and after low tide to maximize subaerial beach coverage. Error in the 3-D topographic data is estimated to be ±3.0 cm, which includes a ±1.5 cm factory-estimated maximum instrument error and an average ±1.5 cm RTK-GPS error. The RTK-GPS error is reported from the instrument as horizontal and vertical error and varies based on factors such as number of satellites, position of satellites and
cloud cover. Each focus site along the island was scanned biannually in association with the beach monitoring program (May 2008 to September 2011).

Table 11-1. Radiocarbon data and sample information

<table>
<thead>
<tr>
<th>Laboratory Identification</th>
<th>Core Location</th>
<th>Core Name</th>
<th>Sample Depth (cm)</th>
<th>Material</th>
<th>Dated</th>
<th>Calibrated*</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS-90480</td>
<td>F1</td>
<td>F1_7</td>
<td>193</td>
<td>Plant material</td>
<td>&gt;Modern</td>
<td></td>
<td>Marsh</td>
</tr>
<tr>
<td>OS-82867</td>
<td>F1</td>
<td>F1_4</td>
<td>177–179</td>
<td><em>Macoma constricta</em></td>
<td>1,390 ±20</td>
<td>885–1003</td>
<td>Lagoon</td>
</tr>
<tr>
<td>OS-82889</td>
<td>F2</td>
<td>F2_5</td>
<td>164–167</td>
<td>Wood</td>
<td>115 ±20</td>
<td>55–145</td>
<td>Marsh</td>
</tr>
<tr>
<td>OS-90478</td>
<td>F2strike</td>
<td>F2strike_4</td>
<td>184–186</td>
<td>Plant material</td>
<td>250 ±25</td>
<td>280–318</td>
<td>Marsh</td>
</tr>
<tr>
<td>OS-90479</td>
<td>F2strike</td>
<td>F2strike_4</td>
<td>226–228</td>
<td>Plant material</td>
<td>660 ±25</td>
<td>560–598</td>
<td>Marsh</td>
</tr>
<tr>
<td>OS-82890</td>
<td>Pier</td>
<td>Pier_5</td>
<td>177–179</td>
<td>Wood</td>
<td>105 ±15</td>
<td>55–140</td>
<td>Marsh</td>
</tr>
<tr>
<td>OS-82891</td>
<td>Pier</td>
<td>Pier_5</td>
<td>202–204</td>
<td>Organic sediment</td>
<td>115 ±15</td>
<td>55–145</td>
<td>Marsh</td>
</tr>
<tr>
<td>Beta-283047</td>
<td>Pier</td>
<td>Pier_5</td>
<td>302–304</td>
<td>Wood</td>
<td>2,270 ±40</td>
<td>2,156–2,268</td>
<td>Fringe marsh</td>
</tr>
<tr>
<td>Beta-283048</td>
<td>Pier</td>
<td>Pier_5</td>
<td>420–422</td>
<td>Wood</td>
<td>3,400 ±40</td>
<td>3,556–3,728</td>
<td>Fringe marsh</td>
</tr>
<tr>
<td>OS-90490</td>
<td>Pier</td>
<td>Pier_1</td>
<td>63–66</td>
<td>Plant material</td>
<td>715 ±35</td>
<td>644–724</td>
<td>Marsh</td>
</tr>
<tr>
<td>OS-90484</td>
<td>Pier</td>
<td>Pier_1</td>
<td>115–117</td>
<td>Wood/plant</td>
<td>1,850 ±25</td>
<td>1,715–1,832</td>
<td>Marsh</td>
</tr>
<tr>
<td>OS-90492</td>
<td>F4</td>
<td>F4_4</td>
<td>144</td>
<td>Wood</td>
<td>520 ±35</td>
<td>505–559</td>
<td>Marsh</td>
</tr>
<tr>
<td>OS-90548</td>
<td>F4</td>
<td>F4_4</td>
<td>198–200</td>
<td>Plant material</td>
<td>1,430 ±30</td>
<td>1,293–1,376</td>
<td>Marsh</td>
</tr>
<tr>
<td>OS-82892</td>
<td>F5</td>
<td>F5_5</td>
<td>218–220</td>
<td>Wood</td>
<td>100 ±15</td>
<td>53–138</td>
<td>Marsh</td>
</tr>
<tr>
<td>OS-82894</td>
<td>F5</td>
<td>F5_5</td>
<td>258–260</td>
<td>Wood</td>
<td>605 ±15</td>
<td>583–649</td>
<td>Marsh</td>
</tr>
<tr>
<td>OS-82895</td>
<td>F5</td>
<td>F5_5</td>
<td>322–324</td>
<td>Wood</td>
<td>975 ±15</td>
<td>902–931</td>
<td>Lagoon</td>
</tr>
<tr>
<td>OS-90602</td>
<td>F6</td>
<td>F6_10</td>
<td>130–133</td>
<td><em>Tagelus plebeius</em></td>
<td>1,000 ±30</td>
<td>525–641</td>
<td>Lagoon</td>
</tr>
</tbody>
</table>

*a Using the CALIB 6.0 program (Stuiver and Reimer, 1993).

*Macoma constricta* = Constricted macoma; *Tagelus plebeius* = Stout tagelus.

Ground points (x, y, and z data points) were isolated from the raw data using an algorithm included in the Terrasolid LTD software package and by manual editing. Surface-grid models were created from approximately 125,000 ground points for sites with narrow cross-shore widths (e.g., F4) and approximately 500,000 ground points for sites with wide cross-shore widths (e.g., F7) using Delaunay triangulation (Guibas and Stolfi, 1985; Lawson, 1977; Lee and Schachter, 1980; Figure 11-7). Woolard (1999) and Woolard and Colby (2002) suggest that Digital Elevation Models (DEMs) derived from airborne light detection and ranging (LiDAR) most accurately represent coastal topography with a spatial resolution of 1–2 m. Given the high density of points derived from the laser scans at each site in this study, a 0.5-m grid spacing was used. This 0.5-m grid spacing is generally much larger than the spacing of the laser returns, thus each grid node is based on an average of several topographic measurements. Areas of the focus sites greater than 5 m² with no laser returns, which only occurs in the dunes, were not included in the surface model (i.e., the areas were defined with blanked grid nodes; Figure 11-7) because the
limited data would not depict the ground surface accurately at the desired resolution. Surface-grid files were imported into Golden Software’s Surfer 10.0 to generate contour maps and DEMs.

Figure 11-7. Mapping shoreline movement.

