Genetic stratigraphy and geochronology of last interglacial shorelines on the central coast of South Carolina

Russell Willis
Louisiana State University and Agricultural and Mechanical College

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GENETIC STRATIGRAPHY AND GEOCHRONOLOGY
OF LAST INTERGLACIAL SHORELINES
ON THE CENTRAL COAST OF SOUTH CAROLINA

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

In

The Department of Geology and Geophysics

by
Russell Austin Willis
B.S., College of Charleston, 2002
May 2006
ACKNOWLEDGEMENTS

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ABSTRACT

This study investigated the shallow subsurface of the Lower Coastal Plain of South Carolina in order to determine the sea-level history and stratigraphic architecture preserved within several emergent shoreline complexes. The absolute age of each shoreline complex was estimated using single-aliquot regenerative-dose (SAR) optically stimulated luminescence (OSL) techniques. The resulting geochronology was incorporated into a high-resolution stratigraphic framework defined by ground penetrating radar calibrated with deep sediment cores, many of which contain a complete sequence of highstand deposition. Three emergent barrier complexes were identified within the Lower Talbot, Pamlico, and Princess Anne terraces, and assigned to sea-level highstands during interglacial periods between 240 to 80 ka, which correspond to marine isotope stages (MIS) 7, 5e, and 5a. The stratigraphic architecture of each shoreline complex consists of a distinct succession of lithofacies deposited in lagoonal, shoreface, and eolian environments typical in a siliciclastic shoreline setting. Relict shoreface facies contain swash zone strata that precisely document the peak elevations attained by specific relative sea-level highstands. First, a transgression during MIS 7 (230 ka) emplaced swash zone strata at 12 ±1 meters above present day sea-level (mASL). This was followed by two separate transgressions during MIS 5e (140 to 125 ka) that attained elevations of 9 and 6 ±1 mASL, respectively. Finally, a MIS 5a (80 ka) highstand peaked at 5 ±1 mASL. The present day elevations of the MIS 7 and MIS 5e highstand deposits can be explained with a consistent uplift rate of ~5 cm/kyrs. However, the elevation of MIS 5a deposits conflicts with most global estimates of this highstand. This implies the MIS 5a highstand was actually closer to present day sea-level, in a global sense, or that complex glacio-hydro-isostatic effects have played a major role through multiple glacial-interglacial cycles in this region.
CHAPTER 1
INTRODUCTION

Oxygen isotopic ratios of foraminiferal calcite from ocean sediments have been used as a proxy for global ice volume and sea-level, and for subdivision of the Pleistocene into glacial vs. interglacial stages (Shackleton et al., 1973; Imbrie et al., 1984). The most recent warm-climate interglacial period, prior to the Holocene interglacial, corresponds with marine isotope stage 5 (MIS 5). Short term highstands ($10^4$ – $10^3$ yr) of sea-level within MIS 5 have also been identified by oxygen isotope studies. One such highstand, MIS 5e (ca. 125 ka), is widely agreed to represent the Last Interglacial maximum (LIGM) when global ice volumes were at a minimum and global sea-level positions were marginally higher than present (Kukla, 1997; 2000). It is also agreed that the more recent MIS 5c (ca. 105 ka) and 5a (ca. 84 ka) highstands represent relatively high sea-level positions, but controversy surrounds their magnitude, both in the global sense and with respect to specific regions (Muhs et al., 2002a; b; 2004).

The South Carolina coast is one region where this controversy exists, as efforts to correlate emergent shorelines to specific highstands have proven problematic due to poor stratigraphic and geochronological control (Szabo, 1985; Wehmiller et al., 1988). This thesis examines a succession of Late Pleistocene clastic shorelines on a portion of the central South Carolina coast, between Charleston and the Santee River (Figure 1). This study documents the sand-body geometry and stratigraphic architecture of several emergent shoreline complexes using cores and ground-penetrating radar data, and utilizes a geochronological framework developed with optically stimulated luminescence dating. This information allowed the correlation of these deposits with specific sea-level highstands as predicted by marine isotope records.
Figure 1. Map of the study area between Charleston, SC and the Santee River. Terraces and bounding scarps are as mapped by Cameron et al. (1984) and Colquhoun (1974; 1991).
1.1 Global Sea-level Estimates

The most widely accepted records of Last Interglacial sea-level positions come from the uplifted coral terraces of Huon Peninsula, Papua New Guinea (e.g. Chappell, 1974; Chappell et al., 1996, Figure 2). The uplift of this region is a consequence of its compressional tectonic setting along the Australian/Pacific plate boundary. The terraces were dated with U-series methods and sea-levels were estimated using three key assumptions: (a) reefs associated with MIS 5e formed at the widely accepted sea-level elevation of +5-6 m, (b) departure from that elevation is due to tectonic uplift, and (c) formative positions for terraces associated with other substages could be calculated using the uplift rates derived from MIS 5e terraces (Chappell, 1974). Chappell and Shackleton (1986) and Shackleton (1987) correlated these sea-level records with those inferred from marine isotope curves and found significant discrepancies between the two for MIS 4-3. These inconsistencies were later reconciled by Chappell et al. (1996), who redated and resurveyed reefs associated with MIS 4-3. Their revised records indicate that MIS 5e was the only time during MIS 5 in which global sea-level was near present day and that sea-level positions during MIS 5c and 5a sea-levels were 20 meters and 30 meters lower than present day (Figure 2).

Figure 2. The most recent sea-level record from Huon Peninsula. This curve has been reconciled with marine isotope curves (after Chappell et al., 1996).
Many studies from different parts of the globe agree with this Huon Peninsula sea-level record. Bard and others (1990) presented data from Barbados which indicated that sea-level achieved a maximum height of several meters above present during MIS 5e, and that MIS 5c and 5a were associated with sea-levels about 20 meters lower than present day. These results were confirmed by additional studies conducted in Barbados by others (Gallup et al., 1994; Edwards et al., 1997) that indicated similar magnitudes and ages for the MIS 5 sea-level highstands. Studies of coral terraces from other locations such as Haiti (Dodge et al., 1983) and Timor (Chappell and Veeh, 1978) have also produced records that reinforce the notion that sea-levels during MIS 5c and 5a were 10 to 20 meters lower than that of present day.

Although records from Papua New Guinea are now widely used as the standard reference for sea-level estimates during MIS 5, contrasting sea-level positions for MIS 5c and 5a, in particular, are suggested by studies of corals from a number of tectonically stable carbonate platforms. Vacher and Hearty (1989) present evidence from Bermuda that indicates sea-level reached present day levels during MIS 5a. Their study is based on the relative formative positions of paleo-shorelines composed of carbonate eolianite, marine limestone, calcarenite protosols, and terra-rossa paleosols. Muhs et al. (2002a) also show high MIS 5a sea-levels from Bermuda. Similarly, Hearty and Kindler (1995) present evidence from the Bahamas for a brief highstand of less than a meter below present during MIS 5a (Figure 3). Ludwig and others (1996) note reefs formed during MIS 5a in the Florida Keys and calculate their associated sea-level as close to present day.

Muhs and others (2002b) suggest that, on a global basis, perhaps an equal number of studies show MIS 5a sea-levels as relatively low (i.e. at -19 to -20 m) or much closer to MIS 5e and present day elevations. In many cases, this controversy likely arises from the difficulty of separating the eustatic component of sea-level from local to regional tectonic or isostatic
influences. If this separation of the two signals of eustasy and tectonic movement is achieved it will reveal information not only about global sea-level change but may also be used to quantify rates and magnitudes of isostatic adjustment, leading to greater understanding of the viscosity of the Earth’s mantle and its spatial variability (Lambeck and Chappell, 2001).

It follows from the above that MIS 5 sea-levels should be evaluated at additional sites outside of tropical latitudes, such as the US Atlantic Coastal Plain, to search for the true magnitudes of sea-level rise during MIS 5c and 5a. The southeastern US Atlantic Coastal Plain has long been known to contain a detailed record of Plio-Pleistocene sea-level highstands (Colquhoun et al., 1991), but a lack of geochronological control has hindered the interpretation of these deposits as a record of sea-level change.

1.2 Geomorphic Setting

The Atlantic Coastal Plain of South Carolina is divided into the Upper, Middle, and Lower Coastal Plains, each having its own distinctive topography and subsurface stratigraphy. The study area for this project lies within the Lower Coastal Plain, which exhibits a stair-stepped topography consisting of various plains (termed terraces) of roughly similar elevation separated by scarps (Table 1). Each terrace has been interpreted to represent a shoreline complex

---

**Figure 3.** Sea-level curve from the Bahamas (after Hearty and Kindler, 1995).
deposited during a Plio-Pleistocene highstand, and contains a range of lithofacies interpreted to represent estuarine, back-barrier, bay, lagoonal, and barrier island environments. Relict shoreline complexes trend southwest-northeast, roughly parallel to the modern coastline, and commonly exhibit ridge and swale topography that parallels these regional trends (Colquhoun et al., 1991).

Table 1. Terraces and bounding scarps. See Figure 1 for locations. Terrace elevations are averages within the Lower Coastal Plain of South Carolina reported by Colquhoun, 1974.

<table>
<thead>
<tr>
<th>Terrace</th>
<th>Avg. Elevation (m)</th>
<th>Landward Scarp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver Bluff</td>
<td>2</td>
<td>Mt. Pleasant</td>
</tr>
<tr>
<td>Princess Anne</td>
<td>5.2</td>
<td>Awendaw</td>
</tr>
<tr>
<td>Pamlico</td>
<td>7.6</td>
<td>Cainhoy</td>
</tr>
<tr>
<td>Talbot</td>
<td>12.8</td>
<td>Bethera</td>
</tr>
<tr>
<td>Penholoway</td>
<td>21.3</td>
<td>Dorchester</td>
</tr>
<tr>
<td>Wicomico</td>
<td>30.4</td>
<td>Surry</td>
</tr>
</tbody>
</table>

The focus area for this study lies within the Francis Marion National Forest between the city of Charleston and the Santee River, about 10 km landward of Bulls Bay (Figure 1). The modern barrier islands in this area fall within Hayes’ (1994) morphological compartment III of the Georgia Bight (Figure 4), which contains classic “mixed energy” prograding barrier islands that exhibit a “drumstick” morphology. The barriers in this region are primarily sourced by sands from piedmont river systems, reworked Pleistocene barrier deposits, and eroding mainland areas (Hayes, 1994).

1.3 Geologic Setting

1.3.1 Cenozoic Stratigraphic Framework

The Pleistocene deposits examined during this study form an unconsolidated thin veneer of sediment that overlies clay, silt, and fine-grained quartz sand interpreted to represent shelf
A.

Figure 4. Barrier island classification of the Bulls Bay area. Shown as a function of tidal and wave regime: (A) Wave height and tidal range in the Charleston area (star) result in a mixed energy barrier morphology. (B) Morphological compartment III contains barriers that are either transgressive or regressive (Modified from Hayes, 1979; 1994).
sediment deposited during Paleocene through Pliocene times. Weems and Lewis (2002) provide a review of Cenozoic stratigraphic studies that span over two centuries and provide a synthesis of an extensive data set of auger and core data collected in investigations related to the 1886 Charleston earthquake. They identify sixteen pre-Pleistocene stratigraphic units in the Charleston region based on lithologic and biostratigraphic data (Figure 5). All but the three oldest of these units were encountered directly below the Pleistocene veneer in the greater Charleston area. A mosaic distributional pattern of these formations was interpreted as a product of complex interactions of tectonic warping, deposition, and erosion through time.

1.3.2 Surficial Deposits

What is best described as a morphostratigraphic framework for the Lower Coastal Plain of South Carolina has been developed over nearly a century of investigation, and has produced a nomenclature that is complex, poorly coordinated, controversial, and confusing (Colquhoun et al., 1991). Cooke’s (1930; 1936) early mapping efforts identified seven terraces, at elevations ranging from 8 m to 82 m above sea-level. These terraces were assumed to represent marine deposition, with each terrace associated with a successively lower Pleistocene sea-level highstand elevation, such that terraces decreased in elevation towards the present day coast. Several decades later, Colquhoun (1974) used geomorphic, outcrop, and shallow subsurface data to define “cyclic units” that retained Cooke’s terrace terminology for the Lower Coastal Plain. Four transgressive-regressive cyclic units were defined, including the Wicomico-Penholoway, Talbot-Pamlico, Princess Anne, and Silver Bluff “terrace-formations”. More recent USGS mapping by McCartan and others (1984) recognize a variety of facies within these different “terrace-formations”, including those deposited in beach, backbarrier, shelf, and freshwater swamp environments. Units were subdivided into “Q1-Q6” (Quaternary) and “T” (Tertiary) and were assigned various ages within the Holocene and Pleistocene (Figure 6).
Figure 5. Cenozoic stratigraphic chart of units known to occur in the Charleston area. The chart under represents the amount of missing time (white area) because the Rhems Formation, Williamsburg Formation, and Santee Limestone each include subunits (not distinguished here) that are bounded by regional unconformities. Modified from Weems and Lewis (2002).
Figure 6. Map units of McCartan et al. (1984). Terrace locations in the background are after Cameron et al. (1984) and Colquhoun (1965; 1974; 1991). Note the presence of Q3 units within the Lower Talbot and Pamlico terraces. The Silver Bluff terrace may be present between Cape Romain and the Princess Anne terrace.
Weems and Lemon (1984; 1993) and Weems and Lewis (1997) also have produced
detailed USGS maps of the surficial and shallow subsurface units in the area. However, they
introduce locally derived terms “Silver Bluff Beds, Wando Formation, Ten Mile Hill Beds,
Penholoway Formation, and Daniel Island Beds” to describe the same Pleistocene through
Holocene stratigraphic framework (Table 2).

