Late Quaternary Development of the Croatan Beach Ridge Complex, Bogue Sound, Bogue
Banks, NC, USA and Implications for Coastal Evolution

Kelly B. Lazar^{1,2*}, David J. Mallinson¹, Stephen J. Culver¹

¹Department of Geological Sciences
East Carolina University
Graham Building
Greenville, NC 27858, U.S.A.

²Present address: Department of Environmental Engineering and Earth Science
Clemson University
123 Calhoun Drive
Clemson, South Carolina 29634, U.S.A.

*Corresponding Author:

Department of Environmental Engineering and Earth Science
Clemson University
445 Brackett Hall
123 Calhoun Drive
Clemson, South Carolina 29634
USA

klazar@clemson.edu
+1 919.559.7381

ABSTRACT

Foraminiferal, sedimentological, geophysical, and geochronologic data were utilized to elucidate the late Quaternary geologic development of the Croatan Beach Ridge Complex (CBRC), Bogue Sound, and Bogue Banks, North Carolina, USA. The CBRC is a relict beach ridge feature located on the mainland. It is separated from the modern barrier island, Bogue Banks, by Bogue Sound. Seventeen cores along shore-normal and shore-parallel transects provided material for sedimentologic and foraminiferal analysis and resulted in the recognition of seven depositional facies representing a variety of coastal depositional environments.

Chronologic and depositional facies data suggest the CBRC was initiated during MIS 5a and rapid southward progradation produced a cape structure. Eolian reactivation of the upper sand of the CBRC occurred during the last glacial maximum (~18 ka). The age of flood tide delta deposits in Bogue Sound suggests that the Holocene barrier island, Bogue Banks, had formed by ~6 ka. Shoreface ravinement resulted in a shoreface landward of the present shoreline by ~3.5 ka. Seaward and westward spit progradation of Bogue Banks began ~1.7 ka and continued to ~1.3 ka. Normal marine salinity conditions were present in Bogue Sound ~1.1 ka, suggesting removal of at least the narrowest parts of the barrier island, coeval with a previously documented segmentation of the southern Outer Banks barrier islands. Previous work has linked this segmentation to climate warming and increased tropical storm activity during the Medieval Climate Anomaly.

This study illustrates the complex response of this coastal system to Pleistocene and Holocene sea-level and climate change over two major sea-level cycles. In particular, the regional geomorphology during MIS5a and the Holocene sea-level highstand differ significantly

49 and this, in large part, was controlled by the antecedent geologic framework, resulted in the
50 contrasting more localized coastal geomorphic response.

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52 **ADDITIONAL INDEX WORDS:** *beach ridges, lagoon, climate change, OSL, Pleistocene,*
53 *Holocene.*

1. INTRODUCTION

As the global climate is shifting towards a warming planet, it is essential to understand how a rising sea level will affect coastal areas. Climate warming will accelerate rates of sea-level rise (Church et al., 2013), deemed potentially the most serious and destructive result of climate change. Estimated costs associated with sea-level rise are in the hundreds of billions of dollars in the USA, Japan, and low-lying European nations (Nicholls and Klein, 2005; Fankhauser, 2013). Sea-level rise will not have a uniform impact along a coastline; regional factors, including geomorphology, climate, ecology, and land use characteristics will create differing effects on a local scale (Bosello et al., 2012). Coastal communities as well as governments will have to mitigate and adapt to numerous environmental changes including erosion, inundation, wetland loss/change, and salinisation. For these reasons, a more complete knowledge of how coastal systems change in response to sea-level rise and associated processes is essential for responsible management of coastal environments.

Sea level has fluctuated significantly during the late Quaternary. Evidence of these fluctuations is preserved on coastal plains and beach ridge systems worldwide. Numerous studies suggest that sea-level change and storm events are responsible for the destruction and subsequent rebuilding of barrier island systems along the mid-Atlantic coast during the late Quaternary (e.g., Culver et al., 2007, 2008; Grand Pre et al., 2011; Mallinson et al., 2005; Pilkey et al., 2009; Riggs et al., 2000; Sager and Riggs, 1998). While barrier islands are typically responsible for protecting the back-barrier environment from storms, their protective capabilities are threatened from the effects of climate change, including rising sea-levels and an increase in storm activity (Moore et al., 1999; Morton and McKenna, 1999; Zhang et al., 2004).

