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# Optically stimulated luminescence age controls on late Pleistocene and Holocene coastal lithosomes, North Carolina, USA

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## Abstract

Luminescence ages from a variety of coastal features on the North Carolina Coastal Plain provide age control for shoreline formation and relative sea-level position during the late Pleistocene. A series of paleoshoreline ridges, dating to Marine Isotope Stage (MIS) 5a and MIS 3 have been defined. The Kitty Hawk beach ridges, on the modern Outer Banks, yield ages of 3 to 2 ka. Oxygen-isotope data are used to place these deposits in the context of global climate and sea-level change. The occurrence of MIS 5a and MIS 3 shorelines suggests that glacio-isostatic adjustment (GIA) of the study area is large (ca. 22 to 26 m), as suggested and modeled by other workers, and/or MIS 3 sea level was briefly higher than suggested by some coral reef studies. Correcting the shoreline elevations for GIA brings their elevation in line with other sea-level indicators. The age of the Kitty Hawk beach ridges places the Holocene shoreline well west of its present location at ca. 3 to 2 ka. The age of shoreline progradation is consistent with the ages of other beach ridge complexes in the southeast USA, suggesting some regionally contemporaneous forcing mechanism.

*Keywords:* Optically stimulated luminescence; Coastal geology; Quaternary sea level; Paleoshoreline; Glacio-isostasy

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## Introduction

The ridges and scarps and associated shallow shelf depositional units along the passive margin coastal plain of the eastern U.S. (Figs. 1 and 2) have been a subject of study and debate for decades (Oaks and Coch, 1963; Oaks, 1964; Cronin et al., 1981; Mixon et al., 1982; Szabo, 1985; Riggs et al., 1992; Wehmiller et al., 1997, 2004; Muhs et al., 2002; Potter and Lambeck, 2003; Burdette, 2005). It is apparent that these siliciclastic deposits are coastal features formed in response to sea-level high stands. Numerous researchers have defined the sand ridges as paleoshorelines based on their geomorphological and geological characteristics (Oaks and Coch, 1963; Oaks, 1964; Mixon et al., 1982; Brill, 1996; Burdette, 2005). As such, they can potentially provide important index points for Pleistocene sea-level curves, and improve the understanding of global ice-volume changes and paleoclimate during the Pleistocene. Complicating the issue, however, is the occurrence of intermediate-field glacio-isostatic adjustments (GIA) during glacial–interglacial oscillations (Lambeck et al., 2002; Peltier, 2002; 2004; Potter and Lambeck, 2003). The intermediate field of glacio-isostasy is associated with isostatic uplift and subsequent collapse along a peripheral bulge surrounding the ice margin (Lambeck, 1993; Pirazzoli, 1996). Direct geologic indicators of relative sea level (RSL), and mantle rheology/GIA models indicate that the Atlantic Coastal Plain has undergone glacio-isostatic uplift and subsequent subsidence in response to the advance and decay of the Laurentide Ice Sheet (Cronin et al., 1981; Peltier, 2002; Potter and Lambeck, 2003; Peltier, 2004; Wehmiller et al., 2004). The RSL recorded within the NC coastal system, then, is a complicated function of glacio-eustasy (ice-

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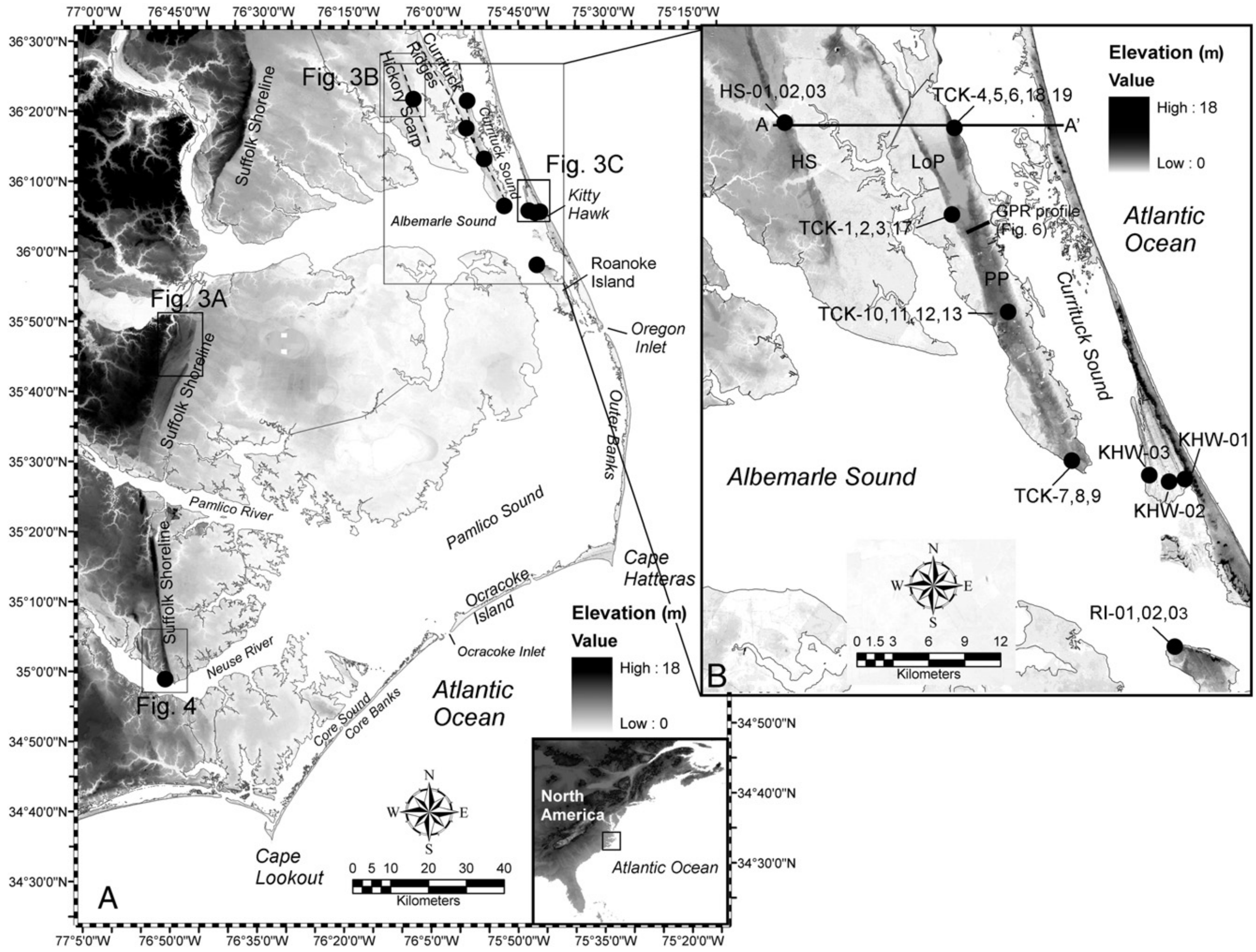

Figure 1. LiDAR topographic map showing the various features discussed in the manuscript, and the sample locations.

volume equivalent sea-level change) and glacio–hydro-isostasy, with a response time and magnitude that is dictated by mantle rheology (Peltier, 2002, 2004; Potter and Lambeck, 2003).