DEMs of Focus Sites 1 and 4 on Onslow Beach, NC, with the shoreline position (mean high water) highlighted in red for November 2007 and white for September 2010. The along-beach extent of each map is the same across time steps (see Figure 11-1 for locations).

The position of the laser scanner was not the same for each re-occupation of the focus sites due to changes in barrier morphology and unavoidable circumstances (e.g., beachgoers, MCBCL training activities). This caused the mapped area of a site to be slightly different for each survey. To account for this, DEMs were cropped to reflect only areas of overlapping survey coverage; resulting in an along-beach extent of approximately 150 m for each focus site. The data points also extend further landward at sites with low-elevation dunes and overwash fans (e.g., F3), but these data are patchy landward of the foredune crest because of shadowing. Portions of the dune landward of the foredune crest were cropped out of the maps to normalize coverage across the beach between surveys. The seaward boundaries were cropped at zero meters North America Vertical Datum of 1988 (NAVD88) on the maps to normalize coverage across the beach caused by differences in tidal height (the laser does not penetrate the surface of the water) between surveys.
Shoreline change was measured from the monitoring data using the mean high water (MHW) line, which is located 0.36 m above NAVD88 at Onslow Beach (Weber et al., 2005). The MHW line was contoured from the DEMs and exported as a shapefile into ArcGIS. Shoreline change at the decadal time scale was measured using shorelines digitized from aerial photos by the North Carolina Division of Coastal Management (NCDCM) since 1935. Shoreline change at the yearly (monitoring data) and decadal (NCDCM) time scales was measured using the Digital Shoreline Analysis System, an extension in ArcGIS that computes shoreline change by calculating the distance each shoreline is away from a known baseline (Thieler et al., 2009). Rates of shoreline movement were calculated using linear regression.

**Results and Discussion**

The facies concept is used in the description and interpretation of the sedimentological and geophysical data and this descriptive methodology has been in use for almost 200 years (since Gressly, 1838). Readers of this report who are unfamiliar with Geology can find an introductory overview of the facies concept in Boggs (2001) and Reading (2000).

**Nearshore Framework Geology**

A mosaic of the side-scan sonar data set shows that the sea floor is composed of three acoustic facies (i.e., Facies 1 through 3; Figure 11-8), identified on the basis of their backscatter characteristics. Facies 1 is located throughout the nearshore and is characterized by a smooth, uniform low-reflectivity, with localized bedforms, including subaqueous sand dunes and ripples. Where this facies exists in the intertidal and shallow subtidal, it is observed from the beach as sand. Facies 2 is located in the southwest in intertidal and shallow subtidal areas and is characterized by moderate to high backscatter with locally developed shadows as linear features and decimeter-scale spots. Facies 2 is interpreted as outcropping peat which forms terraces in the intertidal and shallow subtidal with exposed tree stumps (Figure 11-8E). Facies 3 is primarily located along the center of the island and is characterized by an acoustically patchy sea floor associated with rugged bathymetric relief. Facies 3 is interpreted as outcropping rock of the Oligocene Silverdale Formation, and clasts of this material are commonly found on the beach in areas where this facies exists offshore (Figure 11-8F).

An acoustically transparent seismic unit, which thins across the shoreface in a seaward direction, was imaged below the sea floor along Onslow Beach (Figure 11-9). At the toe of the shoreface, the unit thickens towards the northeast from approximately 0.5–2.5 m (Figure 11-9). The unit pinches out in areas where peat or rock is exposed at the sea floor and is interpreted as sand. As the island transgressed in response to SLR over the past ~9000 years, erosional processes at the shoreface and the shallow elevation of old rock formations have resulted in a the sand-starved coast line (Riggs et al., 1995).
Figure 11-8. Sea-floor bottom types.

The distribution of acoustic facies along the nearshore of Onslow Beach shows that peat (Facies 2) is exposed at the sea-floor in the southwest (A and C), rock (Facies 3) is exposed at the sea floor in the center of the island (B and D) and sand (Facies 1) is exposed at the seafloor in the northeast. These interpretations are supported with observations made from the beach (E and F).
The thickness of shoreface and inner shelf sand decreases towards the southwest and in an offshore direction at Onslow Beach, NC (A and B).

**Depositional Environments and Lithologic Facies**

The depositional environments along Onslow Beach, including beach (foreshore and backshore), dune, marsh, and washover fan, were sampled in the tops of the 43 vibracores. Lithologic-facies descriptions of these modern environments were used as benchmarks to help interpret the older sedimentary units. Two lithologic facies, A and B, were sampled at depth and were not similar to any of the modern depositional environments that exist across Onslow Beach.

**Beach Facies**

The beach facies is characterized by fine to medium quartz sand (0.91-2.38 Φ; for details on the phi scale for grain size, see Krumbein and Sloss, 1963) with gently dipping heavy-mineral laminae and beds and gravelly sand beds (Figure 11-10A). Swash processes in the foreshore
produce the gently dipping to parallel heavy mineral laminae and beds (Davis, 1978), and the weathered shells and gravelly sand beds are the result of reworking and transport in the high-energy surf zone (Komar, 1976). The average gravel content is 6.75%, but can be as high as 41.72% within those coarse-grained beds, which were predominantly sampled in the foreshore and contain abraded *Mercenaria* sp., *Crassostrea virginica*, and *Oliva sayana* shells and well-rounded oblate lithoclasts. The backshore is predominantly influenced by aeolian processes, which results in finer grained and better sorted sands there than in the foreshore. The shell beds that exist in the backshore were likely emplaced during storms and subsequently winnowed by aeolian processes (Figure 11-10A).

The beach facies ranges in thickness from 32 cm to greater than 204 cm (in places where the core was not long enough to sample the entire thickness). Cores from the southwest end of the island commonly sampled pieces of peat where this facies is thin, corresponding to the seismic and side-scan sonar data that imaged peat at shallow depths. Overall, the thickness of the beach facies decreases, and the percent gravel and the mean grain size of the sand fraction increases towards the southwest and from the toe of the foredune seaward. Rodriguez et al. (2012) also recognized those trends in sediment texture at Onslow Island from surface-sediment samples.