Table 2. Stratigraphic correlation chart for surficial deposits. This complex nomenclature for
the Lower Coastal Plain of South Carolina is controversial. Modified from Putney et al.(2004).

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Unit</td>
<td>Age</td>
</tr>
<tr>
<td>Holocene</td>
<td>Recent</td>
<td>Holocene</td>
<td>Q 1</td>
<td>&lt; 8 ka</td>
</tr>
<tr>
<td>Pleistocene</td>
<td>Pamlico</td>
<td>Silver Bluff</td>
<td>Q 2</td>
<td>~100 ka</td>
</tr>
<tr>
<td></td>
<td>Talbot</td>
<td>Princess Anne</td>
<td>Q 3</td>
<td>~ 200 ka</td>
</tr>
<tr>
<td></td>
<td>Talbot-Pamlico</td>
<td>Talbot-Pamlico</td>
<td>Q 4</td>
<td>~ 450 ka</td>
</tr>
<tr>
<td>Penholoway</td>
<td>Wicomico-Penholoway</td>
<td>Wicomico-Penholoway</td>
<td>Q 5</td>
<td>&gt; 700 ka</td>
</tr>
<tr>
<td></td>
<td>Wicomico</td>
<td></td>
<td>Q 6</td>
<td>&gt; 1 Ma</td>
</tr>
<tr>
<td>Pliocene</td>
<td>Duplin Marl</td>
<td>Okefenokee</td>
<td>T</td>
<td>&gt; 2 Ma</td>
</tr>
<tr>
<td></td>
<td>Duplin</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1.3.3 Tectonic Setting and Neotectonic Deformation

The US Atlantic Coast is part of a passive continental margin. However, significant tectonic activity has occurred throughout the Cenozoic, as evidenced by major earthquakes recorded in historic time, the presence of abundant paleoliquefaction structures, and complex subsurface stratigraphy in the region (Cronin, 1981; Talwani, 1985; Talwani and Schaeffer, 2001). Stratigraphic units above the upper Paleocene Williamsburg Formation are thin in the Charleston area and completely absent to the northeast across the Cape Fear arch, whereas the thicknesses of pre-Williamsburg units remain constant. This implies that the Charleston region has been the hinge zone that accommodates tectonic movement between the uplifting Cape Fear arch to the northeast and the subsiding Southeast Georgia embayment to the southwest since late Paleocene time (Weems and Lewis, 2002). This hinge zone is characterized by northeast-southwest oriented compression accommodated by buried reverse and strike-slip faults whose movements result in local zones of uplift and subsidence.

Winker and Howard (1977) suggested that regional-scale warping associated with the Cape Fear arch and Southeast Georgia embayment has influenced the present day elevations of shoreline complexes deposited throughout the Pliocene and Pleistocene. However, precise mapping and correlation of shoreline complexes over the length of their study area had not been undertaken, so the precise rates and magnitudes of tectonic movements on relict shorelines remain poorly constrained. Nevertheless, the wide range of elevations over which shoreline complexes can be found makes it clear that both regional and local tectonic deformation affect the present day elevations of relict shorelines in this region, and they no longer closely reflect formative sea-level positions.

On a more global scale, recent geophysical modeling studies have drawn attention to isostatic deformation of shorelines in response to the redistribution of water and ice that
accompanies glacial-interglacial cycles. Such studies are particularly advanced for the Holocene (e.g. Peltier, 2002; 2004) due to robust ice volume estimates and relative sea-level records available for this time period, but a number of key papers have addressed MIS 5 as well. Lambeck and Nakada (1992) demonstrated that glacio-hydro-isostatic adjustments preclude sites around the world from recording the same timing, duration, or magnitude for the Last Interglacial sea-level maxima. Recently, Potter and Lambeck (2004) presented a preliminary model for such adjustments that suggests vertical displacement of tens of meters along the US Atlantic Coastal Plain in response to the growth and decay of North American ice sheets. However, as described in the following section, critical benchmark elevations of MIS 5 highstands, in particular MIS 5e, along the US Atlantic coast remain unresolved due to poor stratigraphic and geochronological control.

1.4 Previous Geochronological Studies

Much of the controversy concerning the ages, and corresponding significance to paleosea-level elevations, of relict shoreline complexes within the study area, and elsewhere along the US Atlantic Coastal Plain, stems from a lack of fossil material that is datable by conventional U-series radiometric techniques. Tropical localities commonly have well developed flights of coral-reef terraces, with specific coral species that are known to be suitable for U-series dating, whereas regions in higher latitudes, such as the US Atlantic Coastal Plain, merely contain rare species of solitary corals (*Serapstra* and *Astrangia*) encrusted upon the shells of mollusks and gastropods. In the late 1970’s and early 1980’s, specimens of this type from the Pamlico and Princess Anne terraces of southeastern US were dated using U-series alpha-spectrometry techniques (Cronin et al., 1981; 1984; Szabo, 1985) and yielded ages that clustered at ca. 125 ka, 96 ka, and 72 ka. Additional analyses using higher precision TIMS techniques (York et al., 1999; Wehmiller et al., 2004) provide numerous dates that correspond to MIS 5a.
Amino acid racemization (AAR) techniques also have been applied on the US Atlantic Coastal Plain for relative age estimates of MIS 5 highstand deposits (Wehmiller et al., 1988). This technique is based on the natural racemization of L-enantiomeric amino acids into D-enantiomeric configurations within the shells of mollusks. The extent of this racemization increases over time, but is a function of ambient temperature, genus, and a variety of diagenetic processes (Wehmiller, 1993). Wehmiller and others (1982; 1988; 1993) have extensively studied clusters of D/L values (aminozones) of marine mollusks of the US Atlantic coastal plain and correlated two and in some cases three different aminozones with MIS 5, and tentatively associated them with highstands of the Last Interglacial, MIS 5e, 5c, and 5a. However, significant conflicts between U-series dates and aminostratigraphic age estimates were recognized for sites in South Carolina and eastern Virginia. These discrepancies were explained by the many uncertainties surrounding the AAR method, particularly with modeling of the temporal and spatial variability of thermal conditions over glacial-interglacial cycles (Wehmiller et al., 1988; 1993; York et al., 1999). Considering that racemization of amino acids is a reaction that is dependant on a variety of factors other than time, this method’s utility as an absolute dating tool is severely limited and is most appropriate for regional correlation applications. Nevertheless, the significantly different D/L values that define aminozones within a given section or region would seem to suggest different ages for the units in question, and there is little reason to believe that amino acid racemization is not an effective relative age dating tool.

Taking the above in its entirety, it has been suggested that two end-member chronostratigraphic models for the South Carolina Coastal Plain dominate the extensive collection of previous literature (Table 3). The “long-chronology” model is based on extensive AAR analyses of *Mercenaria* valves (Wehmiller and Belknap, 1982). This model assigns a MIS 5 age exclusively to the Princess Anne terrace (late Wando of Weems et al., 1997) and associates
MIS 7 and earlier highstands with landward terraces. A contrasting “short-chronology” model was proposed to explain conflicting U-series radiometric dates from microcorals (Cronin et al., 1981; 1984; McCartan et al., 1984; Szabo, 1985) and AAR analyses of Mulinia valves (Corrado et al., 1986). The “short-chronology” model holds that the Princess Anne terrace was formed during the late stages of the Last Interglacial, MIS 5c and 5a, (92 ka and 72 ka) and assigns the Pamlico terrace to the LIGM, MIS 5e (125 ka). A “revised long-chronology” model has since been proposed (Wehmiller et al., 1997) as a compromise for these contrasting age estimates. This model contains elements of both the “short” and “long” chronologies by recognizing MIS 5c and 5a deposits, but assigns the Silver Bluff terrace to these later highstands, and maintains that the Princess Anne terrace represents MIS 5e.

### Table 3. Ages of Late Pleistocene terraces. Ages are according to various published chronological models (After Zayac, 2002), and are given in terms of oxygen isotope stages.

<table>
<thead>
<tr>
<th>Terrace Name</th>
<th>Long Chronology Model&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Short Chronology Model&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Revised Long Chronology Model&lt;sup&gt;3&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recent</td>
<td>MIS 1</td>
<td>MIS 1</td>
<td>MIS 1</td>
</tr>
<tr>
<td>Silver Bluff</td>
<td>MIS 5?</td>
<td>MIS 1</td>
<td>MIS 5a/5c</td>
</tr>
<tr>
<td>Princess Anne</td>
<td>MIS 5</td>
<td>MIS 5a/5c</td>
<td>MIS 5e</td>
</tr>
<tr>
<td>Pamlico</td>
<td>Pre-MIS 5</td>
<td>MIS 5e</td>
<td>MIS 7</td>
</tr>
<tr>
<td>Lower Talbot</td>
<td>Pre-MIS 5</td>
<td>MIS 7</td>
<td>MIS 9?</td>
</tr>
</tbody>
</table>

<sup>1</sup>After Wehmiller and Belknap (1982) and Harris (2002)<br><sup>2</sup>After McCartan et al. (1982; 1984), Corrado et al. (1986)<br><sup>3</sup>After Wehmiller et al. (1997) and Harris (2002)

The current confusion due to contrasting interpretations of the Lower Coastal Plain of South Carolina is exemplified by these conflicting models. Further frustration is provided by the realization that if one of the above geochronological models proves to be conclusive, very few AAR or U-series age estimates can be directly tied to paleosea-levels. Fossil specimens are often merely assumed to be in situ as they are collected from large borrow pits from nondescript strata interpreted to represent shallow marine deposition.
Harris (2002) provided a notable exception by presenting AAR analyses that were tied to subsurface data in the form of shallow seismic reflection data, GPR profiles, and sediment cores. Kinetic modeling of AAR data coupled with evaluation of the geomorphology and stratigraphy of the Lower Coastal Plain just south of Charleston identified six discrete aminozones. They were correlated to the highstands of MIS 5a, 5c, 5e, 7, 9, and 11, with corresponding sea-levels of 2, 3.5, 4.5, 7, 7, and 8 mASL, and best fit the “revised long-chronology” model.

Zayac (2003) tested the utility of an alternative dating methodology, OSL, along the St. Helena Island area of South Carolina. OSL age estimates also identify deposits associated with MIS 5a, 5c, 5e, and 7 at elevations just above present day sea-level. These results seem to support the “revised long-chronology” model, however, original map units were often incorrectly interpreted, and some OSL age estimates, when considered individually, correspond to U-series ages and the “short-chronology” model. The relative sea-level history of the Last Interglacial on the coast of South Carolina remains controversial and the need for refinement of highstand records in this area with high resolution stratigraphic and geochronological control is clear.

1.5 Project Goals

A crucial objective for this study is to clearly identify the shoreline(s) associated with the LIGM, MIS 5e, by applying OSL geochronology. The ages of other highstand units within the study area will also be evaluated and interpreted within the context of preexisting “short” versus “long” chronology models. These age estimates will be useless without developing a robust stratigraphic context to relate them to paleosea-levels and long-term coastal evolution. Therefore, shallow subsurface investigations will be conducted to characterize the stratigraphic signature of each highstand unit. Ideally, this approach will define: (1) when each shoreline was active, (2) the peak elevation sea-level attained during each highstand, and (3) the sand-body
geometry and stratigraphic architecture of each emergent highstand unit. Several working hypotheses in each of these themes will be tested:

(1) **Geochronological Model:**

- The most seaward shoreline complex is associated with MIS 5 and landward shorelines are associated with previous interglacial periods (MIS 7, 9, etc.), supporting the “long chronology” model.
- The most seaward shoreline complex is associated with MIS 5a and landward shorelines are associated with MIS 5c and 5e, supporting the “short chronology” model.

(2) **Highstand Elevation Model:**

- MIS 5e deposits currently reside at elevations consistent with widely accepted eustatic estimates (+3 to +5m), whereas MIS 5c and 5a deposits are absent, implying long-term tectonic and isostatic stability.
- MIS 5e and other highstand deposits currently reside at elevations consistently higher than eustatic estimates, implying long-term tectonic uplift.
- Some combination of MIS 5e, 5c, and 5a deposits are present at similar elevations, implying that eustatic estimates are invalid or complex deformation has taken place since their formation.