The morphology of the coastal system of North Carolina is a result of Holocene sea-level rise coupled with modern processes and resultant environments, superimposed on relict structures (e.g., paleoshoreline deposits, relict estuarine sediments, paleodrainage systems, etc.) related to late Pleistocene sea-level fluctuations. The late Pleistocene siliciclastic beach ridges of the Atlantic Coastal Plain have been investigated by many researchers (Oaks and Coch, 1963; Mixon et al., 1982; Szabo, 1985; Wehmiller et al., 2004; Mallinson et al., 2008; Parham et al., 2013), yet the effects of regional glacio-isostatic adjustments in the region make pinning down relative sea level complicated. Estimations of local sea level in Eastern North Carolina were at least 9 m above present during MIS 5a (Parham et al., 2013). Such a high relative sea level is much greater than estimates of eustatic sea level based on coral records (Shackleton, 1987; Chappell et al., 1996) and is likely the result of subsidence of a significant glacial isostatic forebulge in North Carolina and southeast Virginia at this time (Davis and Mitrovica, 1996; Potter and Lambeck, 2003; Wehmiller et al., 2004; Mallinson et al., 2008; Parham et al., 2013). Similarly, relative sea level fluctuations during the Holocene for regions along the East Coast were investigated by Engelhart and Horton (2012). Their investigation of southern North Carolina (region 14; approximately the study area for this paper) suggest a relative sea-level rise of ~1.7 mm/yr for the later Holocene (10-4 ka), which slowed to ~0.9 mm/yr from 4 ka to AD 1900 (Engelhart and Horton, 2012).

This study utilizes foraminiferal, sedimentological, geophysical, and geochronologic data to define the late Quaternary geologic history of a barrier island and relict beach ridge system in eastern North Carolina. Specifically, it furthers the knowledge of the controlling factors which influence the position of the late Pleistocene and Holocene shorelines as well as contributes to the understanding of how barrier island systems form and evolve in response to climate change

and sea-level rise. More generally, this study documents how the nature of the coast changes from one sea-level cycle to another and that a return to the original geomorphic setting is possible but unlikely unless similar conditions of sediment supply, height of sea level, rate of sea-level change, local oceanographic conditions, regional climate and geomorphology are repeated.

2. STUDY AREA

Light Detection and Ranging (LiDAR) elevation data of eastern North Carolina indicate northeast-southwest trending ridges on the mainland (Figs. 1A, B). This beach ridge complex, the Croatan Beach Ridge Complex (CBRC), is located just north of Bogue Sound and to the southwest of the Suffolk Scarp (also known as the Suffolk Shoreline; Mallinson et al., 2008), a late Quaternary (MIS 5) paleoshoreline complex (Parham et al., 2013; Fig. 1A). The CBRC is composed of approximately sixty beach ridges extending inland approximately 8 km and running oblique to the coastline for 24 km, eventually converging towards the southwest (Fig. 1C). Originally described by Fisher (1967), the ridges are 9–11 m above mean sea level, but the ridges themselves are located on a coastal plain that rises 7.5 m above mean sea level at the shoreline. Fisher (1967) postulated that the 8 km-wide beach ridge complex formed on the mainland (rather than as a barrier island welded to the mainland during high sea level as a cusate foreland (Fig. 1C). This beach ridge complex is morphologically very similar to the beach ridges present in the Cape Hatteras (North Carolina, USA) cusate foreland (Fisher, 1967), suggesting the CBRC is a relict cape complex at the southern end of the Suffolk Scarp.

The CBRC ridges are the landward-most component of three successive shoreline units; the relict, prograding CBRC, a younger paleoshoreline (currently forming the northern margin of Bogue Sound), and the present Holocene barrier island (Bogue Banks; Fig. 1B). The east-west trending Bogue Banks separate Bogue Sound from Onslow Bay (Riggs et al., 1995). Bogue Sound, a shallow (~2 m) back-barrier lagoon with a mean tidal range of 0.75 m and salinity ranging from 35 to 39, is connected to the Atlantic Ocean via Beaufort Inlet in the east and Bogue Inlet in the west (Fig. 1A).

3. FIELD AND LABORATORY METHODS

3.1 Core Collection and Lithofacies Analysis

Eleven Geoprobe cores ranging in length from 6 to 10 m were collected on the CBRC and Bogue Banks (Fig. 1B). Six vibracores ranging in the length from 2 to 7 m were collected from Bogue Sound. Cores were photographed, logged, and sampled for grain size and foraminifera before being archived. All cores were logged using methods outlined by Folk (1980); these logs were then correlated to determine the vertical and horizontal distribution of distinct lithofacies. Grain-size analysis (~40 g sample size) was performed on each core at either side of a lithofacies boundary.