*Dune Facies*

The dune facies is a well-sorted, pale orange (10YR 8/2) fine-grained siliciclastic sand with highly spherical and rounded grains (Figure 11-10B). Sand-sized fragmented shell beds may be present but are generally only a few centimeters thick. These beds were likely emplaced during storm events and represent thin localized washover fans. Plant roots and organic detritus were sampled particularly near the top of the unit where dune grasses are present (Figure 11-10B). Steeplly dipping heavy mineral cross laminae and bedding are common sedimentary structures preserved in the cores (Figure 11-10B) and are typical of coastal dunes (Davis, 1978). The mean grain size of the dune sand decreases slightly towards the northeast from 1.81 Φ at cross-section F1 to 2.30 Φ at cross-section F6. The thickness of this unit ranges from 83 cm to >274 cm and generally increases towards the northeast. Anthropogenically disturbed material was found at the top of three of the cores collected near roads that were constructed on the dunes.
Figure 11-10. Lithofacies of depositional environments on Onslow Beach, NC.
Photographs of vibracores showing beach (A), dune (B), marsh, (C), pre-Holocene (D), and lagoon (E) lithofacies. Notice scale is in cm.

**Marsh Facies**

The marsh facies is an olive gray (5Y 3/2) to brownish gray (5YR 4/1) bioturbated (mixed by burrowing animals) carbonaceous muddy sand (Figure 11-10C). The fine sediment fraction is mainly produced by biogenic pelletization and settlement from suspension (Davis, 1978). Dense mats of *Spartina alterniflora* and *Juncus roemerianus* plant, roots and woody material contribute
to the organic carbon sediment fraction within the marsh facies, which can be as high as 74%. Marsh sediments have a mean grain size of 3.58 Φ and contain a sand component that is transported from the dunes by aeolian processes. The wind-blown sediment has a similar texture as the adjacent dunes and is recognized as discrete sand beds (3–15 cm thick) or is integrated with the organic-rich muddy sediment through heavy bioturbation. Active burrowing from backbarrier species such as fiddler crabs and mud crabs frequently destroy primary sedimentary structures that may be present, resulting in intermixed clay and fine sand (Staub and Cohen, 1979).

Washover Fan Facies

The washover fans that formed at the southwestern end of the island from Hurricanes Fran (September 1996) and Irene (August 2011) were each sampled by four cores in July 2010 (vibracores) and August 2011 (push cores), respectively. Cores were collected along a transect at each fan oriented from the landward edge of the backshore to the distal margin of the fan in the marsh. The proximal fan is closer to the beach and at a higher elevation than the distal fan. Although the cores displayed predominantly fine sand in sharp contact with the underlying marsh sediment, diverse hydraulic conditions and post-storm modifications resulted in lateral heterogeneity within the washover fan.

Proximal washover fan. This unit is pale yellowish brown (10YR 6/2), medium sand that has a fining-upward trend and is dominated by heavy-mineral laminae (Figure 11-11). Core F2wash_3, from the Irene washover fan, sampled this unit in its entirety and shows that the sand grain size increases from 1.87 Φ to 1.03 Φ and that the gravel content increases towards the base (Figure 11-11C). The basal gravelly sand beds are 15-17 cm thick, predominately composed of shell fragments and contain up to 7.18% gravel. Those beds are likely scour-lag deposits emplaced during high-energy conditions in the channel throat or mid-fan area (Leatherman and Williams, 1983). The heavy-mineral laminae were likely deposited as the result of swash and backwash of waves that followed the initial high-energy scouring. This facies is similar to the “stratified sand” and “normal-graded sand” subfacies identified by (Sedgwick and Davis, 2003).

Distal washover fan. This unit is light olive gray (5Y 6/1) to brownish gray (5YR 4/1) medium sand containing abundant sand-sized shell fragments (Figure 11-12). Heavy mineral sand laminae are present throughout causing grain-size measurements, obtained at 2-cm intervals, to alternate between approximately 1.5 and 2.0 Φ. This unit was likely deposited at intertidal to subtidal elevations and has a finer grain size than the proximal washover fan, which is likely due to reworking of backbarrier sediments during the overwash event and/or lower energy distal flow conditions. Sedgwick and Davis (2003) identified this subfacies as a “bioturbated muddy sand” unit. The lack of fine sand laminae or grading within the “bioturbated muddy sand” unit was related to intense bioturbation by backbarrier species (Sedgwick and Davis, 2003) that has yet to occur within the relatively young Irene and Fran fans (Figure 11-12). Over time, rapid marsh colonization may also take place, which would increase the fine sediment content, bioturbation, and organic matter content.
Figure 11-11. Proximal washover fan facies.
Facies examples from the northeastern transect (A), the Hurricane Fran washover fan (B), and the Hurricane Irene washover fan (C) on Onslow Beach, NC.

Figure 11-12. Distal washover fan facies.
Facies examples from the Hurricane Fran washover fan (A) and the Hurricane Irene washover fan (B) along Onslow Beach, NC.
**Facies A (Lagoonal Depositional Environment)**

Facies A was sampled below the previously described four facies in all transects except F2 and F2strike on Onslow Beach. This facies typically thickens seaward and in places is greater than 231-cm thick (some cores were not long enough to sample its entire thickness). The whole shells sampled in this unit were always backbarrier fauna such as stout tagelus (*Tagelus plebeius*), Eastern mudsnail (*Ilyanassa obsolete*), Eastern oyster (*Crassostrea virginica*), and Baltic macoma clam (*Macoma balthica*). Facies A is composed of two lithologically distinct subfacies (i.e., A1 and A2).

**Subfacies A1.** This unit is medium light gray (N6) to olive gray (5Y 4/1) sand with silty laminae and was sampled by 17 cores (Figure 11-10E). The sediment is 97% sand with a mean grain size of 1.77 Ф. Flaser bedding (the clay-sand labeled on Figure 11-10E, Core F6_5) is common in this subfacies. Sand-sized shell fragments are common throughout the unit while gravel-sized shell fragments are only present as individual beds and can be up to 10-cm thick. These gravel beds are uncommon and were only found in three cores.

Based on the macrofauna and the flaser and gravel beds interpreted as tidal-bedding structures and tidal-channel lag deposits, respectively, this subfacies is interpreted as a marginal lagoon environment. The high sand fraction indicates bed-load transport by tidal currents and waves that can dominate the tidal flat zone (Davis, 1978). Sections of mud interbedded with sand are common within this subfacies and denote alternating bedload and suspension transport and deposition on the sand flats. Shell lag deposits imply scouring that is typically associated with tidal channels or storm deposits (Davis, 1978). This facies is currently being deposited adjacent to the barrier island in Bogue Sound, a shallow lagoon located approximately 40 km northeast of Onslow Beach (Timmons et al., 2010).

**Subfacies A2.** This unit is a light gray (N7) to grayish black (N2) mud with abundant articulated shells and sand burrows (Figure 11-10E, Core F3_3, bottom). Subfacies A2 has a greater mud fraction (61% mud) and is finer grained (mean grain size of 4.0 Ф) than A1. Lenticular (lens-shaped) sand beds up to 5-cm thick are occasionally present.