(3) **Stratigraphic Model:**

- Each terrace is a composite of multiple shoreline complexes emplaced by different highstands, and these complexes are stacked vertically in the subsurface, i.e. older highstand units lie below unconformity bounded younger deposits.
- Each terrace represents a combination of relict barrier and lagoonal environments active during a single highstand, and is bounded below by much older deposits.
CHAPTER 2

METHODS

This study employs a range of techniques designed to test the hypotheses presented above. These include ground-penetrating radar (GPR) and acquisition of cores to delineate subsurface stratigraphic relations and depositional environments, and optically-stimulated luminescence (OSL) to provide a geochronological framework. These methods are described more fully below. The western portion of the Francis Marion National Forest, was identified as an ideal focus area because the succession of shorelines in this area are spatially discrete, separated from each other by broad paleolagoonal areas, and not welded to each other as they are elsewhere along the coast of South Carolina. Land use permits were then acquired from the Department of Natural Resources for permission to gather GPR data and drill boreholes in March of 2004 and January of 2005.

2.1 Ground Penetrating Radar

The GPR method operates by transmitting an electromagnetic pulse in all directions, a portion of which travels into the ground and is reflected back to the surface. Radar reflections generated in the subsurface arise from abrupt changes in the relative dielectric permittivity (RDP) of materials, a measure of the ability of a material to store a charge from an applied electromagnetic field and then transmit that energy. The RDP of a material depends on a variety of factors including its water content, chemical composition, density, and magnetic permeability and susceptibility (Davis and Annan, 1989). In many cases, these subtle dielectric contrasts correspond to sedimentary structures, bedding surfaces, and unconformities in the subsurface. Reflected signals are recorded as amplitudes versus two-way travel time and are subsequently processed and displayed as a GPR profile, in which the vertical axis is expressed as depth and the horizontal axis is distance along the survey line (Bristow and Jol, 2003).
Jol et al. (1996) provide a review of GPR studies along coastal barriers from the Atlantic, Gulf, and Pacific coasts of the United States. Dip-oriented profiles from all examples of modern barriers display moderately continuous seaward-dipping reflections, interpreted to represent paleo-beach surfaces. The geometry of these reflections is used to infer stratigraphic trends, and therefore the directions of progradation and/or aggradation. More recent studies have successfully used this approach to describe long-term geomorphic evolution in a variety of coastal environments including wave-dominated deltas (Smith et al., 2005; Fraser et al., 2005) and barrier systems (O’Neal and McGearry, 2002; Daly et al., 2002; Moller and Anthony, 2003).

This study used the LSU Department of Geology and Geophysics Sensors and Software, Inc. pulseEKKO 100 system equipped with a 1,000 V transmitter and 100 MHz antennae. This transmitter and receiver combination was found to have the best compromise between resolution and depth penetration. The data collected during this study had an average vertical resolution of 25 cm, and depth of penetration ranged from 5 to 15 m, depending upon the water saturation of sediments. GPR reflection data were collected in step mode, with a sampling interval of 0.25 m, antennae spacing of 1 m, and an initial stacking value of 4. About 6,700 m of data were collected along a northwest-southeast paved road that is oriented nearly perpendicular to the trend of relict shorelines within the Lower Talbot, Pamlico, and Princess Anne terraces. Three strike-oriented lines, each over 1,000 m in length, were also collected parallel to the relict shoreline complexes within these three terraces. Two additional dip-oriented lines were collected from the seaward portion of the Princess Anne terrace, one of which crossed onto the Silver Bluff terrace, the topographically lowest along the Lower Coastal Plain of South Carolina.

Radar data were processed using EKKO View Deluxe, a GPR processing and viewing software package produced by Sensors and Software, Inc. A sequence of basic processing steps was applied to all radar datasets (Figure 7). The low-frequency (< 1 MHz) noise component,
commonly termed “wow”, of the data were first removed by a high-pass filter. A horizontal average was then applied to all traces to increase the stacking of the data to 12, and then a migration process was applied. The migration procedure uses a synthetic aperture image reconstruction process to collapse diffraction hyperbolae (patterns created by point reflectors in a GPR profile) back to their original source locations and to correctly position dipping reflectors. An average velocity of 0.1 m/ns was used in the migration process, a value obtained by geometric analyses of the asymptotic tails of diffraction hyperbolae within the data. GPR profiles were then corrected for changes in elevation along survey lines using data obtained with a digital theodolite and differential GPS. The data were finally plotted as GPR profiles with Automatic Gain Control (AGC), a gain that is inversely proportional to signal strength, with a sample window of 1.0 and maximum gain value of 100. This gain enhanced the continuity of reflections but did not preserve any relative amplitude information. Therefore, data were also interpreted without this gain to evaluate the relative strengths of reflections from key horizons. No attempts to remove the air and ground waves of the near field zone were made because GPR data were collected along the surface of roads, the underlying meter of which were likely modified during construction.

Figure 7. Processing flow chart for GPR data used in this study.
Many shortcomings of the GPR method, especially those relevant to the study area, were considered during the interpretation of data. First of all, no resistivity soundings or CMP analyses were conducted during the acquisition of data; therefore radar velocity estimates relied on published values for various lithologies (Davis and Annan, 1989; Sensors and Software, 2003) coupled with assumptions regarding the water content of sediment. Overhead utility lines, passing vehicles, and other large man-made structures above ground also could have produced interference and reflections mistakenly plotted in the subsurface. Signal attenuation related to the presence of dissolved carbonate, salt water, and clay were also identified as possible obstructions to GPR interpretation. Considering these many pitfalls, GPR was only used to infer stratigraphy between core locations, and critical interpretations such as identification of key stratal surfaces and paleosea-level indicators relied solely on core data.

2.2 Sediment Coring

Twenty one holes were bored within the Lower Talbot, Pamlico, Princess Anne, and Silver Bluff terraces landward of Bulls Bay, SC to investigate their near surface stratigraphy and provide ground-truthing for GPR profiles. Seven vibracores, 2 to 4 m in length and 7.6 cm (3 in.) in diameter, were collected by Dr. Michael Blum in January, 2001. Thirteen additional cores were collected in January, 2005 using a track-mounted Geoprobe Systems Model 66DT rig that uses a hydraulic hammer to push a steel core barrel into soft sediment. This rig returned 1.5 m (5 ft) long sections of continuous core in unconsolidated materials within 3.8 cm (1.5 in.) diameter plastic tubes. Total depths of the cores drilled via Geoprobe ranged from 7.6 to 12.2 meters (25 to 40 feet) with an average recovery of about 80%. Cores were obtained along three transects intended to demonstrate the stratigraphic relationships among shoreline complexes. Their locations were recorded by a differential GPS system with sub-meter horizontal resolution and elevation accuracies of ±1 meter.
Cores were split, described, and sampled for sediment analysis and stratigraphic interpretation during the spring of 2005. The cores were logged by a visual description of color (Munsell Color Company, Inc., 2000), grain size, sorting, and presence of organic material such as peat, roots, and wood fragments. Quantitative granulometric analyses using sediment sieves were then carried out on samples interpreted as eolian and swash zone in origin, and grain size frequency plots were used to calculate statistical parameters using the moments methodology (Boggs, 2001). Sedimentary structures and fossils were identified in each core, with special attention given to unconformable contacts and sedimentary structures indicative of swash zone processes. Each section of core was then photographed using a high resolution line-scan camera and packaged for storage. Additional data from auger holes obtained by the USGS (Weems and Lewis, 1997) aided in the interpretation of the units encountered in this study and were used for regional stratigraphic context.

### 2.3 Optical Dating

Optically Stimulated Luminescence (OSL) has been increasingly used in geochronologic studies because it requires no organic material and has an age range of several hundred thousand years. In theory, the various luminescence dating techniques measure the time elapsed since sediment was last exposed to sunlight during transport, a “bleaching event” that zeroes the luminescence signal. After deposition, the luminescence signal builds up again due to alpha, beta, and gamma-ray radiation produced by the decay of thorium, uranium, potassium-40, and rubidium-87 in the surrounding matrix, and by cosmic rays that penetrate the subsurface. This signal is measured in the laboratory by subjecting the sediment to known doses of heat (thermoluminescence or TL), or specific wavelengths of light (OSL), and measuring the amount of luminescence released, which is then converted to a quantity referred to as an equivalent dose, D_e. An age estimate can then be produced by dividing the equivalent dose, D_e,
by the dose rate, which is obtained by measuring the concentration of radioactive elements in the original sediment sample (Aitken, 1998).

The development of OSL single aliquot regeneration (SAR) $D_e$ protocols (Murray and Wintle, 2000) has drastically improved the precision and reliability of luminescence dating techniques. Blue-green light optical techniques, which are commonly used on quartz, require sediment to be exposed to solar radiation for tens of seconds, vs. tens of hours for the older TL technique. This short exposure time leads to more effective bleaching, and significantly less inherited signal in the sediment sample. The SAR method avoids inter-aliquot normalization and improves the precision of $D_e$ estimates by incorporating interpolative estimation techniques (Stokes et al., 2003). SAR techniques have proven successful in dating dune and shoreface sediments (Wintle et al., 1998; van Heteren et al., 2000; Banerjee et al., 2003; Choi et al., 2003) with uncertainties in the range of about 5 to 10%. This error inherent to the OSL method is due to assumptions surrounding the radioactivity and burial history of samples, most importantly that the radioactivity and water saturation of the samples has remained constant over time. Also, uncertainties still remain with the manner in which radioactive energy is stored by sediment grains and subsequently released in the laboratory (van Heteren et al., 2000). Recent investigations along the St. Helena Island area of the South Carolina coast (Zayac, 2003) have demonstrated the suitability of OSL methodology as a means to associate various highstand deposits with the Last Interglacial, MIS 5.

Samples for OSL dating were collected from vibracores within facies interpreted to represent eolian or swash zone depositional environments by Dr. Michael Blum, in January of 2001. Vibracores were split and sampled in a dark room, and samples were extracted and sealed for transport with special care to avoid exposure to light. Additional samples were taken for water-content measurement and chemical dose-rate analyses. Samples were analyzed by Dr.
Ronald Goble of the University of Nebraska and Dr. Michel Lamothe of the Universite du Quebec following methods outlined by Murray and Wintle (2000) for single- aliquot regenerative (SAR) procedures. Analyses were carried out using blue-green light stimulation (480-514 nm) of fine quartz sand (90-125 m). Water contents were calculated from the samples themselves, and dose rates were calculated based on the concentrations of radioactive elements in each sample.

2.4 Sea-level Indicators

Beach ridges are morphological features common to coastal systems like those examined here. Considerable controversy regarding the origin of ridge morphology remains in the literature (see Taylor and Stone, 1996; Otvos, 2000 for reviews), especially as it pertains to their significance for reconstructing paleosea-level elevations. However, few would argue against the observation that all beach ridges owe their origins to some combination of swash and eolian processes occurring along the shoreline active during their formation. Beach ridges are often capped by eolian accumulations of variable thickness, hence surface elevations of relict ridges cannot be reliably linked to past sea-levels. However, the underlying contact between eolian and intertidal intervals within a beach ridge sequence can be a precise sea-level indicator, provided that diagnostic sedimentary textures, structures, and fossils, are preserved within the deposits. The contact between clearly identifiable eolian and swash zone strata is often gradational, but the transition between the two facies generally occurs over less than half a meter. This level of uncertainty pales in comparison to that associated with traditional Last Interglacial sea-level indicators that rely on fossil coral positions. Although coral samples are well suited for radiometric dating, establishing a link to past sea-levels is often problematic, considering the uncertainties about the in situ nature of specimens and the large range of water depths these creatures inhabit. OSL dating of sands that can be linked to swash zone processes represents an
excellent alternative methodology for defining sea-level histories, especially in siliclastic shoreline settings, and was used in this study to produce a relative sea-level record for this portion of the South Carolina coast.
CHAPTER 3
RESULTS

As noted previously, terraces of the Lower Coastal Plain in South Carolina have been distinguished according to elevation, cross-cutting relationships of beach ridge sets, and topographic breaks in the landscape (Figure 1). However, the use of these geomorphic terms in stratigraphic studies is inappropriate due to the uncertain relationships among terraces that share these names elsewhere along the US Atlantic coast. For example, the Pamlico terrace in Georgia may not be equivalent to the Pamlico terrace in South Carolina. USGS geologic maps within the study area abandon the terrace terminology and instead use generic map units (McCartan et al., 1984), or local stratigraphic nomenclature (Weems and Lemon, 1984; 1993) that relate map units to specific sea-level highstands (Figure 6).

Despite the confusing application of terrace terminology, those terraces in the area between Charleston and the Santee River are very well defined in the literature (Colquhoun, 1965; 1974), and are referenced below as geomorphic terms that describe the geographic location of the deposits investigated during this study. Terraces described below should not be considered coeval with those with the same name elsewhere along the Atlantic Coast until further studies merit such correlations. Discussions regarding the subsurface stratigraphy of each terrace reference the stratigraphic nomenclature used by Weems and others (1984; 1993; 1997) and the local names of individual emergent barrier systems (Colquhoun, 1965; 1974).