3.2 Seismic Data Acquisition

High resolution chirp seismic data were acquired in Bogue Sound using an Edgetech SB-216 (2 to 16 kHz) subbottom profiler, and Discovery Software. The SB-216 was towed behind the RV Beeliner (East Carolina University) at 3 knots at the surface using pontoons for flotation.

Positioning was done using a WAAS enabled Garmin GPS, providing spatial accuracy of $\sim\pm 2$ m. SEG-Y data were imported into Seismic Micro-Technology (SMT) Kingdom Suite software, and automatic gain control was applied.

3.3 Foraminiferal Sampling and Processing

A surface Ponar grab sample was collected at each vibracore location in the modern Bogue Sound. Approximately 40 ml of sediment from the top 1 cm of each Ponar grab sample was immediately collected and preserved in alcohol. Cores were brought back to the lab and sampled for foraminifera at depths where lithologic change was noted in the core log. Processing of foraminifera samples was completed using the methods outlined by Culver et al. (1996) and Woo et al. (1997). Ponar samples were stained with rose Bengal to distinguish between live (stained) and dead tests (Walton, 1952). Each sample was washed over nested 710- and 63- μm sieves to isolate the sand fraction and remove alcohol and excess stain from the sample. The foraminifera in the $>63\text{-}\mu\text{m}$ (sand) fraction were separated from the sediment using a sodium polytungstate floatation method (Munsterman and Kerstholt, 1996). Approximately 200 foraminifera were picked from each sample, unless fewer specimens were present. Identifications based on perusal of the literature were confirmed by comparison with type and figured specimens housed in the Cushman Collection, Smithsonian Institution, Washington, D.C., USA.

Foraminiferal biofaces were determined using Q-mode cluster analysis data (Euclidean distances, Ward's linkage; Mello and Buzas, 1968). Only those species which represented $\geq 2\%$ of the assemblage in any one sample were included. The relative abundances were transformed for input into Systat 12 using the following equation:

$2\arcsin\sqrt{p}$

where p = abundance. The average relative abundance was calculated for each taxon in each biofacies (Table 1). Census data are given in Appendix 1. All species representing $\geq 2\%$ of any assemblage were examined using a scanning electron microscope and imaged (Fig. 2).

3.4 Geochronologic Data Collection and Processing

Optically stimulated luminescence dating (OSL) and radiocarbon dating techniques were applied to core material to create a geochronologic framework for the study area. Eleven OSL samples were taken from cores collected under safe light conditions and sent to the USGS Optically Stimulated Luminescence Lab in Denver, Colorado. Samples underwent a 4 M HCl and 35% H_2O_2 bath to dissolve carbonates and organics. Samples were then wet-sieved to collect the 180–250 μm fraction and dried overnight. Once dry, the samples underwent heavy liquid separation using a centrifuge to isolate the quartz grains. Once washed and dried, the quartz grains were etched with HF. The isolated quartz grains underwent blue-light and infrared OSL method and single-aliquot regeneration-dose technique (SAR; Wintle and Murray, 1999). The dose rate of the surrounding sediment was determined by the activity of ^{40}K , ^{238}U , and ^{234}Th .

Accelerator mass spectrometry (AMS) ^{14}C was used to date three samples: two disarticulated bivalves and 2000 specimens of *Elphidium excavatum*. When picking foraminifera for AMS dating, care was taken to choose well-preserved specimens of various sizes to ensure an *in situ* population was being sampled rather than a transported, size-sorted assemblage.

4. RESULTS AND INTERPRETATIONS

4.1 Depositional Facies

Thirteen lithofacies (six dominated by sand, six by mud, and one by oyster shells) were defined based on observed characteristics and grain size analysis of 165 sediment samples. A cluster analysis of transformed foraminiferal abundance data (59 samples, 32 taxa) produced six nested groups (biofacies) distinguished by both distribution and age (Fig. 3). Lithofacies and biofacies data were analyzed and correlated to define seven depositional facies (DF) in the study area. Interpretation of these depositional facies is based on comparisons with previous studies of modern marginal marine and shelf environments along the mid-Atlantic coast (e.g., Culver and Buzas 1980; Grossman and Benson, 1967; Kemp et al., 2009; Schnitker, 1971, Murray, 1969; Robinson and McBride, 2006).