The high mud content, excellent preservation of estuarine fauna, and bioturbation indicates a low-energy, central lagoon environment. Molluscs commonly colonize in reefs within low-energy areas and an oyster reef was sampled in Core F1_5. Silt and fine sands accumulate from suspension while periodic high-energy tidal processes and/or storm events may deposit coarser-grained sand lenses (Davis, 1978). Sedimentary bedding is often disturbed in the central lagoon due to extensive bioturbation and reworking, resulting in a homogenous sandy mud (Reading, 2000). A silty clay unit with abundant *C. virginica*, similar to subfacies A2, was also sampled at the bottom of central Bogue Sound (Timmons et al., 2010).

**Facies B (pre Holocene fluvial)**

Facies B was sampled at the base of 14 cores and displays a wide range of textural characteristics that are distinct from those observed in the two lagoonal subfacies or in the modern depositional units. The cores did not penetrate the entire unit and facies B sediments were sampled at variable depths that generally decrease landward and towards the southwestern end of the island. This
facies is primarily composed of a massive moderate yellowish brown (10 YR 5/4) sand (Figure 11-10D) and is easily distinguished from beach facies by its distinct color, finer-grained texture (mean grain size of 2.19 Φ versus 1.75 Φ for the beach facies), and poorer sorting, which is caused by a minor silt component. Thin beds of well-rounded quartz pebbles within greenish gray (5 G 6/1) to medium gray (N5) or moderate brown (5 YR 3/4) sand were sampled underlying the massive yellowish brown fine sand. These beds could represent scour lag deposits of river channels when sea level was lower. Stiff light gray (N7) clay with yellow mottling is also indicative of oxidation and subaerial exposure. Sedimentary structures and organic material were absent within this basal unit. Although no material from Facies B was appropriate for radiocarbon dating, the homogenous, indurated, and oxidized nature of the upper part of the facies suggests subaerial exposure and the unit is interpreted to be pre Holocene (greater than 10,000 years) in age.

**Stratigraphy**

The stratigraphic cross-sections through Onslow Beach show a typical transgressive facies succession (Figure 11-13). The contact between the basal pre-Holocene unit (Facies B) and the overlying lagoonal mud (Facies A) is sharp and shows evidence of subaerial exposure and pedogenesis indicating that it is associated with a significant hiatus. This unconformity was sampled at variable depths and generally slopes seaward with high relief in the along-beach direction. It is interpreted to have formed during the last glacial maximum when sea level was approximately −120 m. The elevation of the sequence boundary strongly controls the thickness of overlaying Holocene coastal deposits (e.g., modern depositional facies). The sequence boundary is shallow (greater than 0 m NAVD88) in the middle of transect F2 where pre-Holocene strata outcrops in the foreshore but further to the southwest and northeast, the sequence boundary is at deeper elevations and overlain by thick (greater than 5 m) coastal deposits.

At transects F2strike, F2, and Pier, carbonaceous sand to sandy mud (20–90 cm thick) overlies the sequence boundary at depths shallower than approximately −1.50 m NAVD88 (Figure 11-13). That unit is interpreted as fringing marsh and/or maritime forest based on its similar lithology to the modern marsh facies sampled in transects F1BB and F6BB, the presence of wood, and its superposition above the upland pre-Holocene unit. It represents the leading edge of the Holocene marine incursion. Roots extend into the pre-Holocene strata and radiocarbon dates of wood found at the bottom and top of this marsh/maritime forest in the Pier transect are 3556–3728 cal years BP and 2156–2268 cal years BP, respectively (Table 11-1).

Where the sequence boundary is at a depth greater than −1.25 m NAVD88, it is overlain by lagoonal sands and mud. The sequence boundary is at a depth deeper than the cores reached in cross-sections F3 and F6 (Figure 11-13). The lagoonal unit is wedge-shaped and pinches out landward towards the modern backbarrier marsh, which is dictated by the paleotopography of the seaward-dipping sequence boundary. In addition to sea level changes, accommodation controlled by the antecedent topography (the sequence boundary) plays a large role in the timing of flooding along the island and the type of environment that is deposited above the sequence boundary.
Cross-sections from the backbarrier marsh to the beach show along-beach variations in facies architecture on Onslow Beach, NC. Notice the large number of washover fans preserved in the stratigraphy (for more information, see Figure 11-6 and Appendix 11-A).
A natural lagoon does not exist behind Onslow Beach today because of the relatively steep topographic relief on the sequence boundary. At transect F2 and at the landward margin of the Pier transect, the pre-existing topographic highs prevented inundation during Holocene SLR, which resulted in the absence of a lagoon facies and only the presence of a thin fringing marsh and/or maritime forest facies preserved in the subsurface. Overall, the sequence boundary deepens towards the northeastern end of the island which increases local accommodation and permits thick lagoon sediments to accumulate and be preserved beneath the beach facies. Transects F1, F4, F5, and F6 show a sharp contact between pre-Holocene and lagoonal strata indicating that any fringing marsh and/or maritime forest that may have existed, was likely eroded away by bay-ravinement processes (waves and tidal currents). Lagoonal facies thicknesses of 224 cm or greater are common for the northern core transects (F5 and F6), but is also observed at F3, where there is a paleotopographic low (Figure 11-13). The high accommodation at transect F3 could be due to a low stand fluvial channel intersecting the island, which is imaged in seismic data offshore in that area and along adjacent barriers like Bogue Banks to the north (Timmons et al., 2010) and Wrightsville Beach to the south (Thieler et al., 2001).

Radiocarbon dating from the basal Holocene coastal deposits suggests a lagoon formed earlier in the southwest than the northeast part of the barrier system. An *M. constricta* valve, which is a common open-bay species (Andrews, 1981), sampled at the base of the lagoon facies at F1 was dated as 885–1003 cal yr BP. A date obtained from the middle of the lagoon at transect F5 was 902–931 cal yr BP and suggests a deep lagoon was already present at F5 when shallow-water sedimentation initiated at F1. Radiocarbon dates from the middle of the lagoon unit at F6 are 525–641 cal yr BP indicating that a lagoon existed landward of the barrier until at least approximately 600 years ago. Radiocarbon ages from the lagoon facies all fall below the estimated relative sea level for those time periods within error margins (Kemp et al., 2009).