Locations of GPR lines and cores collected during this study are shown in Figure 8 and are discussed according to their location within each terrace in the text below. Core descriptions identify six discrete lithofacies (Table 4), each characterized by a distinctive suite of grain sizes, sorting, sedimentary structures, and organic content. After objectively defining each lithofacies based on these physical criteria, the stratigraphic architecture and internal stratification of
Figure 8. Map showing the location of GPR profiles and cores collected in this study. Optical dates were obtained from core numbers 2, 4, 8, 9, 12, 13, 17, 18, and 19. Terrace and scarps after Cameron et al. (1984) and Colquhoun (1991).
Table 4. Lithofacies encountered in cores. Interpretation of depositional environments is based on integration of data discussed in the text below.

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Grain Size</th>
<th>Sorting</th>
<th>Sedimentary Structures</th>
<th>Organic Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Very Fine</td>
<td>Very Well</td>
<td>Massive</td>
<td>Modern Roots</td>
</tr>
<tr>
<td>B</td>
<td>Silt to Clay</td>
<td>Well</td>
<td>Massive</td>
<td>Extensive Peat</td>
</tr>
<tr>
<td>C</td>
<td>Fine to Very Fine</td>
<td>Moderately Well</td>
<td>Parallel Laminations; Low Angle Cross bedding</td>
<td>Some Shell Fragments</td>
</tr>
<tr>
<td>D</td>
<td>Coarse to Clay</td>
<td>Fining Upwards</td>
<td>Some Cross bedding</td>
<td>None</td>
</tr>
<tr>
<td>E</td>
<td>Clay</td>
<td>Very Well</td>
<td>Massive, some burrows</td>
<td>Roots, Whole Shells</td>
</tr>
<tr>
<td>F</td>
<td>Medium to Fine</td>
<td>Poor</td>
<td>Massive</td>
<td>Shell Fragments and Whole</td>
</tr>
<tr>
<td>G</td>
<td>Medium to Coarse</td>
<td>Moderate</td>
<td>Parallel Laminations; Low Angle Cross bedding</td>
<td>Some Shell Fragments</td>
</tr>
</tbody>
</table>

Various units identified by GPR provided an interpretation of depositional environment for each lithofacies. An objective description of the radar data were also achieved by subdividing the profiles using various high-amplitude reflectors and recognizing collections of distinctive reflection patterns as radar facies (Table 5). Continuity of radar facies was then used to infer subsurface stratigraphic relationships between core locations along GPR transects.

High-amplitude reflectors in this study are interpreted to arise from abrupt changes in dielectric properties at interfaces between sharp based sand deposits and underlying clay rich sediment. In some cases, these sharp lithologic contacts correspond to key stratal surfaces, such
Table 5. Radar Facies classification. Individual facies are grouped according to reflector continuity, shape, and dip orientation.

<table>
<thead>
<tr>
<th>RADAR FACIES</th>
<th>CONTINUITY</th>
<th>SHAPE</th>
<th>DIP ORIENTATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>I(a)</td>
<td>Very Low</td>
<td>Hummocky w/ Sheeted external geometry</td>
<td>Random</td>
</tr>
<tr>
<td>I(b)</td>
<td>Very Low</td>
<td>Hummocky w/ lenticular external geometry</td>
<td>Random</td>
</tr>
<tr>
<td>II</td>
<td>High</td>
<td>Parallel</td>
<td>Flat</td>
</tr>
<tr>
<td>III</td>
<td>Moderate</td>
<td>Parallel</td>
<td>Landward</td>
</tr>
<tr>
<td>IV</td>
<td>Moderate</td>
<td>Nearly Parallel</td>
<td>Perpendicular to Shoreline</td>
</tr>
<tr>
<td>V</td>
<td>Moderate</td>
<td>Parallel</td>
<td>Seaward</td>
</tr>
<tr>
<td>VI</td>
<td>Moderate to High</td>
<td>Parallel, w/ hyperbolas</td>
<td>Flat</td>
</tr>
</tbody>
</table>

as transgressive ravinement surfaces, or regressive surfaces of erosion. Sandy depositional units are also characterized by collections of lower amplitude reflections (radar facies) that are interpreted to arise from subtle dielectric contrasts along bedding surfaces (discussed below). These radar facies indicate if a particular unit has undergone progradation, retrogradation, or aggradation, which in turn aided in the identification of specific depositional environments.

3.1 Lower Talbot Terrace

Colquhoun (1974) interpreted the seaward portion of the Lower Talbot terrace as a relict barrier and named it the “Cainhoy barrier system”. Lower Talbot sediments also correspond to the “Ten Mile Hill beds” of Weems and Lemon (1993). This relict shoreline trend is readily
discernable on satellite imagery (Figure 9) but lacks any distinctive morphological characteristics, likely a result of extensive erosion and/or post-depositional eolian activity. McCartan and others (1984) did not differentiate the Cainhoy barrier, but rather considered it to be part of a menagerie of units Q1-Q4 (Figure 6), whereas Weems and Lemon (1993) cite age estimates from U-series dating of microcorals (Cronin et al., 1981; Szabo, 1985) that assign a MIS 7 age to this shoreline complex.

3.1.1 Core Data

Two vibracores for OSL sample collection were drilled within the Lower Talbot terrace. Core 2 was collected landward of the Cainhoy Scarp, on the crest of the ridge that defines the Cainhoy barrier. Core 4 was collected along the strike of this shoreline complex, to the Northeast. Two continuous Geoprobe cores were also acquired within the Lower Talbot terrace to investigate deeper into the subsurface. Core 1 was collected next to the vibracore location of Core 2, whereas Core 3 was collected on the slope of the seaward-bounding Cainhoy Scarp (Figure 8).

Cores 1, 2, and 4 are capped by 3 to 5 meters of Lithofacies A (LF-A), an interval of very fine, very well sorted, pale brown sand (Figure 10). A darker rooted horizon is present at a depth of about 3 meters in Core 4 and about 1.5 meters depth in Cores 1 and 2. Core 4 terminates in LF-A, whereas Cores 1 and 2 contain an underlying interval of slightly coarser and more poorly sorted sand containing shell fragments and darker parallel laminations (LF-C). Core 2 terminates in LF-C, whereas the deeper Core 1 contains about 2 meters of LF-C, underlain by a fining upwards package of sand that is capped by three clay-rich layers (LF-D). Although the recovery of Core 3 was poor (~40%), the sediments obtained were poorly sorted sands with thin clay interbeds, and classified as LF-D.
Figure 9. Satellite image of study area. Terrace locations after Cameron et al. (1984) and Colquhoun (1965; 1974; 1991).
Core #1  
Surface Elevation: 17.2 mASL

Figure 10. Photograph and descriptive log of Core 1. Three lithofacies (LF-A, LF-C, LF-D) are shown along with distinguishing physical characteristics.
3.1.2 Radar Stratigraphy

A dip-oriented GPR profile (DIP 1 in Figure 8) collected normal to the Lower Talbot terrace contains four distinct radar facies and two prominent high-amplitude reflectors (see Figure 11 for this portion of DIP 1). The landward, shallow portion of the profile consists of Radar Facies (RF) I(a), a blanket-like unit of discontinuous wavy reflections (see Table 5 for description). RF I(a) is underlain by two high-amplitude reflectors (HAR-1 and HAR-2) that bound two additional radar facies, RF-III and RF-II, which are characterized by more continuous reflections. The wedge-shaped unit of RF-III lies immediately below and seaward of RF-I and onlaps HAR-1 in a landward direction. The deepest radar facies, RF-II, contains continuous, nearly flat reflections. Both RF-II and RF-III are truncated seaward, in the vicinity of the Cainhoy Scarp, by RF I(b), which consists of a lenticular body that is internally characterized by discontinuous wavy reflections.

A long strike-oriented (>3,000 m) GPR profile along the Lower Talbot confirms the presence of HAR-1 but lacks HAR-2 (Figure 12). The profile is predominately made up of Radar Facies I and II, but in some portions it also contains Radar Facies IV, a collection of moderately continuous reflections dipping perpendicular to the Cainhoy Scarp and modern shoreline (Figure 12).

3.1.3 Interpretation

Upon comparison with core data, a velocity of 0.15 m/ns was used to ground-truth GPR profiles, a value that is consistent with published estimates for dry sand and soil (Sensors and Software, Inc., 2003) and CMP surveys conducted in the area (Harris, 2002). The local water table is well below the depth of cores from the Lower Talbot, it was observed at an elevation of 8 mASL in the Wambaw swamp on the landward Pamlico terrace. Using this velocity estimate for unsaturated sand, RF-I(a) correlates well with LF-A encountered in Cores 1 and 2. Considering
Figure 11. Interpretation of GPR and borehole data along the Lower Talbot terrace. Four radar facies (Ia, Ib, II, and III) as well as two high amplitude reflectors (HAR-1 and E.AR-2) are evident in this portion of GPR line DIP 1. Refer to Figure 8 for location. Stratigraphic contacts originate from core interpretations (see Appendix) and are inferred based on continuity of radar facies.
Figure 12. A section of strike-oriented GPR line STRIKE 1. Three distinct radar facies are shown. Radar Facies IV likely represents channel fill. Depth axis on right side of figure assumes a velocity of 0.1 m/ns. The reflector separating Radar Facies IV and II may be a horizontal scour surface displayed above as undulating due to velocity variations.
the geometry of RF-I(a) and the physical characteristics of the corresponding LF-A, this 
lithofacies and radar response are interpreted here as representing eolian deposition. Cores 1 and 
2 also indicate that the underlying wedge of RF-III corresponds to the laminated LF-C. 
Moderately well sorted sand containing laminations is commonly deposited in an upper-swash-
zone beach setting (Reineck and Singh, 1975; Hayes, 1994; Boggs, 2001) and is interpreted here 
representing foreshore to backshore facies. The overall shape and landward onlap of RF-III is 
interpreted as a signature of transgressive deposition. Core 3 indicates that RF-I(b) corresponds 
to poorly sorted sand with occasional thin clay interbeds, classified as LF-D. The cross-cutting 
relationship of this radar facies along with the variable lithology obtained from Core 3 are 
interpreted as evidence of a younger episode of reworking associated with lowstand drainage 
and/or a more recent highstand.

3.1.4 OSL Geochronology

Samples for OSL analysis were collected from Cores 2 and 4. One sample from Core 2 
was collected from facies interpreted to represent a swash zone depositional environment, typical 
of a forebeach-backbeach transition, whereas the shallower sample from Core 2, as well as 
samples from Core 4, were collected from facies interpreted as eolian in origin (See Appendix 
for core logs and photographs). This difference in depositional setting does not affect the OSL 
age estimates or their interpretation, as sunlight exposure in either environment is sufficient to 
reset the dating signal. Two prominent buried paleosols were recovered in Core 4 (Figure 13). 
The shallow paleosol, P1, is interpreted as topsoil covered by material during the construction of 
the nearby road, because the ground surface lacks any soil development. The deeper paleosol, P2 
is interpreted as a much older surface because OSL samples collected above and below this 
horizon indicate that a significant amount of time (~100 kyrs) is represented by this surface of 
subaerial exposure. A paleosol horizon similar to P2 was found in Core 2, but both of the OSL
samples from this core were collected below the paleosol, in basal eolian and swash zone strata, considered coeval for the purposes of OSL dating.

OSL age estimates from sediments from Core 2 and the deeper sample from Core 4 fall within the 200-250 ka range, which is consistent with previous estimates from U-series dating of microcorals (Cronin et al., 1981; McCartan et al., 1982; Szabo, 1985) collected from marine deposits within the Lower Talbot terrace. However, dose rates from OSL samples in this study range from 0.5 to 1.1 Gy/ka, which saturate the OSL signal after 150,000 to 240,000 years (Table 6). Therefore, despite the tight clustering of OSL age estimates around MIS 7 for samples collected from this shoreline complex, this particular age assignment is considered only a minimum estimate. Moreover, the ages presented above are considered preliminary until the results from additional aliquots become available. The OSL age estimate for the shallow sample in Core 4 corresponds with MIS 5, suggesting that an additional generation of eolian deposition took place on the Lower Talbot terrace after the emplacement of the Cainhoy Barrier.

3.2 Pamlico Terrace

The emergent barrier complex within the Pamlico terrace is locally known as the “Awendaw” barrier system (Colquhoun, 1974) and corresponds to the “Early (Lower) Wando Formation” of Weems and Lemon (1993). This relict barrier is easily identified on satellite imagery and aerial photographs, as it retains distinctive ridge and swale topography (Figure 9). It is welded directly onto the landward (older) “Cainhoy” barrier, with no intervening marsh or lagoonal deposits. Unlike modern barrier islands in the area (see Figure 9), this barrier system was attached to the adjacent mainland. McCartan and others (1984) map the Pamlico terrace within the study area as Q3 (~200 ka) but suggest some ambiguity by stating that “material labeled...Q3 directly northeast and southwest of Wambaw Swamp may be Q2 (~100 ka)”, while
Figure 13. Photograph and descriptive log of Core 4. Two generations of paleosols are shown. OSL age estimates demonstrate the importance of stratigraphic context of sample collection.
Table 6. OSL results from analyses conducted for this study. Samples are arranged and color-coded according to their location within each terrace: Yellow = Princess Anne, Blue = Pamlico, Green = Lower Talbot. The age estimates of samples 625, 626, and 705 are robust, others are considered preliminary as results of analyses of additional aliquots are pending.