This paper presents new ages, based upon optically stimulated luminescence (OSL) analyses of quartz grains, for various coastal siliciclastic depositional features, including paleoshorelines, in eastern NC. OSL has been shown to be an accurate tool for dating coastal deposits (Ollerhead et al., 1994; Van Heteran et al., 2000; Berger et al., 2003; Havholm et al., 2004) as it indicates the time elapsed since the last exposure to sunlight, and therefore time of burial of quartz sand. The features being dated include barrier sands (overwash and dune) and tidal flat sediments associated with

| Stratigraphic Units of the NC/VA Coastal Plain | | | | Age (ka) | |
|---|---|---|---|---|---|
| Johnson (1976) | | Oaks and Coch (1973) | Lithology and Environment (Oaks and Coch, 1973) | U-series | OSL |
| Tabb Formation | Poquoson Member | Sand Bridge Fm | upper section: lagoon mud; tidal sand and clayey sand; lagoon and barrier sands<br>lower section: clean to muddy f. to m. sand | N/A | 62 to 41 (ave. 51) |
| | Lynnhaven Member | | | | |
| | Sedgefield Member | Kempsville Fm | beach sand, gravel and shells; lagoon peaty clay | ?? | N/A |
| | | Norfolk Fm | upper section: lagoon mud and sand; dune and beach sand and gravel (west); variable silty to clayey sand/sandy silt (east)<br>lower section: beach sand and gravel | ave. 71 | 84 to 61 |

Figure 2. Stratigraphic units found within the general study area (after Oaks and Coch, 1973). The extent and thickness of these formations varies greatly throughout the study area. Uranium-series age is an average based on data from Mixon et al. (1982), Szabo (1985), Cronin et al. (1981), and Wehmiller et al. (2004). OSL ages are from this investigation. Although the Kempsville Formation is proposed to be MIS 5a in age by Szabo (1985), the data supporting this are minimal (one date on a *Mercenaria* shell), hence the "??" label.

the Land of Promise Ridge, Powell's Point Ridge, Hickory Shoreline, Roanoke Island, and the Suffolk Shoreline in eastern NC (Fig. 1). Data are additionally constrained by previously published ages provided by AAR and U-series analyses (Croin et al., 1981; Mixon et al., 1982; York, 1984, 1990; Riggs et al., 1992; Wehmiller et al., 2004), and by comparison to the SPECMAP (Imbrie et al., 1989; MacIntyre et al., 1989), and oxygen-isotope curves (Chappell et al., 1996; Linsley, 1996). The purpose of this paper is to present and evaluate these new OSL ages and address the controls on the late Pleistocene and Holocene chronostratigraphic framework.

## Study area

The NC coastal system occurs in a micro-tidal, wave energy dominated setting along the southeast U.S. continental margin. The underlying geologic framework consists of an 85-m thick section of Quaternary sediments filling a paleotopographic low referred to as the Albemarle Embayment (Ward and Strickland, 1985; Mallinson et al., 2005). Filling of the embayment occurred in response to Quaternary sea-level fluctuations and produced multiple depositional sequences throughout the region, that are characterized by deep to shallow shelf, estuarine, barrier island (eolian, overwash, nearshore, shoreface, etc.), and fluvial sediments (Riggs et al., 1992; Sager and Riggs, 1998; Mallinson et al., 2005; Parham et al., 2007). The occurrence of this embayment in the subsurface is also responsible for the very gradual gradient of this coastal system. Based upon regional tidal gauge records, RSL along this area of the coastline (at Duck, NC, within the study area) is currently rising at an average rate of 4.27 mm/yr (Zervas, 2004) due to the general eustatic rise, glacio–hydro-isostatic mechanisms (Peltier, 2002; Potter and Lambeck, 2003; Peltier, 2004), and local subsidence. The combination of the low gradient of this system, and the regional subsidence makes this coastline particularly responsive to very minor changes in sea level.

Depositional sequences in NC have been defined in the subsurface using high-resolution seismic and core data (Riggs et al., 1992; Boss et al., 2002; Mallinson et al., 2005; Parham et al., 2007). The updip limit of these Quaternary sequences can be seen in the surface geomorphology which is characterized by depositional and erosional features (ridges and scarps) associated with Pleistocene paleoshorelines, separated by broad seaward-sloping terraces.

Oaks and Coch (1963) and Oaks (1964) first defined the post-Miocene stratigraphy of southeastern Virginia, which is contiguous with northeastern NC. Their studies introduced the stratigraphic and geomorphic names that provided the basis for future investigations. Since 1963, numerous investigations have addressed the origin, ages, and stratigraphic relationship of the various geomorphic features (terraces, scarps, ridges, etc.) of the coastal plain (Figs. 1–3) (Oaks and Coch, 1963; Oaks, 1964; Cronin et al., 1981; Mixon et al., 1982; Szabo, 1985; Muhs, 1992; Riggs et al., 1992; Wehmiller et al., 1997; Potter and Lambeck, 2003; Wehmiller et al., 2004; Burdette, 2005). The features discussed in this paper fall into the Norfolk, Kempsville, and Poquoson Members of Oaks and Coch (1973) (Fig. 2), or the Sedgefield, Lynnhaven and Poquoson Members of the Tabb Formation (Johnson, 1976; Peebles, 1984). The associated lithologies have been interpreted as late Pleistocene barrier island and estuarine deposits based upon their geomorphology, lithofacies, and biofacies (Oaks et al., 1974) (Fig. 2).

Cronin et al. (1981) and Mixon et al. (1982) made the first age estimates of the Sedgefield Member using U-series analyses of mollusk shells (*Mercenaria mercenaria*) and coral rubble (genera *Astrangia* and *Septastrea*). Their data and those of subsequent investigations (Szabo, 1985; Wehmiller et al., 2004) firmly established a MIS 5a depositional age for the Sedgefield

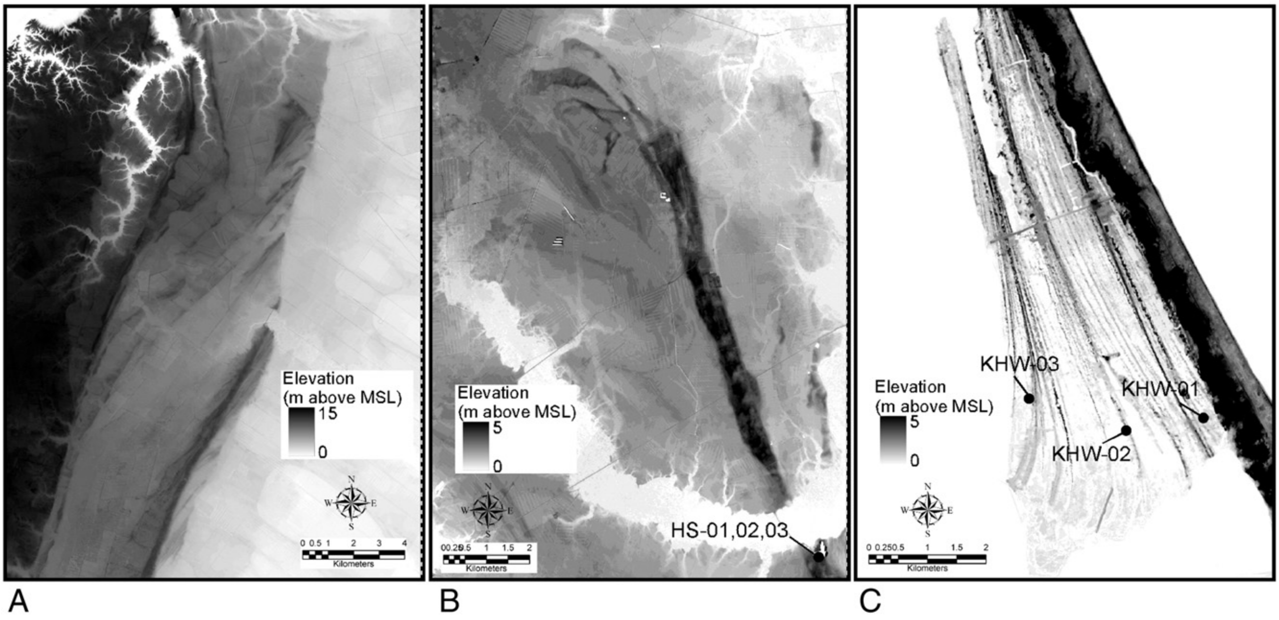

Figure 3. LiDAR data illustrating coastal morphologies. A) Beach ridge, barrier island, and cuspate foreland morphology on the Suffolk Shoreline. B) Recurve spit morphology on the Hickory Shoreline. C) Beach ridge morphology at Kitty Hawk.

Member (Fig. 2), suggesting glacio-isostatic uplift of the region (Cronin et al., 1981). Mixon et al. (1982) and Wehmiller et al. (2004) also acknowledge the existence of the shoreline features that are stratigraphically higher (the Poquoson Member), and therefore younger, than the MIS 5a dated material.

York (1984, 1990) and Riggs et al. (1992) made the first age estimates of the late Pleistocene depositional sequences using AAR techniques. Their data indicate at least seven AAR zones in the upper 30 m, in the vicinity of Roanoke Island (Fig. 1). Sediments within the shallow subsurface (<6 m depth) beneath Roanoke Island and southern Currituck Peninsula (Fig. 1) fall into Amino Zones (AZ) 1 and 2, with an estimated age of ca. 80 ka to 51 ka (spanning MIS 5a, 4 and 3).