Above the lagoon unit, a discontinuous organic-rich clay and peat unit, interpreted as a backbarrier marsh, was sampled. This marsh correlates with the present-day backbarrier marsh sampled at the landward margin of the transects. Due to compaction and decaying organic matter following burial, marsh sediments are preserved in the subsurface as dusky brown (5 YR 2/2) to black (N1) stiff carbonaceous mud with fine-grained organic matter. The marsh unit is absent where lagoonal sediments are directly overlain by the extensive washover fan at F1 and the aeolian dune at F6 and the unit was likely exhumed at those locations by storm and/or tidal ravinement processes. In addition, the marsh unit is missing at F5 and F4 where anthropogenic activities associated with road construction likely removed it.

Sharp-based fine sand beds ranging from 12–80 cm thick that pinch out in a landward direction are intercalated with the marsh unit at the seaward and middle parts of the transects. Based on textural and compositional similarities between these beds and the modern washover facies, the beds are interpreted to be the distal portions of relict washover fans; however, they have experienced some post-depositional modifications. These paleo-washover fans have a mean grain size 2.17 Φ and have greater mud content (approximately 6%) than modern fans. Based on the fine-grained texture of these beds and association with salt marsh sediment they were likely emplaced in the intertidal zone and are interpreted as distal washover fan deposits. These sand beds were re-colonized by marsh vegetation, which was preserved as an overlaying carbonaceous mud bed. Heavily bioturbated sediments dominate the upper portion of the
washover deposit resulting in a mixed sediment of fine sand and organics which increases in organic carbon content from 3% 10-cm below the marsh unit to 20% at the contact in the marsh unit. Primary sedimentary structures, like the heavy mineral laminae observed in the distal portion of the modern Irene fan are rarely preserved in ancient distal washover units due to intensive bioturbation (Sedgwick and Davis, 2003).

The dune facies thickens towards the northeast from 83 cm at F2 to greater than 700 cm at F6 and overlies the backbarrier and lagoon sediments. Sharp-based medium-grained sand beds were sampled across 3 cores in the F1 transect overlying the Hurricane Fran washover fan and two cores behind the high-elevation dunes in the transect at F6. These beds have a mean grain size of 1.57Φ and become more fine-grained upward, with lower portions (5- to 10-cm thick) that contain up to 6.39% gravel and upper portions with heavy-mineral laminae and beds (Figure 11-8). Based on their similarity to modern washover facies, these beds are interpreted as proximal washover deposits that have experienced some post-depositional modification. Reworking by aeolian processes following deposition likely removed some upper heavy-mineral laminae and also transported dune sand that overlays those washover beds (Figure 11-8). At F1, the two washover beds merge at the distal end of the fan. At F6 the beds could not be traces laterally because they were only sampled with single cores. Washover fans are absent in cores collected from the modern backbarrier marsh. The leading edge of the shoreface ravinement surface located seaward of the dune is defined by the erosional truncation of the older units that extend beneath the beach and are exposed and eroding in the surf zone.

**Timing of Washover Fan Emplacement**

In addition to overwash, tidal currents, and aeolian processes are other major mechanisms for transporting sand to the backbarrier environment during transgression, but the sand layers sampled in the marsh preserved below the island are not interpreted as such. These sand beds could not have been generated within a flood-tidal delta due to the absence of deep scours and channels filled with gravel, representative of past inlets, as found along other barrier islands (Heron et al., 1984; Mallinson et al., 2011). Wind-blown sand beds, which were sampled below the present marsh surface, are distinguishable from washover sediments due to their finer grain size, massive bedding and overall thinness (less than 12 cm). Thus the sand beds preserved within the ancient marsh deposit beneath the island could only have been generated by episodic overwash sand deposition in a previous backbarrier marsh environment located seaward of the present-day backbarrier marsh. This microtidal, wave-dominated barrier island system migrated landward mainly by overwash processes.

Nine distinct distal washover fans were identified along the island (Appendix 11-A). Marsh sediments above and below the washover units were radiocarbon dated to determine the timing of overwash events. The age of the marsh below the fan is assumed to better constrain the timing of overwash than the age of marsh above the fan because of the possible long time lag between washover fan deposition and peat formation. The ages of the washover fans are all maximum ages. Along the Pier transect at the seaward margin of the island, marsh sediments above and below the washover fan are 644–724 and 1715–1833 cal yr BP, respectively. The two shoreward cores in the adjacent transect, F3, sampled a thick landward-thinning washover fan with its basal contact at a similar elevation as the washover fan sampled at the Pier transect, which suggests deposition during the same event, or close to the same time.
Ages of the marsh sediments below and above the washover fan sampled in Core F4_4 were 1293–1376 and 505–559 cal yr BP, respectively, and the washover fan sampled in Core F2strike_4 were 560–598 and 280–318 cal years BP, respectively (Table 11-1). At the seaward margin of F1, two distinct washover fans were sampled in the same core. The base of the lower washover fan is at a similar elevation as the base of the washover fan sampled in transect F5 and the base of the marsh unit sampled in transect F2, which are both within the 53–145 cal yr BP time frame (Table 11-1). It is assumed that the lower washover fan in transect F1 was also emplaced at that time. The age of the top washover fan in transect F1 was constrained from plant material in the underlying marsh layer, which was deposited within the past 77 years (post-bomb radiocarbon age). Washover fans were also sampled towards the middle of the island at transects F5, Pier, and F2. Our $^{14}$C data of the marsh sediments directly underlying the fans sampled in Cores Pier_5 and F5_5 show that they were deposited by storm events within the nineteenth century. The washover fan sampled in Core F2_7 was likely deposited in the twentieth century based on a radiocarbon date of 55–145 cal yr BP from wood sampled at the base of the marsh and maritime forest unit sampled in Core F2_5 that is approximately 50 cm below the base of the washover fan.

**Shoreline Movement at Decadal to Yearly Time Scales**

At the decadal time scale (1935–2004), the southwestern part of Onslow beach has the highest shoreline retreat rates and these rates decrease towards the northeast where the beach is accreting (Figure 11-14). Although the rates of shoreline retreat at the decadal scale correspond overall with the measured annual rates (2007–2011), there are some differences. At the annual time scale, the central Onslow beach shoreline (military training zone) has the highest shoreline retreat rates (2–6 m of landward movement/year), but that area experienced much lower rates of shoreline retreat at the decadal time scale. Seaward movement (accretion) of the shoreline at yearly time scales in the southeast contrasts with the decadal record that shows high rates of erosion (2-4 m/yr; Figure 11-14).