<table>
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<tr>
<th>Core #</th>
<th>Sample #</th>
<th>Burial depth (m)</th>
<th>H₂O (%)</th>
<th>K₂O (%)</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>Cosmic (Gy/ka)</th>
<th>Dₑ (Gy)</th>
<th>Number of Aliquots</th>
<th>OSL Age Estimate (ka)</th>
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<td>625</td>
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<td>1.41 ± 0.06</td>
<td>128.1 ± 3.26</td>
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<td>4.7</td>
<td>0.16</td>
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<td>20.8</td>
<td>1.89</td>
<td>0.4</td>
<td>1.2</td>
<td>0.15</td>
<td>152 ± 0.08</td>
<td>122.5 ± 26.6</td>
<td>8</td>
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<tr>
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<td>26.4</td>
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<td>1.1</td>
<td>3.9</td>
<td>0.12</td>
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<td>0.61 ± 0.04</td>
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</tbody>
</table>
Weems and Lemon (1993) cite U-series age estimates for “Early Wando Formation” microcorals that assign a MIS 5e age (~130 ka) to this emergent shoreline complex.

### 3.2.1 Core Data

Five Geoprobe cores and four vibracores were collected within the Pamlico terrace (Figure 8). Cores 5, 6 (Figure 14), 7, 8, and 9 were collected within the landward portion of the terrace that has well preserved ridge and swale topography. These cores are each capped by 2 to 3 meters of LF-A, composed of very well sorted, very fine, massive, pale brown sand (see Core 6 in Figure 14). Cores 8 and 9 terminate in LF-A due to the depth limitations of the vibracoring method, whereas the deeper Cores 5, 6, and 7 contain a more extensive record of deposition.

In Core 5, the top 2.5 meters of LF-A has been replaced by an accumulation of LF-B, which is mostly peat. The underlying LF-A is stained brown, probably from the overlying organic matter. Only a meter of LF-C is present below this lithofacies and is laminated with darker clay layers. A large (4 cm) articulated valve of a hard clam (genus *Mercenaria*) was found immediately below this unit. This species is relatively common along the Atlantic coast of the southeastern US, occupying sand or mud substrata in tidal sand flats and other shallow (<10 m water depth) marine environments (Hadley, 1997). About 2 meters of LF-E is found below this and unconformably overlies 2 meters of LF-F, the top 20 cm of which is stained dark brown. Cores 6 and 7 each contain about 3 meters of LF-A which conformably overlies 2 to 3 meters of LF-C with noticeable parallel laminations and/or gently dipping cross-stratification (see Core 6 in Figure 14). The base of Core 6 is composed of LF-E with whole shells, mostly *Mulinia*, but unfortunately the contact with the overlying lithofacies, LF-C, was not recovered. This contact was recovered however in Core 7. In this core, the shallow portion of LF-E contains two thin (<10 cm) beds of fine sand.
Figure 14. Photograph and descriptive log of Core 6. Note the prominent laminations from 2.5 to 6 meters below the surface (LF-C), interpreted here as evidence of swash zone processes. Especially poor recovery in LF-C was caused by liquefaction.
Cores 10, 11, 12, and 13 were collected within a portion of the Pamlico terrace that lies seaward of an unnamed scarp (Figures 8 and 9). This portion of the terrace does not exhibit ridge and swale topography, but instead hosts dip-oriented features on a prominent shore-parallel ridge. Cores 11, 12, and 13, collected on the crest of this ridge, are capped by between 2 and 3 meters of LF-A. Core 13 terminates in this lithofacies, but Cores 11 and 12 contain an underlying interval of LF-C. Core 11 terminates in this interval of LF-C, whereas the deeper Geoprobe Core 12 contains additional subsurface information. LF-C in Core 12 overlies a meter of mud (LF-E), which in turn, overlies a separate interval of LF-C. The base of this core is composed of LF-F, the top of which contains two prominent layers of shell hash.

3.2.2 Radar Stratigraphy

Some 4,500 m of dip-oriented and 3,000 m of strike-oriented GPR profiles were collected over the Pamlico terrace. Along the landward portion of the Pamlico terrace, GPR profile DIP 1 (Figure 8) contains Radar Facies I(a) and III (see Table 4) that overlie a high-amplitude reflector (HAR-3 in Figure 15). In the seaward direction, these two radar facies grade into RF-V, a collection of moderately continuous, nearly parallel, seaward dipping reflections. This radar facies dominates the dip-oriented profile for over 2,000 meters (Figure 16) before a facies change at the base of an unnamed scarp (Figure 17). Near this abrupt facies change, RF-V begins to downlap seaward onto a nearly horizontal high-amplitude reflector, HAR-4. This prominent reflector as well as the overlying RF-V both terminate into RF-VI at the base of the unnamed scarp. Seaward of this, RF-VI eventually grades into the chaotic RF-I(a), which in turn transitions to RF-V near the Awendaw Scarp. A high-amplitude reflector (HAR-5) lies at the base of this scarp and outlines a separate lenticular body of RF-V (Figure 18).
Figure 15. Interpretation of GPR and borehole data along a portion of the Pamlico terrace. Three radar facies (I, III, and V) as well as a high amplitude reflector (HAR-3) are evident in this portion of GPR line DIP 1. Stratigraphic contacts originate from core interpretations and are inferred based on continuity of radar facies. See Figure 8 for GPR line and borehole locations.
Figure 16. Interpretation of GPR and borehole data along a portion of the Pamlico terrace. Radar Facies V dominates along this 900 meter section. Peat and Muck accumulations correspond to swales in between beach ridges. Stratigraphic contacts originate from core interpretations and are inferred based on continuity of radar facies. See Figure 8 for GPR line and borehole locations.
Figure 17. Interpretation of GPR and borehole data along a portion of the Pamlico terrace. Radar Facies V terminates into Radar Facies VI near the base of the scarp. Radar Facies VI corresponds to a peat and muck accumulation that attenuates the electromagnetic radar signal. See Figure 8 for GPR line and borehole locations.
Figure 18. Interpretation of GPR and borehole data along a portion of the Pamlico terrace. GPR does not resolve any significant stratigraphic boundaries within this portion of the terrace. Illustrated contacts arise from borehole interpretations. Radar Facies VI corresponds to a peat and muck accumulation that attenuates the electromagnetic radar signal.
3.2.3 Interpretation

A velocity estimate of 0.06 m/ns was used to ground-truth GPR data collected within the Pamlico terrace. This value, the published figure for saturated sand (Sensors and Software, 2003), is much less than that used for the landward Lower Talbot terrace (0.15 m/ns) because the Pamlico terrace is lower in elevation, hence closer to the local water table. The approximate elevation of the water table within the Pamlico terrace at the time of data collection was indicated by standing water in Wambaw swamp, which was observed at 8 meters above modern-day sea-level. The elevation of the surface of the Pamlico terrace ranges from 6 to 12 meters above sea-level, and is therefore considered nearly saturated.

Using this velocity estimate, lithofacies and key stratigraphic contacts obtained in cores were compared to radar facies and stratigraphic architecture indicated by GPR profiles. As in the Lower Talbot terrace, LF-A was found to correspond with Radar Facies I(a), and both were interpreted as a signature of eolian deposits. The eolian cover on the Pamlico terrace is noticeably thinner (3 m) than on the Lower Talbot (5 m), both in cores and GPR profiles. No buried paleosols were recovered by Pamlico cores, so only one generation of eolian deposition is found on this terrace. The top section of Core 5 indicates that some eolian deposits have been replaced by younger swamp-derived peat and muck accumulations. Similar sediments were observed on the surface of swales in between relict beach ridges. The GPR response within the swales, although largely obscured by air and ground wave interference, consists of very shallow lenticular bodies of highly continuous, parallel reflections, suggesting comparable deposits exist only just below the surface, within 1 to 2 meters.

RF-V is the most dominant radar facies within the landward portion of the Pamlico terrace (Figures 15, 16, and 17). This radar response correlates with the moderately well sorted, laminated sands of LF-C observed in Cores 5, 6, and 7. The lower amplitude internal reflections
of RF-V likely arise from subtle dielectric contrasts across bedding planes within LF-C, related to slight variations in grain size and/or magnetic permeability or susceptibility. The conspicuous offlapping geometry of RF-V indicates that this unit was deposited under progradational (regressive) conditions, an interpretation supported by the accretionary ridge and swale topography of the surface. Considering the lithology of LF-C and the geometry of RF-V, this lithofacies and its response to GPR are interpreted here as indicators of a regressive shoreface depositional setting.

In Geoprobe Cores 5, 6, and 7 LF-C overlies about 2 meters of the black shelly mud of LF-E, which is remarkably similar to modern sediments, known locally as “pluff mud”, that is deposited in an intertidal-backbarrier-marsh setting. LF-E is interpreted as originating in an analogous depositional environment, behind an early transgressive Awendaw barrier. This lithofacies is bounded above and below by two key stratal surfaces recovered in Core 7 (Figure 19). A sharp contact with the overlying LF-C correlates to a high-amplitude reflector (HAR-4). This contact is interpreted here as a regressive surface of erosion (RSE), an unconformity resulting from erosion by wave and current processes of the seaward migrating shoreface. LF-E is bounded below by LF-F, a lithofacies interpreted here as having an offshore continental shelf origin. The contact between the two is an obvious unconformity, marked by a 20 cm accumulation of shell hash, composed mostly of broken *Mulinia* (Figure 19). This unconformity is interpreted as a transgressive surface of erosion (TRS), a product of a landward migrating shoreface. Similar surfaces of erosion are documented in many modern coastal systems (Hayes, 1994; Fraser et al., 2005) and the stratigraphic records of ancient examples (Nummedal and Swift, 1987).

The interpretation of the seaward portion of the Pamlico terrace is more difficult than the landward portion discussed above. GPR does not clearly resolve any significant stratigraphic
Figure 19. Photograph and descriptive log of Core 7. Four lithofacies are shown. LF-E is bound above by a regressive surface of erosion (RSE) and below by a transgressive ravinement surface (TRS).
boundaries within this portion of the terrace (Figure 18), as Cores 10, 11, and 12 do not seem to correlate to any major reflectors or radar facies.

Core 12 (Figure 20) was collected via Geoprobe on the crest of the seaward ridge of the Pamlico terrace. This core was interpreted as containing two separate barrier island successions. The upper succession consists of about 3 m of LF-A, interpreted as eolian cover, that conformably overlies an interval of LF-C, interpreted as laminated shoreface sand. As in the landward cores, LF-C unconformably overlies an accumulation of backbarrier mud, LF-E. Unlike landward cores however, LF-E unconformably overlies an additional interval of LF-C, interpreted as shoreface sand due to its conspicuous parallel laminations (Figure 20). This lower unit lies on a thin interval of LF-E, which in turn, unconformably rests on a section of LF-F that contains layers of shell hash. The lower interval of shoreface sand (LF-C) is interpreted here as correlable to the landward regressive portion of the Pamlico terrace (Awendaw barrier), while the upper interval of shoreface sand is interpreted as deposits reworked by a later highstand. This interpretation is supported by the surficial appearance of this seaward portion of the terrace. This seaward ridge contains numerous dip-oriented features, the largest of which is a heart-shaped depression stemming from the Awendaw scarp (Figure 9).

3.2.4 OSL Geochronology

Samples for OSL analyses were collected from Cores 8, 9, and 11. The samples were extracted from intervals interpreted as basal eolian or swash zone facies. All OSL age estimates from sediments from Cores 8, 9, and 11 fall within the 120 - 150 ka range (Table 6), which is consistent with previous estimates from U-series dating of microcorals (Cronin et al., 1981; McCartan et al., 1982; Szabo, 1985) collected from marine deposits within the Lower Wando Formation. Although only one OSL age estimate has an adequate number of aliquots to be
Figure 20. Photograph and descriptive log of Core 12. The arrangement of four lithofacies shown above is interpreted as two superimposed barrier island successions, the lower of which is correlable to the landward Awendaw barrier.
considered robust, all estimates fall within a range of 120 - 150ka, which is below the 150 to 240ka limitation provided by dose rates.

These OSL age estimates assign the entire Pamlico terrace to the highstand(s) associated with LIGM, MIS 5e. This age assignment in conjunction with subsurface stratigraphy and preserved geomorphology suggests several fluctuations of sea-level within MIS 5e. First, an early transgression emplaced a thin transgressive root over lagoonal deposits. Next, this thin barrier evolved into a regressive form as sea-level stabilized. This prograding mainland-attached barrier hosted thick accumulations of shoreface sands (LF-C) overlain by ridge and swale topography. These extensive deposits were then reworked by an additional brief transgression to form the prominent ridge on the seaward portion of the Pamlico terrace. A double transgression of MIS 5e is documented elsewhere along the coast of South Carolina (Hollin and Hearty, 1990) as well as other parts of the world including the Bahamas (Hearty and Kindler, 1995) and New Guinea (Chappell et al., 1996). Although it is beyond the resolution of the OSL method to distinguish late MIS 5e deposits from those deposited earlier in the substage, cross-cutting relationships among stratigraphic units and geomorphic features within the Pamlico terrace document a double transgression during LIGM, MIS 5e.