The Shallow Inner Shelf Depositional Facies (DF I), composed of seven samples containing 18 species (Biofacies A), is dominated by *Elphidium excavatum*, with *Ammonia parkinsoniana* as an important subsidiary species (Table 1). This DF has the lowest species richness (Table 1) and is typically found in the central and eastern-most cores of the CBRC. The associated lithofacies are predominately sandy, although a few samples containing Biofacies A are muddy (Fig. 3). Eighteen species are present in this DF but *Elphidium excavatum* and *Ammonia parkinsoniana* comprise >95% of the assemblages (Table 1). The dominance of robust tests (including those of *E. gunteri* and *Quinqueloculina seminula*) and absence of delicate tests likely indicate an energetic environment (and thus possible post-mortem destruction of delicate tests), similar to modern inner shelf assemblages off North Carolina (Schnitker, 1971). The dominance of *Elphidium excavatum* in this DF (93.9%) as well as the presence of *Ammonia*

parkinsoniana (1.9%) compares with modern shoreface and shallow-shelf normal marine salinity (~34) assemblages off the Outer Banks (Workman, 1981).

The Low Energy Inner Shelf Depositional Facies (DF II), composed of twelve samples containing 25 species (Biofacies B), is dominated by *Elphidium excavatum* (76.6%) and *Ammonia parkinsoniana* (6.3%; Table 1). The foraminiferal assemblages of DF I (shallow inner shelf) and DF II are very similar. DF II, however, contains more species than DF I and *Elphidium excavatum* is less dominant. DF II is primarily associated with a shelly muddy sand and shelly sandy mud lithofacies, although a few samples are characterized by mud, sand, shelly sand, large shell, and sandy mud lithofacies (Fig. 3). Two samples from beneath Bogue Sound are characterized by DF II. Most samples, however, are in the CBRC, which is characterized almost entirely by DF I and DF II. The highest relative abundances of *Bolivina lowmani* and *Bolivina paula* in this study occur in DF II; these taxa, along with *Trifarina angulosa*, are typical modern normal marine salinity mid-shelf species off North Carolina (Schnitker, 1971).

The High Energy Inner Shelf Depositional Facies (DF III), composed of 13 samples containing 24 species (Biofacies C), is dominated by *Elphidium excavatum* (54.7%), *Quinqueloculina seminula* (12.8%), *Ammonia parkinsoniana* (10.9%), and *Hanzawaia strattoni* (6.2%) (Table 1). Every sample taken from Bogue Banks cores clustered in DF III, as did five samples from the CBRC and one from Bogue Sound (Fig. 3). Most samples in DF III were mainly characterized by shell-rich lithofacies (shelly sandy mud, shelly sand, shelly muddy sand and large shell; Fig. 3), suggesting a higher energy environment than that of DF II. The robust species *Quinqueloculina lamarckiana*, *Quinqueloculina seminula*, and *Elphidium galvestonense* indicate an assemblage typical of the normal marine salinity inner continental shelf of North Carolina (Murray, 1969; Schnitker, 1971; Workman, 1981).

The Flood Tidal Delta Depositional Facies (DF IV), composed of 16 samples containing 27 species (Biofacies D), is dominated by *Elphidium excavatum* (54.4%), *Ammonia parkinsoniana* (20.9%), *Elphidium mexicanum* (7.5%), and *Hanzawaia strattoni* (2.8%) (Table 1). DF IV has more specimens and species than any other depositional facies as well as more planktonic foraminifera and fossil foraminifera (Appendix 1). This depositional facies is found in down-core samples from Bogue Sound and typically is characterized by coarse sediment. Twelve of the sixteen foraminiferal samples were from shelly lithofacies (shelly muddy sand, shelly sand, shelly mud, large shells, shelly sandy mud), with the remaining four samples in the sand lithofacies (Fig. 3). Coarse molluscan shell lag deposits, similar to those of DF IV, are typical of inlet/flood-tide delta channel deposits (Moslow and Heron, 1978; Culver et al., 1996). Assemblages from the northern Outer Banks and Virginia barrier islands containing similar calcareous normal marine salinity taxa as DF IV were interpreted as indicating flood tidal delta environments by Culver et al. (1996), Robinson and McBride (2006) and Smith et al. (2009). The Pine Knoll Shores area of Bogue Banks (Figs. 1B) is interpreted as a flood-tide delta overtopped by a marsh (Steele, 1980; Timmons et al., 2010), which also explains the coarse shell deposits in Bogue Sound. Three of four foraminifera samples in vibracore BS-08-04, west of BS-08-01 and adjacent to the Pine Knoll Shores flood-tide delta (Fig. 1B), are contained within this depositional facies. The relatively high percentage of *Ammonia parkinsoniana* (20.9%) within DF IV compared to DF I, II, and III (representing shallow inner shelf and normal marine salinity environments) suggests greater estuarine influence.