The various works described above recognized the unusually high elevation of MIS 5a coastal deposits in NC and southeast VA. Potter and Lambeck (2003) modeled the GIA of the Atlantic Coastal Plain and concluded that the area is presently uplifted by ca. 22 m relative to a state of isostatic near-equilibrium that existed at ca. 84 ka. Wehmiller et al. (2004) revisited the “80 ka problem” and also proposed that the position of the MIS 5a deposits must be due to regional GIA. The models of Peltier (2002, 2004) indicate the existence of the glacial forebulge crest in the general area of NC, with forebulge collapse occurring at a rate of ca. 2 mm/yr, accounting for nearly half of the present high rate of RSL rise.

## Methods

Samples for OSL analyses were acquired from exposures in borrow pits in the case of the Land of Promise Ridge, the Powell’s Point Ridge, and the Hickory Shoreline, or from natural cut banks in the case of Roanoke Island, the Suffolk Scarp, and one location on Powell’s Point Ridge (Fig. 1). In the case of the Kitty Hawk beach ridges (Fig. 1), a 0.8-m deep pit was dug into the flank of each sampled beach ridge. Precautions were taken to prevent exposure of the sediments during sampling. The location of each sample was determined using differential GPS (±1 m accuracy). The vertical position of the samples was measured from the ground surface with a measuring tape. The elevation was then determined using LiDAR data (www.ncfloodmaps.com) for ground surface elevation. These data use the NAVD 88 vertical datum, and provide an accuracy of ±25 cm.

Samples analyzed at the University of Georgia were treated with 10% HCl and 30% $H_2O_2$ to remove carbonates and organic matter, then sieved to extract the 150–170-µm-size fraction. Quartz and feldspar grains were separated by density using Na-polytungstate ($\rho$=2.58 g cm$^{-3}$). The quartz fraction was etched using 40% HF for 80 min followed by 12 N HCl for 30 min to remove the outermost layer affected by alpha radiation. The quartz grains were mounted on stainless steel discs using Silkospray™. Light stimulation of the quartz was achieved using a RISØ array of blue LEDs centered at 470 nm. Detection optics comprised Hoya 2×U340 and Schott BG-39 filters coupled to an EMI 9635 QA Photomultiplier tube. Measurements were taken with a RISØ TL-DA-15 reader. β radiation was applied using a 25 mCi $^{90}$Sr/$^{90}$Y in-built source.

The single-aliquot regenerative dose (SAR) protocol (Murray and Wintle, 2000) was used to determine the paleodose. A five-point measurement strategy was adopted with three dose points to bracket the paleodose, a fourth zero dose and a fifth repeat-paleodose point. The repeat paleodose was measured to correct for sensitivity changes and check that the protocol was working correctly. All measurements were made at 125 °C for 100 s after a preheat to 220 °C for 60 s. For all aliquots the recycling ratio between the first and the fifth point ranged within 0.95–1.05. Data were analyzed using the ANALYST program of Duller (1999). Paleodose measurements were made on aliquots of 9.6 mm diameter. In each case 12–16 aliquots from each sample were analyzed.

Duplicate samples were prepared for luminescence dating at the USGS Luminescence Laboratory as described above with slight modifications in heavy liquid separations and hydrofluoric etch treatment (Millard and Maat, 1994, Roberts and Wintle, 2001, Singhvi et al., 2001). Dose recovery and preheat plateau tests were performed to ensure that the sediments were responsive to optical techniques and that the proper temperatures were used in producing the $D_e$ values. Acceptable preheat temperatures ranged from 200–280 °C. All USGS samples were also analyzed by SAR (Murray and Wintle, 2000), using the same model of RISØ reader and software as noted above. The OSL measurements were made at 125 °C for 40 s after preheat of 220 °C for 10 s with a cut heat of the same time. An IRSL stimulation of 100 s before the blue-light stimulation of 40 s was used to completely drain any residual feldspar contamination. Approximately 30 to 50 aliquots per sample were run for the SAR blue-light equivalent dose determination. Ages were determined by dividing the mean equivalent dose ($D_e$) by the dose rate.

Chronostratigraphic data are further constrained or tuned by comparison to the SPECMAP $\delta^{18}$O curve (Imbrie et al., 1989; MacIntyre et al., 1989) and foraminiferal $\delta^{18}$O curves (Chappell et al., 1996; Linsley, 1996). For example, given a typical OSL age error of ±5000 yr, we assume that the shoreline likely formed during a high stand event during that time, as indicated by other proxy data (i.e. $\delta^{18}$O and coral reef data). The shoreline would not be preserved had it formed during a rising sea level, but would be preserved following formation at high stand or early falling-stage conditions.

Ground penetrating radar data were acquired from roads on the Land of Promise and Powell’s Point Ridges using a Geophysical Survey Systems, Inc. (GSSI) SIR-2000 system with a 100 MHz antenna (Burdette, 2005), and a survey wheel. The antenna was towed at ca. 5 km/h and data were acquired at a scan interval of 10 scans/m, and a sampling interval of 1024 samples/scan. A recording window of 500 ns was used, which provided data to a depth of ca. 15 m, based on a dielectric value of 25 (determined by core correlation). Data were filtered, stacked and gain-enhanced using Radan v. 6.0 software (©GSSI).

## Results and interpretations

### Geomorphology

Although numerous workers have defined the various linear ridges and scarps as paleoshorelines, recently acquired high-resolution LiDAR elevation data (www.ncfloodmaps.com)