3.3 Princess Anne and Silver Bluff Terraces

Within the study area, the Princess Anne terrace is composed of two distinct geomorphic units (Figure 9). The landward portion of the terrace lacks surficial expressions of any emergent barrier systems, and seems to be readily erodable as it is dissected by numerous tidal creeks such as Awendaw Creek and the Wando River. However, the seaward portion of the Princess Anne contains the easily discernable Mt. Pleasant barrier system with well preserved beach ridges that are nearly continuous from Charleston Harbor to the mouth of the Santee River. This emergent barrier system is much more continuous than the seaward modern chain, and more closely
resembles the “barrier-lagoon-strand plain coast” of Nayarit, Mexico (Curray, et al., 1967) and the beach ridge plains found on the west coast of Africa (Anthony, 1995). McCartan and others (1984) designate the Princess Anne as a collection of Q2 (~100 ka) beach and lagoonal units, whereas Weems and Lemon (1993) identify the Princess Anne terrace as the “Late Wando Formation” and cite U-series age estimates that assign a MIS 5a age (~85 ka) to the emergent Mt. Pleasant barrier and its adjacent lagoonal deposits.

The seaward bounding Mt. Pleasant Scarp and Silver Bluff terrace are poorly defined in the literature and not common along the central coast of South Carolina. Silver Bluff deposits, as defined locally by McCartan and others (1984) and Colquhoun (1965) lie immediately landward of the extensive mud flats backing Cape Romain (Figure 7 and 8). Weems and Lemon (1993) identify Silver Bluff deposits on the seaward margin of the Mt. Pleasant barrier, just North of Charleston Harbor, and cite a $^{14}$C date of ~33ka obtained from a sample of “surf-polished wood” from a sand pit within these deposits. They accept this “Mid-Wisconsin” age estimate despite $^{14}$C dates of 8ka and 7ka obtained from other wood samples collected via shallow augering nearby. McCartan and others (1984) label Silver Bluff deposits landward of Cape Romain as “modern” with a maximum age of 4ka, without citing geochronological control.

3.3.1 Core Data

One Geoprobe core was collected from the landward portion of the Princess Anne terrace, and a total of seven cores were collected from the emergent Mt. Pleasant barrier on the seaward portion of the terrace (Figure 8). Core 14 was recovered from the base of the Awendaw scarp on the landward margin of the Princess Anne. The top portion of this core is a fining upwards interval of sand that contains prominent cross-stratification from its base nearly to the ground surface (LF-D). This rests on about a meter of peat (LF-B) that contains many wood fragments with very little signs of oxidation. This peat emitted a strong hydrogen sulfide odor
and expanded upon the splitting of the core. The underlying meter of dark grey mud (LF-E) contains no shell material. The base of this core is composed of 1 ½ meters of a well-indurated interval of LF-F with abundant shell hash.

Geoprobe Cores 14, 15, 20, and 21 were collected from the Mt. Pleasant barrier to provide additional stratigraphic context for the OSL dated vibracores 17, 18, and 19. In general, all of these cores are capped by about a meter of LF-A with a surficial soil horizon. Two of the vibracores, 18 and 19, terminate in this lithofacies, while Core 17, as well as the Geoprobe cores contain an underlying section of a lithofacies not yet encountered, LF-G. This lithofacies is very similar to LF-C, except that it is much coarser grained and poorly sorted. Core 17 terminates in this lithofacies at a depth of about 4 meters, whereas the cores obtained via Geoprobe are much deeper. In Core 20, LF-G unconformably overlies three meters of LF-E, which in turn overlies LF-F with abundant shell hash. Cores 15 and 21, collected further inland, also contain an underlying section of LF-E, but in these cores it includes interbeds of coarse sand. Both of these cores terminate in this lithofacies at a depth of about 9 meters.

Core 16, the only core collected from the Silver Bluff terrace, is capped by LF-A, which conformably overlies only half a meter of LF-C with very faint laminations. This in turn overlies a very thick (~4m) accumulation of LF-E that contains abundant shell material and interbeds of fine sand. About 20 cm of shell hash (LF-F) is found at the base of this core.

3.3.2 Radar Stratigraphy

Three dip-oriented GPR lines were collected within the Princess Anne terrace. The last 1300 meters of DIP 1 (Figure 8) contains only Radar Facies VI, flat lying shallow reflections underlain by numerous hyperbolic point reflections. The radar signal from this area is severely attenuated by peat and mud within the Little Wambaw Swamp (Figure 18).
The dip-oriented lines collected from the seaward portion of the Princess Anne terrace contain a much different radar signature. DIP 6 (Figure 8) was acquired along the eastern portion of the Mt. Pleasant barrier system, roughly perpendicular to the trend of ridge and swale topography. This GPR profile is composed of a shallow expression of Radar Facies V that is confined to the upper 5 meters of the profile, below which the radar signal is attenuated (Figure 21). The final dip-oriented GPR profile (DIP 7, Figure 8) was collected to investigate the seaward margin of the Princess Anne terrace, Mt. Pleasant Scarp, and Silver Bluff terrace. This GPR profile is of extremely poor quality, likely due to interference from nearby utility lines and signal attenuation due to salt water in the subsurface. A shallow expression of RF-V, nearly identical to that seen in DIP 6 persists along the seaward margin of the Mt. Pleasant barrier, and terminates at the base of the scarp into RF-VI with very large hyperbolic point reflections (Figure 22).

3.3.3 Interpretation

A velocity estimate of 0.06 m/ns, the value for saturated sand, was used to ground truth all GPR data acquired from the Princess Anne terrace. Using this velocity estimate, the contact between LF-D and LF-B in Core 14 corresponds with a high-amplitude reflector (HAR-5). Considering the physical characteristics of this lithofacies, and the lenticular geometry seen in the GPR profile (Figure 18), LF-D is interpreted as fill material deposited within a ephemeral stream along the base of the Awendaw scarp. This stream can still be seen in aerial photographs and satellite imagery (Figure 9) near the core location. The sandy channel fill in Core 14 unconformably overlies a peat and muck accumulation (LF-B). HAR-5 arises from a strong dielectric contrast between these two lithologies, and likely represents a fluvial scour surface.

The remaining seaward portion of this GPR profile (DIP 1) is composed of a very shallow RF-VI, below which the radar signal is quickly attenuated. Although this weak GPR
Figure 21. Section of GPR line DIP 6 showing correlation with Core 20. Vertical exaggeration of GPR profile is about 10x. Photographs show 3 major lithofacies: LF-C, LF-E, and LF-F, discussed in text. See Figure 8 for core and GPR profile locations.
Figure 22. GPR line DIP 7. The Princess Anne terrace and Mt. Pleasant scarp contain a shallow expression of RF-V, which corresponds to LF-C in Cores 15 and 16. No discernable stratigraphic contacts are provided from the Silver Bluff terrace, likely from interference from overhead powerlines and signal attenuation by subsurface salt water. See Figure 8 for GPR profile location.
signal does not identify any significant stratigraphic contacts, it does suggest that no sandy sediments are present here in the shallow subsurface. This information, along with surface geomorphology that resembles modern backbarrier lagoons and tidal flats shown in satellite imagery (Figure 9) implies that this portion of the Princess Anne was deposited in an analogous backbarrier setting.

In contrast, GPR profiles from the Mt. Pleasant barrier on the seaward portion of the Princess Anne terrace contain RF-V several meters below the surface. This radar facies correlates fairly well with the sandy top portions of Cores 15 and 20 (LF-G), collected along the dip-oriented GPR transects. However, unlike the GPR profile from the Pamlico and Lower Talbot terraces, no high-amplitude reflectors are found within Princess Anne profiles. One would expect a prominent reflector from the sharp contact between LF-G and LF-E. This can be explained by signal attenuation caused by subsurface salt water, as this terrace is much closer to the modern ocean, both in altitude and horizontal proximity. As in the Pamlico terrace, the offlapping geometry of RF-V here in the Princess Anne indicates that the Mt. Pleasant barrier was deposited under progradational (regressive) conditions, an interpretation again supported by the accretionary ridge and swale topography of the surface. However, there are important sedimentological differences between this shoreline complex and landward (older) deposits. In general, Princess Anne (Mt. Pleasant barrier) cores have an eolian cover of one meter or less, whereas Pamlico and Lower Talbot (Awendaw and Cainhoy barrier) cores have eolian units of 3 and 5 m average thicknesses, respectively. Princess Anne cores are also less sorted and contain very coarse layers in which feldspar grains are abundant. These differences likely reflect contrasts in hydrographic conditions and local sediment supply at the formative time of this shoreline complex.
GPR line DIP 7 contains no coherent reflections within the Silver Bluff terrace (Figure 22). The upper 3 meters of Core 16 is composed of sand (LF-A and LF-C), and again should produce some GPR response analogous to that seen in the landward shoreline complexes. Therefore, signal attenuation and interference must be responsible for RF-VI here, unlike the landward portion of the Princess Anne where this radar response is linked to backbarrier deposits. Although Core 16 was collected seaward of a prominent scarp and contains sand that appears to be slightly laminated, this portion of the core cannot be definitively described as swash zone strata from an emergent beach ridge deposit. The sand found on the surface here could easily be slope wash material derived from the erosion of the adjacent Mt. Pleasant barrier deposited on modern backbarrier mud. Additional data are needed to confirm the presence of the Silver Bluff terrace and its associated beach deposits that others have identified (McCartan et al., 1984; Colquhoun, 1965) between the Princess Anne and modern backbarrier in this region.

3.3.4 OSL Geochronology

Cores 17, 18, and 19 were collected via vibracore from the seaward portion of the Princess Anne terrace and sampled for OSL analyses. Core 17 was sampled within coarse sandy layers that were clearly deposited in a swash zone setting, while Cores 18 and 19 were sampled in shallower intervals interpreted as basal eolian. Both of these facies are suitable for OSL dating considering that they are essentially synchronous and were sufficiently bleached during deposition. All OSL age estimates from sediments from the Princess Anne terrace fall within the 85-90 ka range, which agree with previous estimates from alpha-spectrometry (Cronin et al., 1981; McCartan et al., 1982; Szabo, 1985) and higher resolution TIMS techniques (York et al., 1999; Wehmiller et al., 2004) for U-series dating of microcorals that assign an MIS 5a age to the Late (upper) Wando Formation. Two OSL age estimates from Core 19 (Table 6) are considered
robust because analyses were repeated with many aliquots of each sample. Age estimates from other Princess Anne samples are consistent with those from Core 19, but are only preliminary.

3.4 Relative Sea-level History

This study relies on the assertion that linking shoreline complexes to formative sea-levels can not be done using the surface elevation of beach ridges, but rather must rely on identification of specific strata deposited within a swash zone setting. Swash zone strata and the overlying contact with eolian sediments was identified qualitatively here, based on the occurrence of parallel laminations and visual estimates of grain size and sorting (Figure 23).

These qualitative interpretations of eolian/intertidal boundaries are supported by quantitative grain size data that show strata interpreted to represent swash zone deposition is more coarsely skewed and slightly less sorted than that interpreted to represent eolian reworking and deposition (Figure 24). Sedimentological differences and varying thickness of eolian cover among the shoreline complexes studied here suggest contrasting modes of beach ridge formation over time. For example, the greater thickness of eolian caps on Awendaw barrier deposits implies that its ridge and swale topography originates primarily from relict foredunes, as suggested by Hesp (1984, 2002) for beach ridges elsewhere. By contrast, the beach ridges of the Mt. Pleasant barrier have only a thin veneer of eolian sand, which seems to validate emergent swash bar models (Curray et al., 1967; Psuty, 1967).

Although the eolian/swash contact is gradational in most cores, the transition between the two facies usually occurs over less than half a meter, and can therefore be used as a very precise indicator of past sea-levels. A relative sea-level record for this portion of the South Carolina coast was compiled using the upper limit of swash zone sediments which were dated directly by OSL methods, or by association with nearby dated samples (Table 7). This sea-level record indicates that at least four major sea-level highstands are recorded within the Lower Talbot,
Figure 23. Interpretation of a portion of Core 6. An example of the inorganic sea-level indicators used in this study is shown above.
Figure 24. Granulometric analyses of eight samples from eolian and swash zone strata. (A) Grain size frequency plot of 4 eolian and 4 swash zone sediment samples. Note the grouping of the two populations of data. (B) Plot of the average grain size frequency of the eolian and swash zone samples, along with average statistical parameters calculated using the moments method (Boggs, 2001).
Table 7. Relative sea-level history of the study area. Elevations of swash zone strata are average values obtained from Vibracores and Geoprobe cores from each emergent barrier. The Silver Bluff terrace is not listed here, although it may be present within the study area.