The Low Energy High Salinity Estuary Depositional Facies (DF V), composed of four samples containing 19 species (Biofacies E), is dominated by *Elphidium excavatum* (39.1%), *Ammonia parkinsoniana* (36.2%), *Elphidium mexicanum* (8.0%), and *Haynesina germanica*

(7.0%) (Table 1). This depositional facies, associated with dominantly muddy lithofacies (Fig. 3), occurred in down-core samples within Bogue Sound and contains the fewest specimens and species of all biofacies. It is similar to the High Salinity Estuary B Biofacies described by Pruitt et al. (2010) in Core Sound (Fig. 1A). Both contain similar percentages of *Ammonia parkinsoniana* and *Elphidium excavatum*. High Salinity Estuary B (Pruitt et al., 2010) was located on the eastern margin of Core Sound (Fig. 1A), adjacent to the barrier island, which is a similar setting to the location of the samples comprising DF V of this study.

The High Energy High Salinity Back-Barrier Estuary Depositional Facies (DF VI) is composed of 22 species from seven Bogue Sound samples (Biofacies F), including five surface sediment samples. Every sample was characterized by the shelly sand lithofacies (Fig. 3). DF VI is dominated by *Elphidium excavatum* (41.3%), *Ammonia parkinsoniana* (23.4%), and *Elphidium mexicanum* (13.9%) (Table 1). DF VI also contains numerous calcareous species indicative of an inner shelf environment such as *Ammonia* cf. *A. beccarii* and *Elphidium poeyanum* (Murray, 1969), and the robust species *Elphidium galvestonense* and *Elphidium gunteri* (Workman, 1981), suggesting exchange of oceanic water with Bogue Sound. However, the agglutinated taxon *Ammotium salsum* represents an average of 4.9% in the assemblages (Table 1). *A. salsum* is found (although with a greater percentage, 34%) in the Estuarine Low Salinity Biofacies of Core Sound (Pruitt et al., 2010). Abbene et al. (2006) described a similar abundance of *Ammotium salsum* in a low brackish estuary biofacies within Pamlico Sound, a system with far less oceanic influence than Bogue Sound. DF VI is interpreted as a high salinity estuarine deposit due to the known salinity (~35) at surface sample sites and the presence of numerous inner shelf taxa. Lower salinity estuarine environments are nearby, however, as indicated by the presence of *Ammotium salsum*.

The Eolian Sand Depositional Facies (DF VII) occurs mainly in the cores on the CBRC and on Bogue Banks. These samples, generally barren of foraminifera and not included in the cluster analysis, occurred primarily within the sand and organic-rich sand lithofacies, but were also present in the interbedded mud/sand and gravelly sand lithofacies. This depositional facies represents the upper section of cores located in the CBRC and Bogue Banks. On Bogue Banks, DF VII occurs in barrier island sand/overwash sand and back-barrier sand flats. In the CBRC, the draping of this depositional facies over older coastal features suggests it represents eolian sand accumulation.

4.2 Geochronology

4.2.1 OSL Age Estimates

Several studies (Ballarini et al., 2003; Havholm et al., 2004; Mallinson et al., 2011; Owen et al., 2007; Rink and Forrest, 2005; van Heteran et al., 2000) have shown the effectiveness of OSL in coastal environments. This technique is especially useful when no organic material is present or its preservation *in situ* is suspect. Eleven OSL samples were collected, five from the CBRC, four from Bogue Sound, and two from Bogue Banks (Fig. 1B; Table 2). The northernmost OSL sample obtained in the CBRC from core CR-08-GP3 (Fig. 1B) was collected at an elevation of 3.95–4.06 m above MSL from a unit interpreted to be part of the Eolian Sand Depositional Facies (DF VII), and yielded an age estimate of 80.8 ± 9.00 ka. Another sample from this depositional facies, collected from CR-08-GP4 in the CBRC, was taken at an elevation of 7.14–7.19 m above MSL and yielded an age estimate of 95.2 ± 9.25 ka. Three OSL samples, from CR-08-GP1 (2 samples) and CR-08-GP5 (1 sample), were taken from the southernmost

sand ridge of the CBRC that stretches along the northern coastline of Bogue Sound (Fig. 1B). The shallowest sample in CR-08-GP1 was collected from the Eolian Sand Depositional Facies (DF VII) and yielded an age estimate of 18.3 ± 1.60 ka. The deeper sample was collected in the Low Energy Inner Shelf Depositional Facies (DF II) and yielded a significantly older age estimate of 50.4 ± 3.80 ka, suggesting it was deposited during a different stage of beach ridge development. The OSL sample from CR-08-GP5 was collected at an elevation of 4.45-4.53 m above MSL from the Eolian Sand Depositional Facies (DF VII), and yielded an age estimate of 83.4 ± 8.92 ka.