**Along-shore variability in rates of shoreline movement**

*Shoreline movement at millennial-centennial time scales*

The internal facies architecture of Onslow Beach (Figure 11-13) varies along its 12-km length, similar to its geomorphology (Figure 11-8), suggesting that its landward retreat history was not uniform along the island. Deposition at the southwestern end of Onslow Beach was influenced by a pre-Holocene topographic high that correlates with the submarine limestone headland exposed on the inner shelf (shown on Figure 11-8). The Holocene record at this portion of the island is generally thin due to low accommodation, except at F3 in which a more complete sedimentary record is preserved in a paleochannel (Figure 11-10, Appendix 11-A). Basal lagoon sediments at the southwestern end of the island at transect F1 were deposited at the same time (~1000 cal yr BP) as sediment at the northeastern end of the island sampled in transect F5 from the middle of the lagoon facies. This indicates that the initial flooding of the southwestern end of the island occurred as the lagoon was already well established on the northeastern end.
Figure 11-14. Decadal and annual rates of shoreline movement along the various zones on Onslow Beach, NC.
In addition, marsh sediment that was radiocarbon dated as 1292–1376 cal yr BP and 1715–1832 cal yr BP was sampled above the lagoon facies in transects F4 and Pier, respectively, indicating that a lagoon existed at the northern part of the study area for greater than 1,000 years before the southern area of Onslow Beach was inundated. The variable timing of backbarrier lagoon emplacement along the island is a consequence of the greater accommodation (lower elevation pre Holocene surface) at the northern end of the region. Variations may also be due to the variable preservation of lagoon deposits along the island, which is related to rates of island transgression. The lagoonal deposits being younger in the south than the north could be due to the rates of shoreline transgression being higher in the south than the north over 1,000 years ago. Higher rates of transgression in the south would have eroded those older lagoon deposits situated in an offshore location. Alongshore variability in shoreline migration rates may be linked to local offshore sand sources at the northeastern end of the island, but the lack of preservation of paleo ocean-shoreline indicators limits our ability to quantify shoreline-retreat rates at long time scales (millennial).

The oldest washover fan was emplaced approximately 1,800 cal yr BP at Onslow Beach, indicating the island was close to its present position at that time and was separated from the mainland by an open-water lagoon. Onslow Beach exhibited landward retreat via recurring overwash events along the entire length of the island during the late Holocene. More regionally, the overwash-dominated barrier islands of southwestern Onslow Bay that comprise the high-energy flank of the Cape Fear foreland (east facing; Cleary and Hosier, 1979) have a similar transgressive history as Onslow Beach. Radiocarbon ages of peat sampled beneath Masonboro Island, southwest of Onslow Beach, are 902–1066 and 545–797 cal yr BP. These ages are similar to the dates from the peat underlying Onslow Beach revealing a rapid transgressive history of Masonboro Island. The inner shelf of southwestern Onslow Bay is sediment-starved and dominated by rock outcrops (Thieler et al., 2001), similar to the southwestern end of Onslow Beach.

Onslow Beach and Masonboro Island reached their present positions within the past approximately 1,000 years and are considerably younger than the barriers in northeast Onslow Bay. The barrier islands on the lower energy limb south of Cape Lookout such as Bogue Banks, have a history of progradation as evidenced by a higher, wider profile with multiple beach ridges which are younger in a seaward direction (Cleary and Hosier, 1979; Heron et al., 1984; Timmons et al., 2010). The oldest beach ridge on Bogue Banks formed approximately 3,300 years ago, and lagoon sediments sampled in the center of Bogue Sound are approximately 5,500 cal yr BP. During the Holocene, the northeastern barriers along Onslow Bay retreated at a slower rate, a shorter distance and reached their current positions approximately 1,300 years before the central-southeastern barriers, including Onslow Beach. The young radiocarbon ages and resultant rapid retreat rates in central Onslow Bay, from our stratigraphic data, supports the Ashton et al. (2001) prediction that the highest shoreline retreat rates should occur in the central embayment areas between capes at centennial to millennial time scales.

Shoreline Movement at Decadal to Yearly Time Scales

The geologic record (based on the vibracores) suggests that the southwestern part of Onslow Island moved landward more rapidly than the northeastern part of the island over the past 1,000–2,000 years, which generally corresponds to the pattern of shoreline movement along Onslow
Beach at the decadal and yearly time scales. Along-beach variations in shoreline-change rates at sub-centennial time scales are principally controlled by variations in the underlying framework geology. A rock ridge intersecting the shore where military training occurs forms a headland resulting in a steeper beachface there than in the adjacent embayments. The military training zone has the highest annual shoreline retreat rates (2–6 m of landward movement per year), but high shoreline change rates existed prior to Base operations (pre-1940s) and are likely related to the sediment supply and storage of this island compartment being low, as evidenced by the thin sand veneer that exists at the beach and nearshore above older less erosive sedimentary units. The region of highest decadal shoreline retreat extends southwest of the training zone and the geological record shows that this erosional hotspot existed long before the Base was established. The shoreline in the recreational zone where foot traffic is the main anthropogenic impact is moving seaward (accretion) at less than 1 to 4 m/yr (Figure 11-14). Unlike the military training zone, this northeastern third of the island shows high variability in the direction and magnitude of shoreline movement at annual and decadal time scales, but overall displays long-term accretion. The southwestern third of Onslow Beach, conversely, has exhibited sustained landward migration (beach erosion) over both short and long time periods (Figure 11-14).

Impacts of Changes in Storminess and the Rate of SLR on Island Evolution

Storms have played an important role in the evolution of Onslow Beach over at least the past approximately 1,800 years. Island overwash principally occurs during storms and deposits a washover fan. The landward extent of the washover fan is dependent upon the size of the storm and the morphology of the island. Generally, larger storms produce larger washover fans and low-elevation barriers are more vulnerable to overwash than high-elevation barriers. The landward pinch out of the relict and modern washover fans that impacted the backbarrier marsh at Onslow Beach was measured against a baseline, which is the best-fit linear regression through the 2006 shoreline, digitized from a rectified aerial photograph (Figure 11-15). Older washover fans are positioned closer to the baseline than younger washover fans, which correspond with the open-ocean and backbarrier shorelines continually moving landward throughout the late Holocene. All of the paleo-washover fans addressed here impacted the backbarrier marsh and became colonized with new marsh suggesting that emplacement was the result of large events like recent hurricanes Fran and Irene. Smaller events can overwash the island, but typically only impact the dune or older washover fans as sampled in the dune and washover facies in transects F6 and F1, respectively (Appendix 11-A). Those smaller washover fans are not included in Figure 11-15 because those events did not displace the backbarrier shoreline landward. Although the morphology of the barrier varies significantly from the southwest to the northeast today, paleo-washover fans were sampled along the entire island, even from areas where the modern dunes are high and continuous (transect F5), supporting the fact that tall dunes can accrete or erode over sub-millennial time scales.