<table>
<thead>
<tr>
<th>Terrace (Relict Barrier)</th>
<th>Preliminary OSL age (MIS)</th>
<th>Max. Elevation of Swash Zone Strata (mASL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Talbot (Cainhoy)</td>
<td>240 ka (MIS 7)</td>
<td>12</td>
</tr>
<tr>
<td>Pamlico (Awendaw)</td>
<td>130 ka (MIS 5e)</td>
<td>9 and 6</td>
</tr>
<tr>
<td>Princess Anne (Mt. Pleasant)</td>
<td>85 ka (MIS 5a)</td>
<td>5</td>
</tr>
</tbody>
</table>

Pamlico, and Princess Anne terraces within the study area. The Lower Talbot terrace contains highstand deposits with swash zone strata at a maximum altitude of 12 meters above present day sea-level (mASL), a highstand which preliminary OSL ages suggest occurred during MIS 7 (~240 ka). The Awendaw barrier on the Pamlico terrace was emplaced by an early MIS 5e highstand that peaked at ~ 9 mASL. This was followed by a late MIS 5e highstand of ~ 6 mASL that reworked the seaward margin of the Awendaw barrier. The peak of MIS 5a sea-level is recorded within the Mt. Pleasant barrier on the Princess Anne terrace, where it is preserved at a maximum elevation of ~ 5 mASL (Table 7).
CHAPTER 4

DISCUSSION

Core data, GPR profiles, and OSL age estimates from the Bulls Bay area of the central coast of South Carolina identify at least four unconformity-bounded highstand units deposited by multiple Late Pleistocene transgressive-regressive cycles of relative sea-level. These units comprise the Cainhoy, Awendaw, and Mt. Pleasant relict barrier systems within their respective Lower Talbot, Pamlico, and Princess Anne terraces (Figure 25). Each of these emergent shoreline complexes is bounded below by two types of unconformities associated with erosion by wave and current processes of the migrating shoreface: (1) a transgressive ravinement surface (TRS), above which transgressive backbarrier muds are emplaced on older shelf sediments during relative sea-level rise and (2) a regressive surface of erosion (RSE), above which shoreface sands are emplaced on older sediments during relative sea-level fall (Nummedal and Swift, 1987; Plint and Nummedal, 2000). The landward extent of the transgressive ravinement surface is defined as the shoreline of maximum transgression (SMT), and roughly corresponds to the landward bounding scarp of each terrace. These scarps all trend SW - NE, roughly parallel to the modern day coast, whereas major faults in the region, such as the Adams Run and Charleston faults, have a SE - NW trend in response to SW - NE oriented compression (Weems and Lewis, 2002). Therefore, the presence of these scarps is not directly related to neotectonic deformation, however local uplift or subsidence may play a role in the present-day elevations of each relict shoreline complex and its bounding marine erosion-derived scarps.

The deposits studied here were emplaced during a very small portion of the glacio-eustatic cycle: the very latest stages of sea-level rise, a brief period of highstand stability, and the very beginnings of sea-level fall. Designation of the allostratigraphic units produced by these
Figure 25. Cross sections of the emergent shoreline complexes investigated by this study. TRS= Transgressive Ravinement Surface, RSE= Regressive Surface of Erosion, SMT= Shoreline of Maximum Transgression. Discussion of each complex in text.
sea-level oscillations into systems tracts commonly used to aid in seismic interpretation (Highstand, Falling Stage, Forced Regressive, Lowstand, etc.) depends on the sequence stratigraphic nomenclature employed (as described by Posamentier and Vail, 1988; Plint and Nummedal, 2000, and many others) and was not a priority in this study. Development of a sequence stratigraphic framework from the identification of sequence boundaries, parasequence sets, and their stacking patterns obviously requires a more robust regional stratigraphic framework that can be linked to the stratigraphic record in along-strike and basinward directions. Each shoreline complex identified by this study can be subdivided into various lithofacies deposited in backbarrier, beach, and open marine environments. Relict beach facies contain preserved swash zone strata that accurately indicate the elevations of sea-level highstands responsible for the emplacement of each barrier system.

4.1 Coastal History of the Study Area

The oldest shoreline complex studied here, the Cainhoy barrier system, lies on the Lower Talbot terrace. Unlike its younger counterparts, this emergent barrier lacks any preserved morphological features, likely a result of extensive erosion and/or eolian modification. It is capped by an interval of eolian sand that is much thicker than the eolian cover found atop landward shoreline complexes, interpreted as evidence of additional generations of eolian activity, likely sourced by the adjacent mainland-attached Awendaw barrier system. Strike-oriented GPR profiles suggest a portion of this shoreline complex has been modified by younger fluvial activity, whereas a dip-oriented profile delineates a thin transgressive beach.

Optical age estimates place the Cainhoy barrier within MIS 7, but this estimate is considered only a minimum because a limited number of sample aliquots were analyzed and dose results are near OSL signal saturation. However, a MIS 7 age for the Cainhoy barrier system is consistent with the short chronology model (Table 8), based on Uranium-series
Table 8. Comparison of Late Pleistocene units identified by various studies. Terrace names are referenced only for geographic location, and are not equivalent to others along the US Atlantic Coast, or South Carolina Geological Survey map units (Doar, 2001). The original Short Chronology based on Uranium-series coral ages is supported by this study.

<table>
<thead>
<tr>
<th>Terrace Name¹</th>
<th>Formation Name²</th>
<th>Long Chronology Model³</th>
<th>Revised Long Chronology Model⁴</th>
<th>Short Chronology Model⁵</th>
<th>THIS STUDY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recent</td>
<td>N/A</td>
<td>MIS 1</td>
<td>MIS 1</td>
<td>MIS 1</td>
<td>MIS 1?</td>
</tr>
<tr>
<td>Silver Bluff⁶</td>
<td>N/A</td>
<td>MIS 5?</td>
<td>MIS 5a/5c</td>
<td>MIS 1</td>
<td>MIS 1?</td>
</tr>
<tr>
<td>Princess Anne</td>
<td>Late Wando</td>
<td>MIS 5</td>
<td>MIS 5e</td>
<td>MIS 5a/5c</td>
<td>MIS 5a</td>
</tr>
<tr>
<td></td>
<td>Formation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pamlico</td>
<td>Early Wando</td>
<td>Pre-MIS 5</td>
<td>MIS 7</td>
<td>MIS 5e</td>
<td>MIS 5e</td>
</tr>
<tr>
<td></td>
<td>Formation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower Talbot</td>
<td>Ten Mile Hill</td>
<td>Pre-MIS 5</td>
<td>MIS 9?</td>
<td>MIS 7</td>
<td>MIS 7</td>
</tr>
<tr>
<td></td>
<td>Beds (informal)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹After Colquhoun (1965, 1974, 1991)
²After McCartan et al. (1982) and Weems et al. (1993; 1997)
³After Wehmiller and Belknap (1982) and Harris (2002)
⁴After Wehmiller et al. (1997) and Harris (2002)
⁵After McCartan et al. (1982; 1984), Corrado et al. (1986)
ages from corals collected from the Lower Talbot terrace, South of Charleston Harbor (Szabo, 1985). Swash zone strata were penetrated by two cores (see 1 & 2 in Appendix I) at an elevation of about 12 meters above present day sea-level. MIS 7 is generally regarded as a relatively moderate interglacial period that produced sea-level highstands near present day levels (Chappell, 1983; Shackleton, 2000; Muhs et al., 2004). This implies that either the Cainhoy barrier is in fact much older than MIS 7, or that it has experienced about 12 m of uplift since its formation. Averaged over time, this uplift yields a long term rate of about 5 cm/kyrs.

The next landward shoreline complex, the Awendaw barrier system, resides on the Pamlico terrace. This mainland-attached shoreline complex is easily identified on satellite and aerial images, because of its well preserved accretionary ridge and swale topography. The emergent barrier is less than a kilometer wide near Charleston Harbor, but widens to over 4 km near Bulls Bay, likely in response to greater sediment supply from the Santee River. An unnamed scarp, parallel to the modern shoreline, cuts through the center of the Awendaw barrier. At the base of this scarp lies a portion of Wambaw Swamp, which resides just landward of a prominent sandy ridge whose surface contains numerous dip-oriented features (Figure 9).

A dip-oriented GPR profile across the Awendaw barrier documents an early transgressive phase of deposition below the landward portion of the Pamlico terrace. This GPR response transitions to prominent offlapping clinoforms that characterize the extensive regressive beach deposits that underlie accretionary ridge and swale topography of a well-preserved strand plain. Unfortunately, the value of GPR data are severely limited landward of the unnamed scarp due to signal attenuation by the Wambaw Swamp.

OSL age estimates indicate that the entire Awendaw barrier system (Pamlico Terrace) is associated with the LIGM, MIS 5e. A MIS 5e age for this emergent shoreline supports the short chronology model (Table 8), as Early Wando Formation corals fall within the 120 to 140 ka
range (Szabo, 1985). The subsurface stratigraphy and preserved geomorphology of this emergent barrier system document a complex MIS 5e sea-level history. First, an early MIS 5e transgression emplaced a thin barrier over lagoonal deposits, which eventually evolved into a regressive (progradational) form as sea-level stabilized. A later MIS 5e brief regressive-transgressive episode then formed the unnamed scarp and adjacent ridge on the seaward portion of this emergent barrier. This double transgression of MIS 5e is documented elsewhere along the coast of South Carolina (Hollin and Hearty, 1990) as well as other parts of the world including the Bahamas (Hearty and Kindler, 1995) and New Guinea (Chappell et al., 1996). Although it is beyond the resolution of the OSL method to distinguish late MIS 5e deposits from those deposited earlier in the substage, cross-cutting relationships among stratigraphic and geomorphic units within the Pamlico terrace indicate two separate transgressive-regressive cycles.

The upper limits of swash zone facies associated with each of these highstands range from 6 to 9 meters above present day sea-level. The highstand associated with MIS 5e was supposedly the highest since MIS 9 (Martinson et al., 1987) and its associated shoreline(s) are universally agreed to have formed at an elevation of about 3 meters above present day sea-level (Muhs et al., 2004). This implies that the Awendaw barrier has been uplifted about 6 meters since its formation, yielding an average long-term uplift rate of about 5 cm/ 1,000 yrs, consistent with the uplift rate derived from landward Lower Talbot deposits (Figure 26).

The most controversial terrace, the Princess Anne, can be separated into two distinct geomorphic compartments, a landward portion that is extensively dissected by tidal creeks, and a topographically higher seaward portion with preserved ridge and swale topography, locally known as the Mount Pleasant barrier system. These two units are identified as the lagoonal and barrier lithofacies of the Late Wando Formation by McCartan and Weems (1982) and Weems and others (1993; 1997) who cite U-series coral ages that assign a MIS 5a (~85 ka) age to these
deposits (Szabo, 1985). Although these results have been recently confirmed by more accurate TIMS techniques (Wehmiller et al., 2004), their use as indicators of past sea-levels remains controversial because of conflicts with widely accepted eustatic records (Chappell et al., 1996; Martinson, 1987). Critics point out isotopic evidence for diagenetic alteration of coral samples, problematic implications of amino acid racemization results (Wehmiller et al., 1988), and inadequately defined stratigraphic context of the fossil coral specimens.

![Figure 26. Inferred formative elevations of highstand deposits. Present day elevations are shown by pink dots, and calculated eustatic formative elevations are blue. The averaged long-term uplift rate is derived from MIS 5e deposits. Note that this method requires that the MIS 5a highstand was close to present day sea level.](image)

This study supports these controversial U-series coral ages, as OSL age estimates of Mt. Pleasant barrier sediments fall within the 80 to 90 ka range, offering further support for the short chronology model (Table 8). Cores from the Mt. Pleasant barrier contain swash zone sand at
elevations up to 5 meters above present day sea-level. If the long-term uplift rate derived from
the landward Cainhoy and Awendaw relict barriers (5 cm/1,000 yrs) is assumed constant over
time, the Mt. Pleasant barrier has been uplifted about 4 meters since its formation (Figure 26).
Although uplift rates in this region may not be constant over such time scales (Talwani and
Schaeffer, 2001), this uniform uplift correction, that uses the MIS 5e highstand as a benchmark,
is the standard method used to calculate eustatic levels from many other shoreline records, most
notably the widely cited studies from Papua New Guinea (Gallup et al., 1994; Chappell et al.,
1996). Applying this same methodology to the relative sea level history produced by this study
requires that the global elevation of the MIS 5a highstand was close to present day level, as some
eustatic proxies suggest (Shackleton, 2000).