The eastern-most OSL sample from Bogue Sound, taken from BS-08-01 at a depth of 5.67-5.77 m below MSL from the Flood Tide Delta Depositional Facies (DF IV; Fig. 1B), yielded an age estimate of 2.49 ± 0.25 ka. A sample from the central region of Bogue Sound (BS-08-03), collected from the Low Energy High Salinity Estuary Depositional Facies (DF V) at a depth of 7.96-8.06 m below MSL, yielded an age estimate of 41.0 ± 3.78 ka. An adjacent sample from BS-08-04, at a depth of 7.61-7.71 m below MSL, collected from the Flood Tide Delta Depositional Facies (DF IV), and gave an age estimate of 5.18 ± 0.53 ka. The western-most sample from Bogue Sound, collected in BS-08-05 at a depth of 3.30-3.40 m below MSL in the High Energy Inner Shelf Depositional Facies III, yielded an age estimate of 1.18 ± 0.17 ka.

The eastern-most sample from Bogue Banks, taken from BB08-GP1 at a depth of 0.15-0.25 m below MSL in the Eolian Sand Depositional Facies (DF VII), gave an age estimate of 1.72 ± 0.14 ka. A second sample from Bogue Banks, collected from BB08-GP2 at a depth of 0.80-0.90 m below MSL from DF VII, yielded an age estimate of 1.35 ± 0.15 ka. This sample returned a younger age estimate from a deeper sample than that in BB08-GP2. BB08-GP1 is

located on the eastern end of a westward-prograding spit complex which built the eastern segment of Bogue Banks.

4.2.2 AMS ^{14}C Age Estimates

Three radiocarbon dates were obtained from *in situ* carbonate within Bogue Sound (Table 3). A well-preserved, delicate, articulated *Cyrtopleura costata* (angel wing clam) collected from BS-08-03 (Fig. 1B) at a depth of 4.59 m below MSL within the Low Energy Inner Shelf Depositional Facies (DF II) yielded an age estimate of 3.92 ± 0.10 ka. An articulated oyster preserved *in situ* in BS-08-02 at a depth of 3.24 m below MSL within the Low Energy High Salinity Estuary Depositional Facies (DF V), yielded an age estimate of 3.39 ± 0.07 ka. A sample of 2,000 specimens of the foraminifer *Elphidium excavatum*, collected from BS-08-03 at a depth of 7.06-7.09 m below MSL within the Flood Tide Delta Depositional Facies (DF IV), yielded an age estimate of 6.05 ± 0.13 ka.

4.3 Seismic Data

Numerous reflections were defined within the study area, to a depth of ~ 20 meters below sea level (mbsl). It is not entirely clear where the Holocene-Pleistocene (H/P) boundary occurs. However, age control in core BS-08-03, and correlation to seismic line BS08-L6f1 indicate that the H/P boundary is near the bottom of the core, likely associated with the medium to high amplitude reflection with variable relief between ~ 14 and 7 mbsl (Fig. 4). Holocene deposits are characterized by a complex geometry, with low-relief channel structures containing high-amplitude subhorizontal to gently dipping beds near the base (~ 14-10 mbsl), areas dominated by subparallel, subhorizontal reflections, and other areas containing channel structures and channel-

fill consisting of steeply dipping clinoforms. A prominent subhorizontal reflection occurs at ~ 4 mbsl in many areas. Correlation to BS-08-03 suggests that this surface represents an upward transition from flood-tide delta deposits (DFIV) to low energy inner shelf facies (DFII); thus, a flooding surface is interpreted. A shallower reflection is seen in some areas at ~ 3 to 2 mbsl, with variable relief, and is interpreted as a bay ravinement surface (Fig. 4, A-A', B-B').