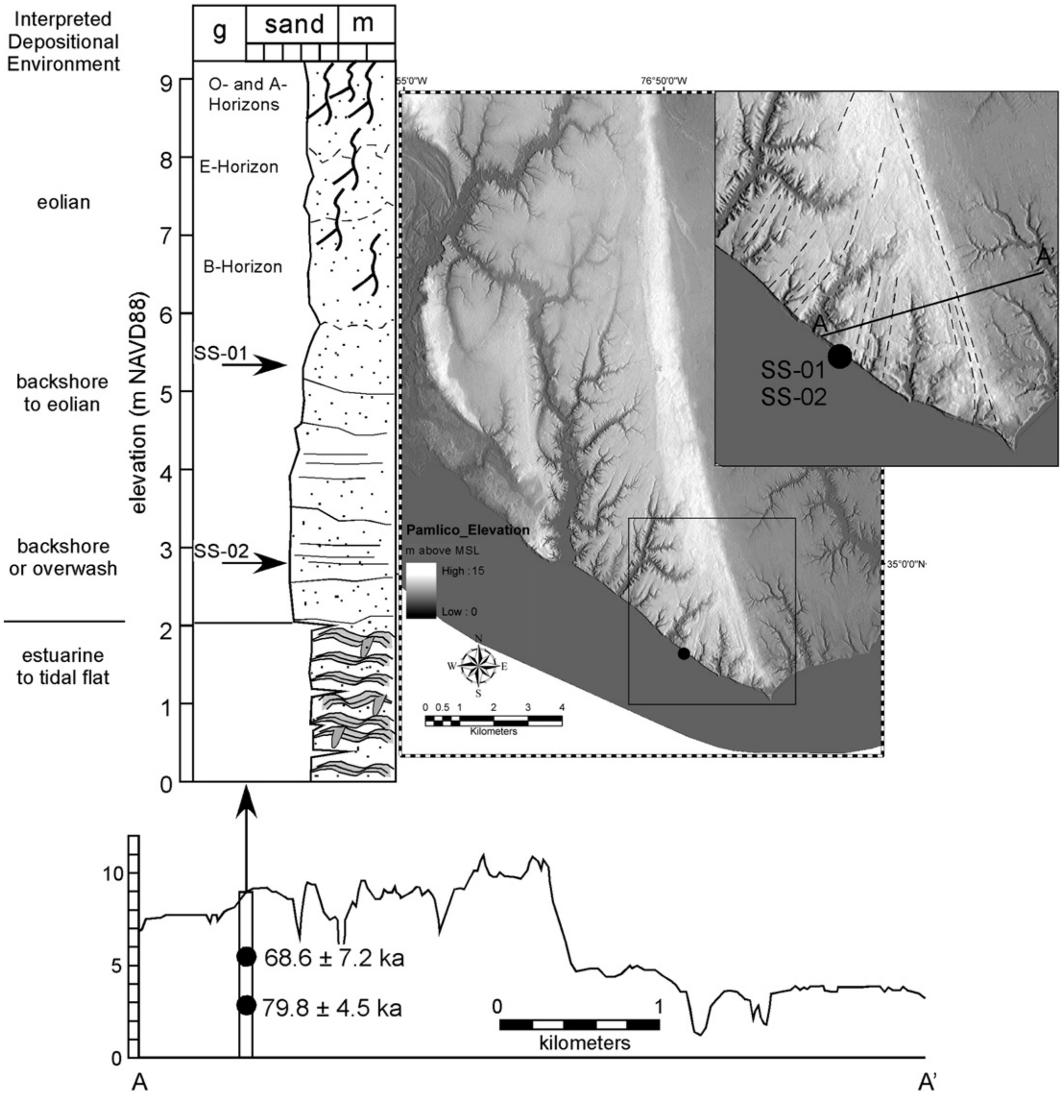

Figure 4. LiDAR topographic map showing the location of the samples from the Suffolk Ridge, and recurve spit/beach ridge morphology (inset, with beach ridges dashed). Also shown is a topographic profile (bottom and A–A′ on inset map) extracted from LiDAR data, and the stratigraphic column with interpretations from the sampled location (see Fig. 5 for the legend).

provide a new perspective on this assertion (Figs. 3 and 4). Analyses of these data reveal the preservation of coastal geomorphologies associated with the various ridges sampled. In addition to the coast-parallel, highly linear ridges, these data reveal beach ridges, recurve spits, and cuspate foreland morphologies (Figs. 3 and 4).

### *Stratigraphy and lithofacies*

Vibracores and bluff exposures from the various sites reveal several different lithofacies, characteristic of coastal depositional environments including eolian, tidally influenced shallow estuarine (flaser and wavy bedding), wetland (peat), and nearshore, backshore and overwash sands (Figs. 4 and 5).

At the Suffolk Scarp location (Figs. 1 and 4) the deposits are associated with the Sedgefield Member of the Tabb Formation (Johnson, 1976) and are interpreted as a basal tidal estuarine unit (burrowed wavy bedding) overlain by parallel-bedded sands likely of overwash origin, grading upward to eolian sands. The entire system appears to be associated with beach ridges that are part of a spit complex extending southward from the main depositional shoreline (Fig. 4).

The Hickory Scarp site occurs in a sand pit where exposures reveal a lower herringbone cross-bedded tidal sand flat section grading upward to burrowed wavy beds with obvious tidal rhymites and rip-ups, and flaser bedding (Fig. 5). This tidal flat sequence extends over a vertical range of ca. 7 m, to the modern ground surface. It is not clear whether these deposits belong to the upper Sedgefield Member (Kempsville Formation) or the Poquoson Member (Sand Bridge Formation). This unit unconformably overlies a basal unit consisting of interbedded molluskan shell gravelly, sands and muds.

The more eastward sites (Land of Promise and Powell's Point Ridges, and Roanoke Island) belong to the Poquoson

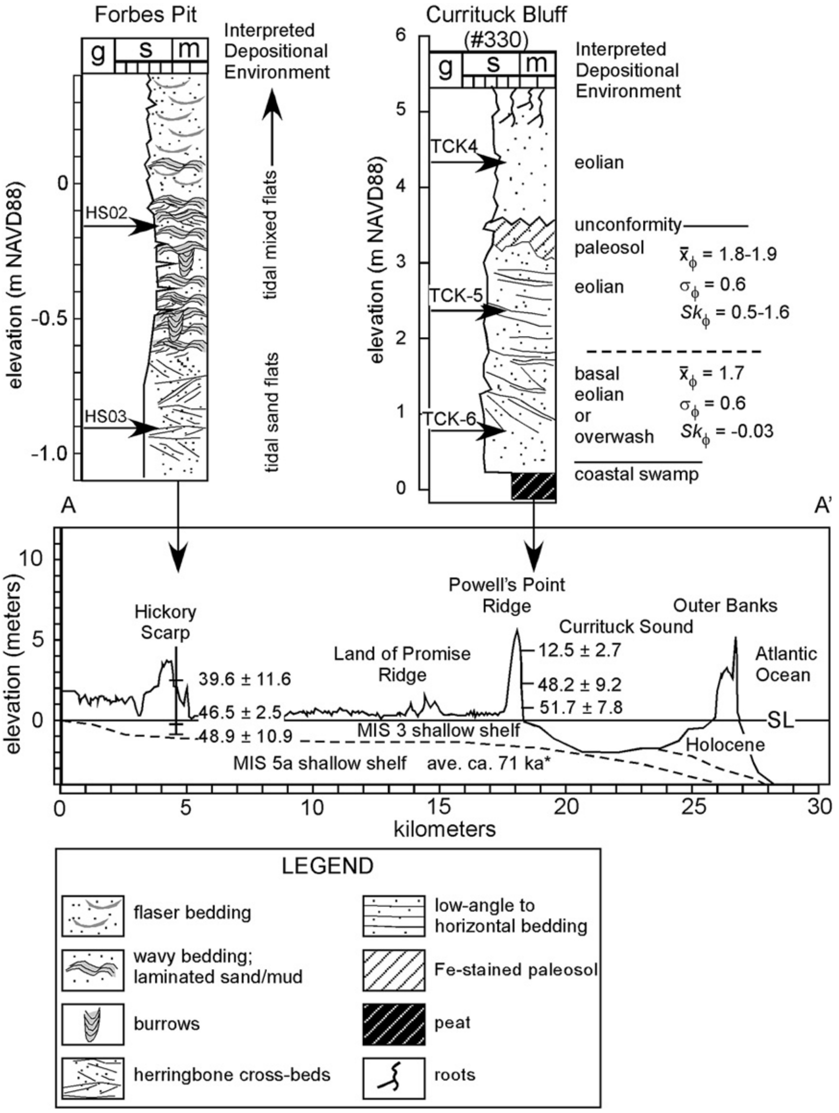

Figure 5. Topographic profile with photographs and interpretations of sampled exposures at the Hickory Shoreline and Powell's Point Ridge (see Fig. 2 for location). OSL ages are shown on the profile. ∗Average age of U-series analyses from corals beneath the Hickory Shoreline in northern NC (Moyock) and southern VA (Gomez Pit) (Wehmiller et al., 2004). Grain-size statistics (mean, sorting, and skewness) in phi units are shown for the Powell's Point site.

Member. The Land of Promise and Powell's Point Ridges exhibit a classic transgressive coastal succession of a basal peat overlain by overwash facies, grading upward into eolian facies (Fig. 5). An erosional contact and paleosol is also apparent at several locations within ca. 1–2 m of the ground surface (Fig. 5). Ground penetrating radar (GPR) data from the Powell's Point Ridge reveal the presence of a basal peat layer, overlain by overwash and eolian deposits (Fig. 6). The Roanoke Island section is more difficult to interpret as it appears overprinted by several episodes of possible dune reactivation and paleosol development.

Finally, the Kitty Hawk Woods sites are situated on the modern barrier island system, and are thus part of the undifferentiated Holocene section. These sites are associated with a seaward prograding beach ridge complex that formed during the latest Holocene RSL rise, prior to the modern transgressive shoreline.

## *Age data*

All OSL ages are presented in Table 1. The distributions of the measured equivalent doses ($D_e$) for each sample indicate that aliquots are neither saturated, nor significantly mixed, with the few exceptions discussed below. The youngest Pleistocene-aged samples from the Land of Promise and Powell's Point Ridges in particular exhibit low standard deviation and normal distribution (Fig. 7). SS-2 and RI-1 exhibit high standard deviations (34% and 32%, respectively), suggesting the incorporation of some partially bleached grains during deposition (making the sample appear slightly older than the true age). However, the SS-2 age agrees statistically with the SS-1 age, which exhibits a standard deviation of only 13%, so the SS-2 age is still considered reliable. The effects of pedoturbation may be indicated at Roanoke Island, where burrowed horizons were noted and samples become significantly younger upward (Bateman et al., 2003).