Alternatively, the deformation of these relict shorelines could arise primarily from
isostatic adjustments of the Earth’s crust to loading and unloading by ice and seawater, both of
which vary dramatically from interglacial to glacial periods (Potter and Lambeck, 2003). The
response of the crust to these changing loads would also behave in a non-linear fashion due to its
reliance on physical properties of the underlying lithosphere and mantle, the spatial and
especially temporal variability of which are complex and presently poorly-constrained (Peltier,
2002). Potter and Lambeck (2003) recently identified a gradient of MIS 5a sea-levels that
suggests isostatic adjustments related to the North American Ice Sheet played a pivotal role in
determining the relative height of the MIS 5a highstand in the Western Atlantic region (Figure
27). Identification of the isostatic mechanisms responsible for this regional variability in relative
sea-level is beyond the scope of this study. However, deposits from both the MIS 5e and MIS 5a
highstands have been clearly identified above modern sea-level on this portion of the Lower
Coastal Plain of South Carolina. Future studies should be conducted on other parts of the US
Atlantic margin to investigate the spatial variability of the present day elevations of MIS 7, 5e,
Figure 27. Observations in the Caribbean region for peak sea-level during MIS 5a and 5e. Records are based on AAR and U-series dates of coral samples or submerged speleothems and are referenced below. Note the apparent increasing gradient of MIS 5a sea-levels from South to North, towards the former positions of North American ice sheets, with MIS 5e levels remaining constant (modified from Potter and Lambeck, 2003). References: (1) Hearty and Vacher, 1994 (2) Hearty and Kaufman, 2000 (3) Ludwig et al., 1996 (4) Dodge et al., 1983 (5) Edwards et al., 1997 (6) Lundberg and Ford, 1994 (7) Chen et al., 1991

and 5a highstand deposits. Such information could provide valuable constraints for ongoing efforts to model the isostatic response of the lithosphere in this region (Potter and Lambeck, 2003), or may delineate localized zones of active uplift (Weems and Lewis, 2002). This may ultimately separate the eustatic, tectonic, and isostatic components of the relative sea-level history documented by this study, as well as nearby records from the US Atlantic margin.

Highstand deposits from MIS 5c (~100 ka) were not encountered by this study. Several explanations could account for the absence of this highstand along this portion of the Atlantic coast: (1) The shoreline complex associated with MIS 5c was eroded by the subsequent MIS 5a transgression, (2) The magnitude of the MIS 5c highstand was smaller in either a relative or
eustatic sense and produced deposits below present day sea-level, or (3) remnants of MIS 5c deposits lie beneath the landward portion of the Princess Anne terrace, which was not investigated in great detail by this study. Weems and his colleagues at the USGS (Weems and Lemon, 1993; Weems and Lewis, 1997) suggest that shelf sands associated with MIS 5c lie below estuarine deposits of the Late Wando Formation (MIS 5a), but incorrectly reference corals dated at 80 to 90 ka as geochronological control. Harris (2002) and Zayac (2003) identify MIS 5c deposits south of Charleston Harbor, however, MIS 5c deposits are absent between Charleston and the Santee River. Additional coring within the Princess Anne terrace is needed to confirm this assertion and investigate the apparent along-strike variability of the MIS 5c highstand as recorded in South Carolina, and elsewhere along the Atlantic Coastal Plain.
CHAPTER 5

CONCLUSIONS

Terraces of the Lower Coastal Plain of South Carolina contain a well preserved succession of unconsolidated marine sediments deposited during successive Late Pleistocene transgressive-regressive cycles of relative sea-level. These highstands emplaced an unconformity-bounded relict barrier complex on each terrace that can be subdivided into lithofacies deposited in lagoonal, beach, and offshore environments. OSL dating of beach facies supports a short chronology model that relies on Uranium series radiometric ages of encrusting microcorals (Szabo, 1985; Wehmiller et al., 2004) to assign the emergent Cainhoy, Awendaw, and Mt. Pleasant barrier systems to MIS 7, MIS 5e, and MIS 5a, respectively (Table 8).

The validity of the MIS 5a coral ages (~80 ka) in particular, has been controversial because previous eustatic estimates of this highstand place it at over 20 m below present day sea-level elevation (Chappell et al., 1996; Schellmann and Radtke, 2003). Critics often attribute this discrepancy to the diagenetic history of microcoral samples, or their uncertain stratigraphic relationships to sea-level. This study used independent methodology to directly estimate the age of an alternative sea-level marker, the upper limit of swash zone strata found within beach ridge deposits. A combination of GPR profiling and deep sediment coring provided a robust stratigraphic framework for the interpretation of these swash zone sediments as an important record of relative sea-level. This record indicates that MIS 7, MIS 5e, and MIS 5a deposits are currently at elevations 12, 9 to 6, and 5 meters above present day sea-level, respectively.

Since the emergence of new geochronological methods that extend beyond Carbon-14 limitations, such as Uranium series, AAR, and OSL techniques, a great deal of attention has been focused on evaluating stratigraphic records of relict shorelines to independently test ice volume and eustatic sea-levels as predicted by oxygen isotope data. Although age estimations of a
variety of sea-level indicators continue to improve, the sea-level histories produced by shoreline studies always document *relative* sea-level because they contain not only eustatic, but also variable amounts of tectonic and/or isostatic components. Identifying the tectonic and isostatic portions of a particular sea-level record can be difficult and usually requires broad assumptions regarding the tectonic or isostatic history of the study area.

Although the study area of this project lies within the passive US Atlantic margin, the shoreline complexes attributed to MIS 7 and 5 highstands clearly no longer reside at their formative elevations. They have moved tens of meters in the vertical sense relative to present day sea-level, and possibly with respect to one another, throughout time. Identification of complex isostatic and/or tectonic components of the relative sea-level record documented by this study will require continued collaboration with the geophysical research community, as modeling efforts to describe the response of Earth’s surface to glacio-eustatic changes are refined. Also, careful stratigraphic studies that document relative sea-level change elsewhere along the US Atlantic Coastal Plain will provide useful constraints on the spatial variability of tectonic and/or isostatic deformation and the time frames over which they have occurred. This may ultimately improve the characterization of past climate, sea-level, and coastal evolution in both a global and regional sense and provide an analog by which to measure climate change and coastal response during our present interglacial period.
REFERENCES


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APPENDIX: CORE LOGS AND PHOTOGRAPHS

A descriptive diagram of each core was prepared based on qualitative lithologic descriptions. For most cores, a photograph of the core is included with a scale bar. In these photographs, stratigraphic “up” is always to the top left. All cores obtained via Geoprobe are 3.8 cm (1.5 in) in diameter, whereas vibracores have a diameter of 7.6 cm (3 in). Core sediments were characterized by qualitative grain size, dry color, mineralogy, sedimentary structures, and the presence of organic or shell material. When possible, recovered shells were identified to the genus level. Ground surface elevations reported for each core were obtained via differential GPS and have a vertical uncertainty of less than one meter.
Core # 1
Field #: RW_1_12-2
Surface Elevation: 17.2 mASL
Total Depth: 10.7 m
Core # 1
Field #: RW 1_12-2
Surface Elevation: 17.2 mASL
Total Depth: 10.7 m
Core # 2
Field #: MB 1.7-1
Surface Elevation: ~ 15 mASL
Total Depth: 3.8 m

Burrows (undifferentiated)
Massive Sand
Laminated Swash Zone Sand
Lagoonal Mud (w/ shells)
Shell Hash
Peat
Roots

*= OSL Sample
Core # 2
Field #: MB 1_7-1
Surface Elevation: ~ 15 mASL
Total Depth: 3.8 m
Core # 3
RW 1_12-1
Surface Elevation: 14.7 mASL
Total Depth: 12.2 m

- Burrows (undifferentiated)
- Massive Sand
- Laminated Swash Zone Sand
- Lagoonal Mud (w/ shells)
- Shell Hash
- Peat
- Roots
Core # 3  
RW 1_12-1  
Surface Elevation: 14.7 mASL  
Total Depth: 12.2 m
Core # 4
Field #: MB 1_3-1
Surface Elevation: ~15 mASL
Total Depth: 4.0 m

- Burrows (undifferentiated)
- Massive Sand
- Laminated Swash Zone Sand
- Lagoonal Mud (w/ shells)
- Shell Hash
- Peat
- * = OSL Sample
- Roots
Core # 4
Field #: MB 1_3-1
Surface Elevation: ~15 mASL
Total Depth: 4.0 m
Core # 5
Field #: RW 1_13-1
Surface Elevation: 11.9 mASL
Total Depth: 9.1m
Core # 6
Field #: RW 1_13-2
Surface Elevation: 11.5 mASL
Total Depth: 9.1m
Core # 7
Field #: RW 1_11-2
Surface Elevation: 10.4 mASL
Total Depth: 9.1m

- Burrows (undifferentiated)
- Massive Sand
- Laminated Swash Zone Sand
- Lagoonal Mud (w/ shells)
- Shell Hash
- Peat
- Roots
Core #7
Field #: RW 1_11-2
Surface Elevation: 10.4 mASL
Total Depth: 9.1m
Core #8

Field #: MB 1_6-1
Surface Elevation: ~10 mASL
Total Depth: 3.0 m
Core # 9
Field #: MB 1_7-2
Surface Elevation: ~11 mASL
Total Depth: 3.0 m

Burrows (undifferentiated)
Massive Sand
Laminated Swash Zone Sand
Lagoonal Mud (w/ shells)
Shell Hash
Peat
= OSL Sample
Roots
Core #9
Field #: MB 1_7-2
Surface Elevation: ~11 mASL
Total Depth: 3.0 m
Core #10
Field #: RW 1_13-3
Surface Elevation: 8.8 mASL
Total Depth: 9.1 m

DEPTH (m)

- Burrows (undifferentiated)
- Massive Sand
- Laminated Swash Zone Sand
- Lagoonal Mud (w/ shells)
- Shell Hash
- Peat
- Roots
Core # 10
Field #: RW 1_13-3
Surface Elevation: 8.8 mASL
Total Depth: 9.1m
Core # 11
Field #: MB 1_6-2
Surface Elevation: ~10 mASL
Total Depth: 3.5 m
Core # 11
Field #: MB 1_6-2
Surface Elevation: ~10 mASL
Total Depth: 3.5 m
Core # 12
Field #: RW 1_10-1
Surface Elevation: 9.7 m ASL
Total Depth: 10.7 m
Core # 12
Field #: RW 1_10-1
Surface Elevation: 9.7 mASL
Total Depth: 10.7 m
Core # 13
Field #: MB 1_6-3
Surface Elevation: ~9.5 mASL
Total Depth: 3.0 m

Burrows (undifferentiated)
Massive Sand
Laminated Swash Zone Sand
Lagoonal Mud (w/ shells)
Shell Hash
Peat
Roots
Core # 13
Field #: MB 1_6-3
Surface Elevation: ~9.5 mASL
Total Depth: 3.0 m
Core # 14
Field #: RW 1_11-1
Surface Elevation: 5.7 mASL
Total Depth: 7.6 m

- Burrows (undifferentiated)
- Massive Sand
- Laminated Swash Zone Sand
- Lagoonal Mud (w/ shells)
- Shell Hash
- Peat
- Roots
Core # 14
Field #: RW 1_11-1
Surface Elevation: 5.7 mASL
Total Depth: 7.6 m
Core # 15
Field #: RW 1_15-1
Surface Elevation: 6.7 mASL
Total Depth: 9.1 m

DEPTH (m)

- Burrows (undifferentiated)
- Massive Sand
- Laminated Swash Zone Sand
- Lagoonal Mud (w/ shells)
- Shell Hash
- Peat
- Roots
Core # 15
Field #: RW 1_15-1
Surface Elevation: 6.7 mASL
Total Depth: 9.1m
Core # 16
Field #: RW 1_15-2
Surface Elevation: ~3 mASL
Total Depth: 7.6 m
Core # 16
Field #: RW 1_15-2
Surface Elevation: ~3 mASL
Total Depth: 7.6 m
Core # 17
Field #: MB 1_7-3
Surface Elevation: ~5.5 mASL
Total Depth: 4.2 m
Core # 17
Field #: MB_1_7-3
Surface Elevation: ~5.5 mASL
Total Depth: 4.2 m
Core # 18
Field #: MB 1_9-3
Surface Elevation: ~ 9.1 mASL
Total Depth: 1.8 m
Core # 18
Field #: MB 1_9-3
Surface Elevation: ~ 9.1 mASL
Total Depth: 1.8 m
Core #19
Field #: MB 1_9
Surface Elevation: ~8 mASL
Total Depth: 2.1 m

- Burrows (undifferentiated)
- Massive Sand
- Laminated Swash Zone Sand
- Lagoonal Mud (w/ shells)
- Shell Hash
- Peat
- (*) = OSL Sample
- Roots
Core # 20
Field #: RW 1_14-1
Surface Elevation: 3.7 mASL
Total Depth: 9.1m

- Burrows (undifferentiated)
- Massive Sand
- Laminated Swash Zone Sand
- Lagoonal Mud (w/ shells)
- Shell Hash
- Peat
- Roots
Core # 20
Field #: RW 1_14-1
Surface Elevation: 3.7 mASL
Total Depth: 9.1m
Core # 21
Field #: RW 1_14-2
Surface Elevation: 5.5 mASL
Total Depth: 9.1m
Core # 21
Field #: RW 1_14-2
Surface Elevation: 5.5 mASL
Total Depth: 9.1m
Russell Willis was born in Lafayette, Louisiana, and moved to Edgefield County, South Carolina, two years later. There, he attended grade school and eventually graduated with honors from Strom Thurmond High School in 1998. Higher education was pursued under a full academic scholarship to College of Charleston, where he earned a Bachelor of Science in geology in 2002. He then worked as a laboratory technician for General Engineering Laboratories, Inc., for a year in Charleston, South Carolina, before moving to Baton Rouge, Louisiana, in August of 2003 to begin graduate studies. Upon graduation he will pursue a career in the oil and gas exploration industry with Dominion Exploration and Production, Inc., in New Orleans, Louisiana.