5. DISCUSSION

5.1 Late Pleistocene Evolution of the Croatan Beach Ridge Complex

Transect A (Figs. 1B, 5, 6A) provides an 18 km-long N-S section across the CBRC. The basal units of the CBRC are composed of normal marine DFs I-III. They vary from 1 m to -3 m mean sea level. Ground penetrating radar data indicate that these deposits are part of a normal regressive shoreface system (Fig. 5). Overlying the marine units are 8-m thick eolian sand deposits that show the beach ridge geomorphology of the CBRC (Fig. 5, 6A). Based on the subsurface data, the beach ridges appear to be multiple backshore foredune ridges (Otvos, 2000). The ridge located along the northern shoreline of Bogue Sound is the youngest in the CBRC and the limit of the southernmost progradation of the CBRC.

Transect B (Figs. 1B, 6B) illustrates a 12.5 km-long beach ridge-oblique section, located to the west of Transect A. Similar to Transect A, basal units representative of depositional facies I-III are overlain by eolian sand (DF VII), and a profile of the youngest ridge in the CBRC is evident.

OSL samples from eolian sand (CR-08-GP3) in the northern-most beach ridges in the CBRC yielded an age estimate of 80.8 ± 9.00 ka (Table 2). This indicates formation of the

CBRC beach ridges during MIS 5a. OSL samples from southern ridges in the CBRC (Croatan-08-GP5 and Croatan-08-GP4) yielded statistically similar age estimates of 83.4 ± 8.92 ka and 95.2 ± 9.25 ka, respectively. The two OSL samples taken from CR-08-GP1 in DF VII yielded age estimates differing by nearly 30,000 years. The deeper sample from +1.3 m MSL yielded an age of 50.4 ± 3.80 ka, while the shallower sample (+3.8 m MSL) is estimated at 18.3 ± 1.60 ka. This suggests some reactivation of these eolian deposits during two time intervals, ~50 ka and ~18 ka, subsequent to the formation of the CBRC. These reactivation events are separated with the oldest reactivation occurring ~30,000 years after the formation of the CBRC, and the younger reactivation ~30,000 years after the first.

The similarity of age estimates returned from the northern CBRC (in CR-08-GP3; 80.8 ± 9.00 ka) and the southernmost ridge of the CBRC (in CR-08-GP5; 83.4 ± 8.92 ka) suggest a cape began to develop in this area during MIS 5a (Fig. 1C). These ages agree with ages from the Suffolk Shoreline to the north (Mallinson et al., 2008; Parham et al., 2013) and indicate the formation of a cape at the southern terminus of this shoreline complex during MIS 5a. The eolian origin of the CBRC strandplain, as evidenced by the thick DFVII deposits of approximately sixty beach ridges (Fig. 1C), indicates an abundant sand supply, likely resulting from shoreface ravinement to the north, and southward sediment transport along the Suffolk Shoreline. The transgressive ravinement surface associated with MIS5 has been mapped using seismic data to a depth of ~10 mbsl in the western Pamlico Sound to the north of the study area (Mallinson et al., 2010).

Along the southern ridge (Fig. 6B) the 18.3 ± 1.60 ka age estimate of the younger OSL sample from CR-08-GP1 suggests eolian reactivation coeval with the sea-level lowstand of MIS 2 (Chappell et al., 1996; Fairbanks, 1989). Similar reactivation of an analogous Pleistocene

facies sequence has been described in nearby Swansboro, NC (Mallinson et al., 2008), ~25 km west of the CBRC (Fig. 1A).

5.2 Holocene Evolution of Bogue Banks and Bogue Sound

The balance between underlying geologic framework, sediment supply, and island morphology ultimately determine how a barrier island will respond to changes in relative sea level (Riggs et al., 1996; Rodriguez et al., 2004; Timmons et al., 2010). The oldest Holocene deposits in Bogue Sound are composed of the Low Energy High Salinity Estuary Depositional Facies DF V, shown in Transect A (Fig. 6A). An age estimate of ~41 ka was returned for this unit in BS-08-03. This likely results from the rapid reworking of Pleistocene sands and redeposition during Holocene ravinement resulting in partial bleaching of the sand grains collected for OSL analysis at this interval. During analysis, this would result in an averaging of the Holocene and Pleistocene sands, yielding an age of ~40 ka.

Holocene sea-level rise resulted in shoreline transgression and development of Bogue Banks near the MIS5a paleoshoreline (the southern extent of the CRBC). However, the modern shoreline to the north of Cape Lookout is well east of the MIS5a shoreline (the Suffolk Shoreline; Mallinson et al., 2008; Parham et al., 2013). The CBRC marked a north-south to east-west change in shoreline trend which now occurs at the modern Cape Lookout cusped foreland (Fisher, 1967) well east of the CRBC. This geomorphic configuration is likely the result of a lower elevation on the paleotopographic surface south of Cape Lookout due to the dearth of major fluvial systems within the Onslow Bay coastal compartment and consequent lack of late Pleistocene deposition. Thus, as sea-level rose, the shoreline transgressed rapidly to form a coast-

parallel barrier island near the MIS5a shoreface just south of the CBRC, separated from the mainland by Bogue Sound.