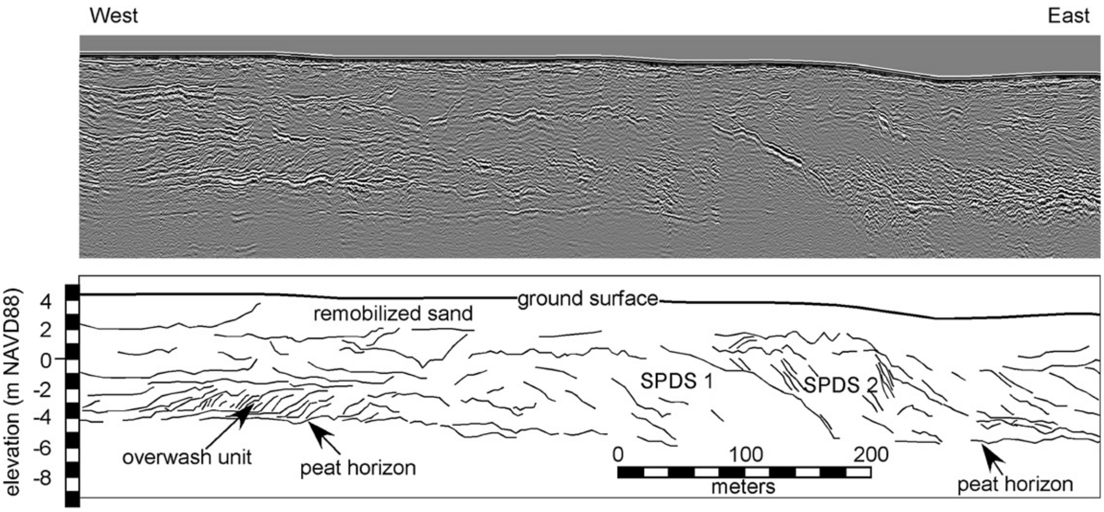

Figure 6. Filtered, stacked, and surface normalized GPR data (top) and line interpretation (bottom) near the junction of the Land of Promise and Powell's Point Ridges (see Fig. 1 for location). Data reveal a horizontal peat layer overlain by seaward prograding dune sand (SPDS) facies in the east, and an overwash facies in the west. SPDS 1 is associated with the Land of Promise Ridge, whereas SPDS 2 is associated with the Powell's Point Ridge.

The consistent nature of the dates and interlaboratory agreement (with the exception of TCK-5 and TCK-18; Table 1) provide confidence in the ages. Also, OSL analyses of samples from the Sedgefield Member (SS-1, SS-2 and TCK-3) yield MIS 5a ages, corroborating U-series and AAR ages of the Sedgefield Member (Szabo, 1985; Wehmiller et al., 2004). There is further agreement, in terms of superposition, with existing U-series and AAR ages in that the OSL ages on barrier sands associated with the Poquoson Member are younger than U-series ages from underlying deposits associated with the Sedgefield Member.

The oldest sediments are associated with the Suffolk Shoreline. These sediments yield ages of 84 ka to 61 ka (full 2-sigma error range) (Table 1; Fig. 8), and overlap statistically. Based upon comparison to the oxygen-isotope curves, we interpret the sediments of the Suffolk Shoreline (at least in the sampled location) as being deposited during the sea-level high-stand associated with Marine Isotope Stage 5a. Several studies suggest two significant sea-level peaks during MIS 5a; the first at ca. 84 ka, and the second at ca. 77 ka (Schellmann and Radtke, 2003; Cutler et al., 2003; Potter and Lambeck, 2003; Thompson and Goldstein, 2005). It is notable that there are two ridges present along the trend of the Suffolk Shoreline between the Roanoke River and the Pamlico River (Figs. 1 and 3). It is possible that the westernmost ridge represents a mainland-attached shoreline formed during the 84 ka peak, and the easternmost ridge represents the shoreline formed during the 77 ka sea-level peak.

Sediments from Roanoke Island, the Hickory Shoreline, the Land of Promise Ridge, and Powell's Point Ridge overlap statistically and range from 62 ka to 41 ka (Table 1). These ages were initially unexpected, as we were working under the hypothesis that these paleoshorelines were of MIS 5a age. The OSL ages are consistent with published AAR ages from these areas (York, 1990; Riggs et al., 1992), however these AAR ages are undergoing revision (Wehmiller, pers. com.). Several younger ages of 34 to 12.5 ka were obtained from reworked (via eolian reactivation or bioturbation) sediments above a paleosol horizon in Powell's Point Ridge (Fig. 5), and are associated with Carolina Bay sediments, which mantle the surface of the area. Likewise an upper sample at Roanoke Island, also above a paleosol horizon, dates from 19 ka to 14 ka. The stratigraphy at Roanoke Island suggests the greatest amount of sediment remobilization or pedoturbation of any of the sites.

Based upon comparison to the SPECMAP oxygen-isotope curve, we interpret these various features to have formed during MIS 3. It is possible that all three of these shorelines may have formed at ca. 52 ka, and represent a falling-stage systems tract formed in response to a forced regression, or glacio-isostatic uplift. Alternatively, based upon cross-cutting relationships, the Hickory Shoreline and Land of Promise Ridge may have formed during the peak MIS 3 high stand at ca. 60 ka or 52 ka (Chappell, 2002), and the Powell's Point Ridge may correspond to the MIS 3 high stand at 52 ka or 44.5 ka (Chappell, 2002).

As expected, sediments from the Kitty Hawk beach ridges (KHW-1, KHW-2, KHW-3; Fig. 2) yield the youngest ages of approximately 3 to 2 ka and overlap statistically (Table 1). Specifically, the western ridge (KHW-1) (not the westernmost ridge in the system) yields an OSL age of 2.6 ± 0.5 ka, the middle ridge (KHW-2) yields an OSL age of 2.9 ± 0.3 ka, and the easternmost ridge that was accessible (not covered by the modern dune fields) yields an IRSL age of 2.5 ± 0.6 ka. An OSL age of 0.34 ± 0.05 was acquired from KHW-3, but is deemed to be altered as it does not agree with the IRSL age (all other samples do), and the IRSL age agrees statistically with the OSL ages from KHW-1 and KHW-2. Additionally, the KHW-3 OSL age is too young based upon the reported ages of dunes that occur above the beach ridge (Berger et al., 2003; Havholm et al., 2004). These sediments represent a regressive phase of Holocene barrier island development.

## Discussion

Samples that were dated include eolian sands, probable overwash facies, and tidal estuarine deposits. Preservation of the coastal geomorphic features and stratigraphy indicating tidal