At millennial time scales, SLR is another important factor that determines the landward extent of washover fans. If sea level rose at a constant rate during the late Holocene, all else being equal (island morphology, storminess and preservation), then a plot of the landward pinch out of washover fans through time would also be linear and would match the rate of island transgression. Figure 11-15 shows that the landward pinch-out distance of washover fans increases sharply at around 1850 A.D. More washover fans that moved the backbarrier shoreline landward formed along Onslow Beach over the past approximately 150 years (seven washover
fans) than the preceding approximately 1650 years (four washover fans) and the more recent fans extend two to four times farther landward than the older fans (Figure 11-15). This trend could be explained by an increase in storminess or acceleration in the rate of SLR.

The earliest washover fans preserved in our sedimentary record were emplaced approximately 200 A.D. (transects F3 and Pier; Appendix 11-A) indicating that the island was near its current position at that time. Four washover fans were sampled that formed between 200 A.D. and 1375 A.D. and indicate that the island was likely migrating landward at a relatively slow rate because the landward extent of those fans did not increase more than 60 m over that 1175-year time period. Correspondingly, sea level was rising at a very low rate at that time (1–1.4 mm/yr; Kemp et al., 2011). The MWP (approximately 800–1300 A.D.) was a time of increased tropical storm landfall along the U.S. Atlantic Coast (Mann et al., 2009) that resulted in increased erosion along the lagoon side of Bogue Banks, NC (Timmons et al., 2010) and island “collapse” and inlet formation along the northern Outer Banks (Culver et al., 2007; Mallinson et al., 2011). No evidence exists along Onslow Beach for increased erosion or washover fan formation during that time period; however, it is possible that washover fans were emplaced between our sampling sites during the MWP.

Figure 11-15. Record of washover fans along Onslow Beach, NC.
The number and landward extent of washover fans increases sharply along the island at approximately 1850 A.D. The width of the blue line indicates the uncertainty in the age of the paleo washover fan.
The Slott et al. (2006) numerical model simulation of the cumulative effects of increased tropical and extra-tropical storms predicts that cuspate bays will erode at increased rates while the cape tips will accrete at centennial time scales. In response to the increase in storminess during the MWP at Onslow Beach, neither the number of washover fans nor the rate of island transgression increased; however, we cannot discount that some washover fans from that time period were not preserved and/or sampled along the island. Bogue Banks, located on the southern flank of Cape Lookout, experienced rapid erosion of the backbarrier shoreline during the MWP that caused the island to narrow at its center (Timmons et al., 2010); however, it is unclear if the ocean shoreline experienced accretion as predicted by the numerical model. An obvious increase in shoreline transgression at Onslow Beach and regression at Bogue Banks was not associated with the increase in storminess during the MWP as predicted by the Slott et al. (2006) model.

Possible discrepancies between model predictions and coastal impacts from increased storminess during the MWP along Onslow Bay could lie in the model assumptions that wave-driven alongshore forcing is the dominant mechanism for sediment transport and the sea floor is composed of unconsolidated sand. In the barrier-lagoon complexes that dominate the North Carolina coast, the significant role of cross-shore sediment transport is evident in the abundant relict washover fans and tidal inlets that this study and many others have mapped (Mallinson et al., 2011; Moslow and Heron, 1978. Overwash and inlet processes are two primary mechanisms that control island widening and the removal of sediment from the active littoral zone and deposition into the backbarrier environment. These processes were not factored into the Slott et al. (2006) model and are driven by rising sea level and storms. During periods of increased storm activity, sediment lost from the active system cannot be delivered to the cuspate foreland region in its entirety. In addition, the entire shoreface is not composed of unconsolidated sandy sediment and the inherited geologic framework, in part controls sediment supply and accommodation in Onslow Bay due to the shallow limestone rock outcrops on the shelf near Onslow Beach and sandy paleochannels offshore of Bogue Banks (Timmons et al., 2010).

The past approximately 150 years, when the number and landward extent of washover fans increased along Onslow Beach does fall within the Little Ice Age (approximately 1400 A.D.–1900 A.D.), a time when tropical storm activity was at a low (Mann et al., 2009; Figure 11-15), but nor’easters along the US Atlantic coast may have been more intense (Mallinson et al., 2011). Intense nor’easters during the Little Ice Age are thought to have caused the formation of large inlet complexes along the northern Outer Banks but most of those inlets formed around 1400 A.D.–1700 AD., at least 150 years earlier than the washover fans preserved along Onslow Beach. In addition, Onslow Beach is southeast facing and thought to be impacted less from nor’easters than the Outer Banks north of Cape Hatteras, which are east-northeast facing (Mallinson et al., 2011). It is unlikely that more intense nor’easters played a role in the increased number and landward extent of washover fans emplaced along Onslow Beach over the past approximately 150 years than the previous 1,700 years.

The rate of relative SLR increased at 1865–1892 A.D. from 1 mm/yr to 3.2 mm/yr (Kemp et al., 2011), the same time as the number and landward extent of washover fans increased along Onslow Beach. This sharp increase in the rate of SLR likely had an immediate effect on the vulnerability of Onslow Beach to overwash. Higher sea level causes increased dune erosion lowering the elevation of an island and increasing its potential to overwash. Because overwash is the mechanism for island transgression, the rate that the open-ocean and backbarrier shorelines
were moving landward also increased approximately 1850 A.D. This increased rate of island transgression also decreased the preservation of older washover fans, including those that may have been associated with the MWP, especially along the southwest part of the island where shoreline retreat rates were most rapid.

Conclusions and Implications for Future Research

Onslow Beach is a transgressive barrier island that moved landward during the late Holocene principally through overwash processes and washover fan formation. The oldest washover fan deposits preserved in the stratigraphy of the island are approximately 200 A.D. indicating that the island has been close to its present position since that time. Around 200 A.D. an open-water lagoon separated Onslow Beach from the mainland, as opposed to marshes and tidal channels that have characterized the backbarrier landscape since at least 1850 A.D. Assuming that the oldest washover fans were similar in size to the largest modern washover fan, which was emplaced during Hurricane Fran, then the coeval ocean shoreline would be located approximately 300 m seaward of its present location at approximately 200 A.D. Because the landward extent of washover fans was fairly constant 200 A.D.–1850 A.D., the rate of island transgression was also likely low during that period (0.2 m/yr), which corresponds to the low rates of SLR that the North Carolina coastline was experiencing (1–1.4 mm/yr; Kemp et al., 2011).