Table 1
Sample locations and luminescence age data

| Sample ID | Lab no. | Elev. (cm) | Lon | Lat | U (ppm) | Th (ppm) | *K* (%) | Dose rate (Gy/ka) | Paleodose (Gy) | Age (ka) 2-sigma error |
|---|---|---|---|---|---|---|---|---|---|---|
| *LoP Ridge* | | | | | | | | | | |
| TCK-1 | UGA04OSL-187 | 234.5 | −75.91137 | 36.26978 | 0.66±0.16 | 2.44±0.57 | 0.46±0.01 | 0.9±0.1 | 55.7±7.2 | 65.3±10.2 |
| TCK-2 | UGA04OSL-188 | 34.5 | −75.91137 | 36.26978 | 0.7±0.08 | 0.8±0.29 | 0.44±0.01 | 0.7±0.1 | 43.9±6.7 | 59.6±10.2 |
| TCK-3[a] | UGA04OSL-189 | 4.5 | −75.91137 | 36.26978 | 0.78±0.08 | 0.86±0.33 | 0.43±0.01 | 0.8±0.1 | 61.4±4.6 | 81.8±8.8 |
| TCK-17 | USGS-TCK-2 | 34.5 | −75.91137 | 36.26978 | 0.54±0.04 | 1.20±0.12 | 0.51±0.01 | 0.68±0.03 | 36.9±1.95 | 54.3±6.7 |
| *PP Ridge* | | | | | | | | | | |
| TCK-4 | UGA04OSL-180 | 432.6 | −75.90663 | 36.33494 | 1.97±0.53 | 6.13±1.81 | 0.4±0.01 | 1.3±0.2 | 16.4±2.7 | 12.5±2.7 |
| TCK-5 | UGA04OSL-183 | 232.6 | −75.90663 | 36.33494 | 1.23±0.2 | 2.16±0.7 | 0.29±0.01 | 0.8±0.1 | 38.8±6.2 | 48.2±9.2 |
| TCK-6 | UGA04OSL-190 | 82.6 | −75.90663 | 36.33494 | 1.11±0.17 | 2.24±0.61 | 0.33±0.01 | 0.8±0.1 | 42.2±4.9 | 51.7±7.8 |
| TCK-7 | UGA04OSL-208 | 193.8 | −75.8073 | 36.08172 | 2.61±0.49 | 3.96±1.67 | 0.39±0.01 | 1.2±0.2 | 34.4±5.9 | 28.2±6.2 |
| TCK-8 | UGA04OSL-214 | −206.2 | −75.8073 | 36.08172 | 1.07±0.16 | 1.64±0.6 | 0.36±0.01 | 0.8±0.1 | 32.8±5.1 | 43.2±7.9 |
| TCK-9 | UGA04OSL-213 | −406.2 | −75.8073 | 36.08172 | 1.0±0.17 | 1.85±0.6 | 0.57±0.01 | 0.9±0.1 | 42.1±3.6 | 45.2±5.6 |
| TCK-13 | UGA04OSL-209 | 198.5 | −75.86211 | 36.19523 | 1.65±0.29 | 2.61±0.99 | 0.55±0.01 | 1.1±0.1 | 36.9±4.6 | 33.7±4.6 |
| TCK-11 | UGA04OSL-207 | −151.5 | −75.86211 | 36.19523 | 0.91±0.13 | 1.54±0.48 | 0.39±0.01 | 0.7±0.1 | 36.1±3.4 | 48.8±6.2 |
| TCK-12 | UGA04OSL-212 | −211.5 | −75.86211 | 36.19523 | 0.91±0.09 | 0.9±0.3 | 0.38±0.01 | 0.7±0.1 | 35.1±4.2 | 50.6±7.3 |
| TCK-10 | UGA04OSL-211 | −341.5 | −75.86211 | 36.19523 | 0.88±0.09 | 1.05±0.35 | 0.31±0.01 | 0.6±0.1 | 35.6±2.7 | 54.9±6.3 |
| TCK-18 | USGS-330-1 | 232.6 | −75.90663 | 36.33494 | 1.67±0.08 | 4.48±0.19 | 0.29±0.01 | 0.99±0.03 | 30.9±0.93 | 31.2±2.7 |
| TCK-19 | USGS-330-2 | 82.6 | −75.90663 | 36.33494 | 1.29±0.07 | 3.14±0.17 | 0.35±0.01 | 0.75±0.03 | 34.0±0.83 | 45.3±4.3 |
| *Kitty Hawk* | | | | | | | | | | |
| KHW-01 | USGS-KHW-01 | 31 | −75.70307 | 36.06506 | 3.18±0.12 | 8.37±0.25 | 1.74±0.03 | 2.07±0.04 | 5.29±8.93 | 2.6±0.5 |
| KHW-02 | USGS-KHW-02 | 133 | −75.71778 | 36.06350 | 1.17±0.08 | 2.94±0.18 | 1.06±0.04 | 1.07±0.04 | 3.10±2.38 | 2.9±0.3 |
| KHW-03 (IRSL) | USGS-KHW-03 | 31 | −75.73597 | 36.06893 | 0.76±0.11 | 1.74±0.25 | 1.06±0.04 | 0.78±0.04 | 0.36±4.51 | 2.5±0.6 |
| *Hickory Shoreline* | | | | | | | | | | |
| HS-01 | UGA05OSL-314 | 245 | −76.06402 | 36.34273 | 0.9±0.1 | 0.8±0.4 | 1.6±0.01 | 1.7±0.1 | 66.8±18.7 | 39.6±11.6 |
| HS-02 | USGS-HS-02 | −15 | −76.06402 | 36.34273 | 1.72±0.06 | 5.17±0.04 | 2.04±0.05 | 2.04±0.05 | 94.6±0.95 | 46.4±2.5 |
| HS-03 | UGA05OSL-315 | −90 | −76.06402 | 36.34273 | 0.8±0.1 | 1.1±0.4 | 0.99±0.01 | 1.2±0.1 | 58.1±12.2 | 48.9±10.9 |
| *Raonoke Island* | | | | | | | | | | |
| RI-01 | USGS-RI-01 | 250 | −75.71756 | 35.93911 | 1.11±0.07 | 2.74±0.19 | 0.37±0.04 | 0.85±0.04 | 14.1±0.95 | 16.6±2.7 |
| RI-02 | UGA05OSL-312 | 157 | −75.71756 | 35.93911 | 2.4±0.3 | 3.6±1.1 | 0.31±0.01 | 1.1±0.1 | 27.9±1.7 | 25.4±3.2 |
| RI-03 | USGS-RI-03 | 5 | −75.71756 | 35.93911 | 0.30±0.02 | 0.72±0.01 | 0.34±0.03 | 0.50±0.03 | 27.7±0.69 | 55.4±7.2 |
| *Suffolk Shoreline* | | | | | | | | | | |
| SS-01 | USGS-SS-01 | 535 | −75.83069 | 34.97749 | 0.63±0.05 | 1.84±0.15 | 0.42±0.01 | 0.70±0.03 | 48.0±0.89 | 68.6±7.2 |
| SS-02 | USGS-SS-02 | 285 | −75.83069 | 34.97749 | 1.64±0.07 | 5.92±0.21 | 1.07±0.01 | 1.55±0.06 | 124±1.86 | 79.8±4.5 |

Water content was assumed to be 15±5% for all samples.

[a] Statistical certainty for TCK-3 is minimal due to the analysis of only 3 aliquots.

estuarine and barrier island environments indicates that these coastal features are, for the most part, unmodified (i.e., not reworked and minimally bioturbated) since deposition. Additionally, the ages from eolian sands, and shallow subtidal sediments are in agreement. The eolian ages could not be significantly younger than the age of the shorelines, as significant dune reactivation independent of shoreline processes and controls would not preserve the coastal geomorphic features and stratigraphy. Except at Roanoke Island, sediment remobilization appears to have occurred only within the upper 1 to 2 (maximum) meters of sediment.

If we assume that the OSL ages are reliable, as suggested by statistical analysis of luminescence data and stratigraphic relationships, then these chronostratigraphic control points provide a perspective on the late Pleistocene and Holocene evolution of the coastal system in response to eustatic sea-level change, and glacio–hydro-isostatic effects.

### *MIS 5a*

Portions of the Suffolk Shoreline record the position of a MIS 5a shoreline, based upon our OSL ages (SS-1, 2; Table 1) (79.8±4.5 and 68.6±7.2 ka). However, it is clear from geomorphic evidence, indicating the existence of two prominent ridges (Fig. 3B), that this shoreline was likely occupied at least twice, possibly during the high stands at 84 ka and again at 77 ka. Alternatively, the western shoreline may have been occupied during MIS 5e (Brill, 1996).

The OSL age for TCK-03 of 81.8±8.8 ka (though not as reliable as other ages; see Table 1) was taken from a muddy unit lying unconformably below the Powell's Point Ridge well to the east of the Suffolk Shoreline. Based upon the age and lithology, we propose that these sediments represent the Sedgefield Member and are a lateral correlative facies to the updip shoreline associated with the sands of the Suffolk Shoreline. This interpretation is

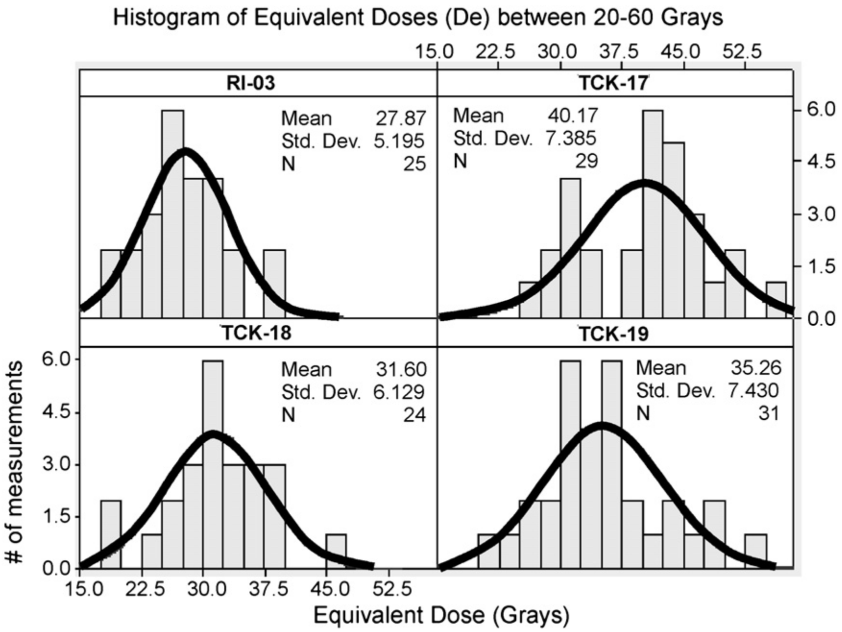

Figure 7. Histograms and frequency distribution curves of equivalent dose values (Grays) measured on four of the OSL samples which yield MIS 3 ages.

consistent with the interpretation of Oaks et al. (1974). These ages and correlations agree well with the U-series coral data from the Sedgefield Member as described by Mixon et al. (1982) and Wehmiller et al. (2004), which yield an average age of 71 ± 7 ka. The OSL and U-series ages are also consistent with AAR ages of *M. mercenaria* valves from borrow pits and cores in eastern NC (York, 1984, 1990; Riggs et al., 1992), which place these beds in Amino Zone 2, corresponding to an age range of ca. 120–70 ka.

Sea-level position during MIS 5a is controversial. MIS 5a marine facies containing coral rubble from South Carolina through

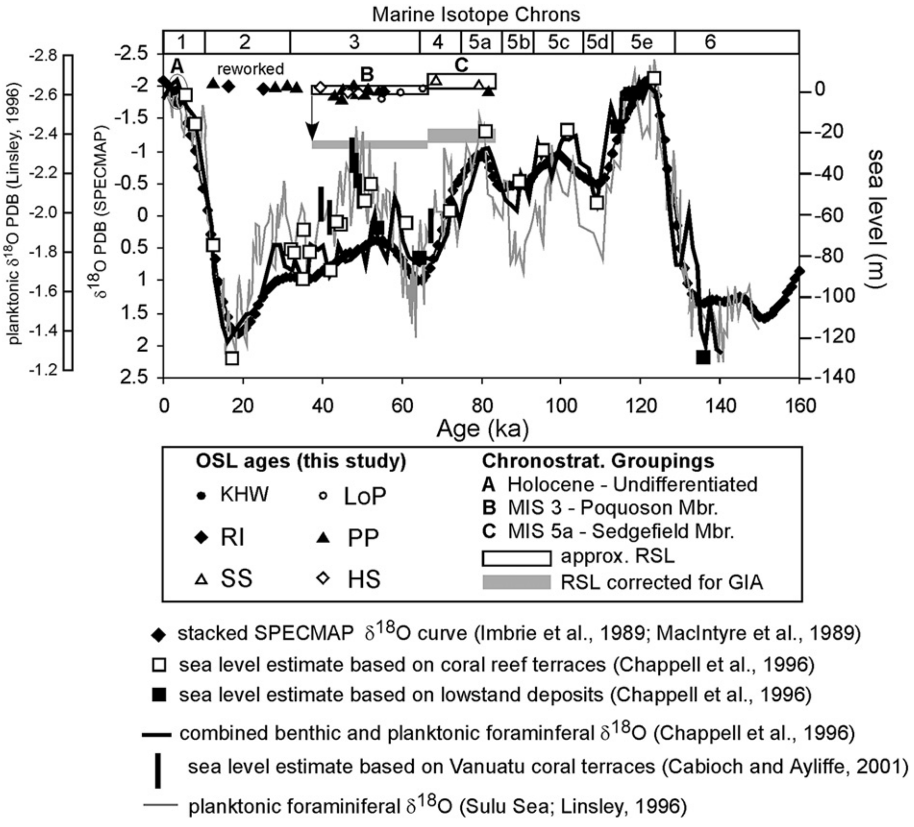

Figure 8. Comparison of OSL ages (central ages) from this study with the SPECMAP marine $\delta^{18}$O curve (Imbrie et al., 1989; MacIntyre et al., 1989), coral reef terraces (Chappell et al., 1996; Cabioch and Ayliffe, 2001), and foraminiferal $\delta^{18}$O data (Chappell et al., 1996; Linsley, 1996). Error bars are not indicated on the OSL ages, but are presented in Table 1, and discussed in the text.

Virginia suggest relative sea-level heights of ca. +4 to +10 m above present (Cronin et al., 1981; Mixon et al., 1982; Szabo, 1985; Wehmiller et al., 1997; Muhs et al., 2002; Potter and Lambeck, 2003; Wehmiller et al., 2004). The Suffolk Shoreline ranges in elevation from ca. +4 m (at the toe) to ca. +16 m at the crest within the study area. The OSL-dated sands are interpreted as eolian or backbarrier overwash based upon ground penetrating radar data and their grain-size, sorting, and bedding structure. Cronin et al. (1981) determined that the Sedgefield Member in the NC-VA border area represents a maximum sea-level position of ca. +7 m (±3 m).

MIS 5a coral reef terraces that are at or above modern sea level in Bermuda and Hawaii yield U-series ages corresponding to MIS 5a (Muhs, 1992; Muhs et al., 2002; Potter and Lambeck, 2003). However, data from coral reef terraces from the Huon Peninsula (HP) in New Guinea and Barbados place eustatic sea level during MIS 5a at a minimum depth of ca. −20 and −18 m, respectively (Lambeck and Chappell, 2001; Potter and Lambeck, 2003).

A further complicating factor is the observation that summer insolation at 65°N at ~80 ka was similar to the 11 ka insolation maximum (Berger and Loutre, 1991), and recent pollen and diatom studies from Baffin Island indicate a climate that was warmer than the Holocene (Miller et al., 1999; Wolfe et al., 2000). These data suggest that there may not have been a Laurentide Ice Sheet during MIS 5a, and ice-equivalent sea level would, therefore, be similar to today (Muhs et al., 2002).

The discrepancy between the NC/VA record of MIS 5a and the ice-equivalent record as potentially recorded by coral reef terraces in New Guinea has been a point of research and debate (Mixon et al., 1982; Muhs et al., 2004; Wehmiller et al., 2004). If we assume that the HP terraces are providing accurate ice-equivalent sea-level estimates for MIS 5a, as proposed by Chappell et al. (1996), then the elevation of the MIS 5a deposits in Virginia through South Carolina suggests that the current coastal system is uplifted by ca. 23 m to 29 m relative to a state of isostatic equilibrium (Cronin et al., 1981; Potter and Lambeck, 2003). Potter and Lambeck (2003) address this discrepancy and attribute it to deposition of MIS 5a shorelines along a profile of equilibrium following isostatic adjustment to the penultimate deglaciation (MIS 6 termination). Their data suggest that presently the east coast of North America is in a state of disequilibrium (uplifted, but subsiding) in response to the last glacial maximum. Potter and Lambeck (2003) interpret the crest of the uplift to occur in the region between Virginia, North Carolina, and South Carolina. The ICE5G VM2 model of mantle rheology (Peltier, 2004) also places the position of the pro-glacial forebulge in the general location of NC, and indicates subsidence of ca. 2 mm/yr due to GIA.

### *MIS 3*

The OSL data yielding MIS 3 ages are stratigraphically consistent with previous U-series analyses and AAR analyses from the general study area, and with vertebrate paleontology data. Currituck Peninsula and Roanoke Island contain *M. mercenaria* valves with D/L ratios which place them in Amino Zone 1 (78–51 ka) (Riggs et al., 1992). This age range matches quite well with the basal OSL age at Roanoke Island (RI-01) of 55±7 ka, and with most of the Land of Promise and Powell's Point Ridge ages (Table 1; Fig. 8). Furthermore, in southeast Virginia (Norfolk area), gravel beds overlying the Sedgefield Member contain bones of walrus and immature gray seal (*Halichoerus grypus*) and gannet (*Morus bassanus*), indicating a cold-temperate to subarctic climate (Ray et al., 1968; Mixon et al., 1982). A cold-temperate climate is consistent with deposition during MIS 3, but not MIS 5.