At around 1850 AD, the number and landward extent of washover fans increased sharply along the entire island. This corresponds to an increase in the rate of SLR to 3.2 mm/yr and a low number of annual tropical cyclones in the Atlantic (Kemp et al., 2011; Mann et al., 2009). The increase in number and landward extent of washover fans at 1850 A.D. also implies that the rate of island transgression increased. The increase in the rate of SLR likely lowered the elevation of the island principally through erosion of the dunes, and made the island more vulnerable to overwash. These data suggest that Onslow Beach is extremely sensitive to increases in the rate of SLR, which cause an immediate decrease in the elevation of the island and its resistance to overwash. This sensitivity is likely the result of the island being sediment starved, a product of its framework geology (limestone outcropping near the shoreface) and its location at the center of a coastal embayment (Ashton et al., 2001).

Given that the rate of SLR is predicted to increase in the next 100 years, it is appropriate to use our data across the most recent increase in the rate of SLR at 1850 A.D. as an analog to future changes. Our recommendation is that the Base needs to plan for an increase in the frequency and magnitude of overwash events, regardless of future changes in storminess, which will occur as higher sea levels increase dune erosion and lower the elevation of the island making it more vulnerable to overwash. Currently, the island is most vulnerable to overwash in the southwest where elevation is lowest, annual erosion rates are high, sediment supply is low, and accommodation is low. Differences between the northeastern and southwestern parts of the island are principally due to the high elevation of pre-Holocene rock and sediment that is erosion resistant in the southwest. The distance between the ocean and the ICW is also smallest in the southwest, indicating the waterway may be impacted by overwash in the near future (see results of Research Project CB-1). Given the high rates of landward shoreline movement at the center of the island and the narrow dunes, soon (1–20 years) the island will overwash there again, as it did in approximately 1850 A.D. We recommend that if MCBCL has plans to build additional
permanent structures or modify existing structures located on the dunes, they recognize that the vulnerability of these sites to inundation will increase in the near future (within the next 10–20 years). Depending on the construction project, it might be more prudent to place additional infrastructure further landward than the existing bathhouses and cottages are located today. In addition, the Base should plan to increase expenditure for post-storm clean up on the island.

Military training activities have little impact on island evolution because the decadal record of shoreline movement and the geological record of island evolution show that the military training zone has been vulnerable to overwash and experienced high rates of shoreline retreat since at least 1850 A.D., long before MCBCL existed. High rates of shoreline retreat at the military training zone (the “erosional hot spot”) is due to the low sediment supply there as compared to the northeastern part of the island where nearshore sand thicknesses are greater. The limestone outcrops located seaward of the military training zone are not producing enough new sediment through bioerosion to compensate for the erosion there. Yearly rates of shoreline retreat at the military training zone, based on November 2007–September 2011 measurements and the resulting model (Figure 11-14), are up to four times higher than the decadal rates. The magnitude of the difference between the yearly and decadal retreat rates is too large to be explained by error differences between the methods (aerial photography for the decadal record and terrestrial laser scanning for the yearly record). The increase is also difficult to explain because the time period 2007–2011 was not stormier than previous time periods and island management did not change. However, there was an anomalous increase in water level in 2009 when sea level was approximately 20 cm higher than predicted (Sweet and Zervas, 2011; Sweet et al., 2009). Future work needs to focus on that event because if that brief sea level anomaly is the cause for the high rates of shoreline retreat recorded between 2007 and 2011, then the island could be even more sensitive to SLR than the geological record indicates.
Literature Cited


Scott, D.B., E.S. Collins, P.T. Gayes, and E. Wright. 2003. Records of prehistoric hurricanes on the South Carolina coast based on micropaleontological and sedimentological evidence,


Appendix 11-A

Onslow Beach Cross Sections
Cross-section F2

Cross-section F2wash
Cross-section Pier

<table>
<thead>
<tr>
<th>DEPTH</th>
<th>MATERIAL DATED</th>
<th>AGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Pier_5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Wood</td>
<td>55-140</td>
</tr>
<tr>
<td>2</td>
<td>Wood</td>
<td>55-145</td>
</tr>
<tr>
<td>3</td>
<td>Wood</td>
<td>2156-2268</td>
</tr>
<tr>
<td>4</td>
<td>Wood</td>
<td>3556-3728</td>
</tr>
<tr>
<td>Core Pier_1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Wood/Plant</td>
<td>644-724</td>
</tr>
<tr>
<td>6</td>
<td>Wood/Plant</td>
<td>1715-1832</td>
</tr>
</tbody>
</table>

Shoreface Ravinement
Surface
Sequence Boundary
Cross-section F4

- Dune
- Anthropogenically Disturbed
- Washover
- Marsh
- Lagoon
- Pre-Holocene

Elevation (m, NAVD88)

ICW

MSL

505-559 cal BP

1293-1376 cal BP

meters

100
Cross-section F5

<table>
<thead>
<tr>
<th>DEPTH</th>
<th>MATERIAL DATED</th>
<th>AGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>218-220 cm</td>
<td>Wood</td>
<td>53-138</td>
</tr>
<tr>
<td>258-260 cm</td>
<td>Wood</td>
<td>583-649</td>
</tr>
<tr>
<td>322-324 cm</td>
<td>Wood</td>
<td>902-931</td>
</tr>
</tbody>
</table>
Cross-section F6
Cross-section F6BB
List of Scientific Publications

Papers


Thesis

Theuerkauf, E.J. 2012. Evaluating proxies of subaerial beach volume change using terrestrial LiDAR data from Onslow Beach, NC, USA. Department of Marine Sciences, University of North Carolina at Chapel Hill, Chapel Hill, NC.

Yu, W. In preparation, expected in 2012. Impacts of storms and sea-level rise on coastal evolution between two capes: Onslow Bay, NC, USA. Department of Marine Sciences, University of North Carolina at Chapel Hill, Chapel Hill, NC.

Presentations


America, Gulf Coast Association of Geological Societies with the Gulf Coast Section of the Society for Sedimentary Geology, Houston, TX. October 5–9. 40(6).
Appendix 11-C

List of Students

- Ethan Theuerkauf, M.S., University of North Carolina at Chapel Hill, Chapel Hill, NC. Graduated May 2012.
- Winnie Yu, M.S., University of North Carolina at Chapel Hill, Chapel Hill, NC. Expected graduation in December 2012.