Although data from coral reef terraces in New Guinea and Barbados place maximum eustatic sea level during MIS 3 at ca. −46 to −36 m (Lambeck and Chappell, 2001; Chappell, 2002), Vanuatu coral terraces indicate MIS 3 sea level to ca. −22 m at the upper error limit (Cabioch and Ayliffe, 2001), and are in agreement with planktonic foraminiferal $\delta^{18}$O data from the Sulu Sea (Linsley, 1996). High stand estimates made by Bloom and Yonekura (1990), also from the Huon Peninsula, suggest a 60 ka high stand higher than −24 m. Additionally, there are siliciclastic deposits that are consistent with the Vanuatu corals. Estimates of MIS 3 sea levels have been made using seismic data and chronostratigraphic information constrained by the MIS 5 flooding surface and MIS 2 unconformity on the Texas continental margin (Rodriquez et al., 2000). They determined the existence of a MIS 3 barrier island and estuarine system that constrains the elevation of MIS 3 RSL to a depth of ca. −15 m. Likewise, Carey et al. (2005) recognize a MIS 3 marine depositional sequence at −21 m along the New Jersey continental shelf. The updip coastal lithosomes corresponding to the shelf unit would necessarily be at a shallower depth. Wellner et al. (1993) also identified a MIS 3 barrier island system on the inner New Jersey continental shelf at ca. −20 m. On the east coast of Florida, beach ridges associated with Merritt Island returned MIS 3 ages using OSL techniques (Rink and Forrest, 2006). On the south coast of Australia, Murray-Wallace et al. (1993), and Cann et al. (2000) recognize a MIS 3 shallow marine sequence at −22 m.

Chappell (2002) discusses the timing of sea-level oscillations and abrupt warming events during MIS 3. On the basis of coral reef terraces on the Huon Peninsula (HP), Chappell proposed interstadial peaks (sea-level high stands) at ca. 60 ka (−50 m), 52 ka (−36 to −46 m), 44.5 ka (−50 to −56 m), 38 ka (−71 m) and 33 ka (−72 m). These interstadials are associated with millennial scale warming events (Dansgaard–Oeschger cycles) recorded in oxygen-isotope fluctuations in Greenland ice cores. They represent very rapid changes in sea level of tens of meters (Yokoyama et al., 2000; Chappell, 2002; Lambeck et al., 2002). A hydraulic model based upon salinity records from the Red Sea also suggests large (ca. 35 m) high frequency sea-level changes during MIS 3 (Siddall et al., 2003). Our data suggest that we have recorded the maximum MIS 3 RSL position on the NC Coastal Plain. If the glacio–hydro-isostatic function can be adequately deconvolved in this region, then an accurate estimate of MIS 3 ice-volume equivalent sea level may be obtained.

Beneath the Currituck Peninsula, overwash deposits are evident in GPR data at an elevation of ca. −2 m (Fig. 6). Tidal flat deposits with ages ranging from 48.9±10.9 ka to 46.5±

2.5 ka are evident above present sea level (ca. +0.5 m) beneath the Hickory Shoreline (Fig. 5). An absolute datum for sea-level position is not evident, but the tidal flat unit suggests that RSL was at least at present sea level (0 m). Tidal range variations due to shelf width and resonance factors, and sediment compaction may add an additional 1 to 2 m of uncertainty.

The GIA estimates from Potter and Lambeck (2003) suggest that we must adjust the position of these MIS 3 shorelines downward by at least 20 m (Fig. 8). Assuming that the MIS 5a and MIS 3 shorelines were deposited along an isostatic equilibrium profile, that the proposed MIS 5a eustatic sea-level height of −19 m is correct (Chappell, 2002), and that the Suffolk Shoreline represents a RSL of ca. +7 m (+4 to +10 m; Cronin et al., 1981), then the study area is presently uplifted by ca. 26 m. Assuming that no significant subsidence occurred between MIS 5a and MIS 3, then the MIS 3 high stands attained heights of ca. −26 m. This is higher (by ca. 10 m) than the maximum (including error) sea-level interpreted from HP coral reef terraces, but is consistent with data from Vanuatu coral reefs that indicate MIS 3 sea-level high stands to −22 m (Cabioch and Ayliffe, 2001), and from siliciclastic systems (Murray-Wallace et al., 1993; Wellner et al., 1993; Cann et al., 2000; Rodriguez et al., 2000; Carey et al., 2005). The shallow shoreface associated with these paleoshorelines is also consistent with the concept of extremely high rates of sea-level rise, as indicated by other proxy data (Yokoyama et al., 2000; Chappell, 2002; Lambeck et al., 2002; Siddall et al., 2003).

### *MIS 1*

The Holocene age of the Kitty Hawk beach ridges (ca. 3 to 2 ka) places important constraints on the development and evolution of the North Carolina barrier island system. Recent LiDAR data indicate the existence of at least 30 prominent beach ridges (Fig. 3C). The relative ages of the beach ridges and sets are indicated by cross-cutting relationships, with the younger sets truncating older sets. The oldest beach ridge sets are to the west, adjacent to Albemarle Sound, while the youngest sets are undergoing erosion at the present shoreline at Kitty Hawk and northward (Fisher, 1967). The beach ridges are fronted and overlain by a continuous N–S trending, active to stabilized coastal dune field.

The significance of the Kitty Hawk beach ridge ages lies in the fact that they represent a Holocene shoreline and regressive deposits situated west (by at least 5 km) of the present transgressive shoreline, that occurred between ca. 3 ka and 2 ka. The age of these features matches the age of other cuspate forelands in the southeast U.S., such as Cape Sable, Florida, and Cape Canaveral, Florida (Roberts et al., 1977; Rink and Forrest, 2006). Although there are suggestions of minor sea-level oscillations (e.g., a mid-Holocene high stand) along the southeast U.S. Atlantic and Gulf of Mexico margin during the middle Holocene time period (Gayes et al., 1992; Morton et al., 2000; Blum et al., 2001), they are highly controversial (Otvos, 2004). Our data support some kind of regional mechanism that controlled the timing of the formation of progradational shorelines in the SEUSA, but we do not currently have the data to support or refute the possibility of rapid minor sea-level oscillations during the late Holocene.

We propose that the formation of the beach ridges at Kitty Hawk was initiated in response to rapid flooding and landward translation of the shoreline at ca. 4–3 ka. A rapid RSL rise is also indicated in the Gulf of Mexico at 4 ka (Rodriquez, 1999). The development of the beach ridges was then modulated by varying sediment flux to the system in response to varying wave energies. Rapid shoreline translation would have resulted in a new shoreface profile that was out of equilibrium (i.e., too shallow) with the ambient wave energy. As the shoreface eroded downward to attain a new profile of equilibrium, sand was transferred shoreward to build the Kitty Hawk beach ridge complex (a general mechanism for beach ridge formation proposed by Tanner, 1995). Alternatively, or perhaps additionally, a greater sediment flux within the longshore transport pathway may have been available as a result of dryer, cooler, and windier conditions occurring in the North Atlantic between 3 and 2 ka (Oppo et al., 2003).

## Conclusions

Stratigraphic and geomorphic investigations of the sand ridges in northeastern NC are consistent with previous investigations suggesting that these features are paleoshorelines. Optically stimulated luminescence data from coastal lithosomes in eastern NC are consistent with previously reported U-series and AAR dates, and provide a previously unavailable constraint on the formation of the siliciclastic paleoshorelines. These data indicate that RSL in this area was at or above present sea level during MIS 5a and MIS 3. The discrepancy between MIS 5a and MIS 3 RSL on the NC coast, and the ice-equivalent record as measured by coral reef terraces in New Guinea and elsewhere may be attributed to glacio–hydro-isostatic adjustments of the North American Atlantic Coastal Plain. With a correction for GIA, the MIS 3 shorelines suggest sea-level elevations ca. 10 m above those interpreted from HP coral reef terraces, but equivalent to sea levels estimated from Vanuatu coral reef terraces and siliciclastic shelf and shoreline deposits around the world.

The Holocene ages of the Kitty Hawk beach ridges indicate a MIS 1 shoreline west of the modern shoreline between 3 and 2 ka. The regressive system also indicates a large sediment flux to the coastal system, possibly in response to a cooler, dryer, and windier climate at that time.

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