The flood-tide delta deposits (DF IV) located above the low energy high salinity estuary DFV were dated by both radiocarbon and OSL techniques. The radiocarbon age estimate was 6.05 ± 0.13 cal ka (at 7.075 mbsl; Table 3) and OSL age estimate was 5.18 ± 0.53 ka (at 7.61–7.71 mbsl; Table 2; Fig. 6A). Thus, Bogue Banks must have existed by ~6 ka. A ~6 ka age of formation for Bogue Banks is in agreement with the evolutionary history described by Timmons et al. (2010), and coincides with a decreasing rate of eustatic sea level rise which would have allowed for barrier island development (Horton et al., 2009; Mallinson et al., 2008; Rodriguez et al., 2004; Timmons et al., 2010). The Low Energy Inner Shelf DF II overlying the flood tidal delta deposits yielded a radiocarbon age estimate of 3.92 ± 0.10 ka (Table 3, Fig. 6B), suggesting the barrier island was breached at this time, coeval with segmentation of a large segment of the southern Outer Banks barrier islands (Grand Pre et al., 2011; Peek et al., 2013).

The evolution of Bogue Banks and Bogue Sound can be broken into five time slices (Fig. 7). At the base of the Holocene section, the low-relief channel structures containing high-amplitude subhorizontal to gently dipping beds (~14–10 mbsl) suggest fluvial to estuarine deposition with some tidal influence. At ~6 ka, the barrier island began to form near its present location (as evidenced by the OSL and radiocarbon ages of flood-tide delta deposits in cores BS-08-03 and BS-08-04; Fig. 6A). A highly-segmented barrier island system likely existed at this point, based on the extent of flood tidal delta deposits under Bogue Sound. The island transgressed rapidly between ~6 and ~4 ka to a position north of the present island, producing the flooding surface seen in seismic data (Fig. 4; A-A', B-B'). This is indicated by the 4 ka age of the Low Energy Inner Shelf DFII within Bogue Sound, which grades laterally to the High

Energy Inner Shelf DF III beneath Bogue Banks (Fig. 6A). DF III deposits likely represent an upper shoreface environment (cf. Timmons et al., 2010). The extent of this facies as seen in core BS-08-05 (Fig. 6B, 7), suggests that the ocean shoreline was at least 1.2 km north of the present ocean shoreline. This is consistent with the position of several small islands discussed by Timmons et al. (2010) as representing the maximum landward position of the barrier island following transgression.

The Flood Tidal Delta DFIV and the Low Energy Inner Shelf DFII in BS-08-03 and BS-08-04 occur within a channel (likely an inlet channel) imaged in seismic data (Fig. 4; A-A', B-B'). The base of the channel occurs at ~10 mbsl in the BS-08-04 area, and slopes upward to the north. The channel is filled with sub-horizontal parallel beds in the south, and seaward-dipping clinoforms in the north (BS-08-03 area). The age of the Flood-Tidal Delta DFIV and associated inlet ranges from a maximum of ~6 ka to a minimum of ~4 ka. Likewise, a tidal (inlet?) channel filled with clinoform deposits occurs behind the Pine Knoll Shores area (Fig. 4; C-C'). Clinoform dip directions reverse across the unit, which may indicate beach ridge growth in a seaward direction (progradation) as well as spit growth into an inlet. Further seismic control would be required for a definitive identification. No cores or dates are available for this channel-fill/spit complex. However, given age control from other cores in this study and Timmons et al. (2010), and the extent of the High Energy Inner Shelf DFIII in Bogue Sound, it is likely that these prograding deposits represent the northward and westward extent of the earliest beach ridges comprising the Pine Knoll Shores area, suggesting formation at ~3 to 4 ka. These data indicate that as the system transgressed, and during initial regression, the barrier was segmented by at least two inlets; one in the Indian Beach area, and one in the Pine Knoll Shores area (Figs. 4, 7).

At ~1.7 ka (as evidenced by OSL-dated deposits at Pine Knoll Shores; Table 2), seaward and westward spit and beach ridge progradation continued (or re-occurred) in western Pine Knoll Shores, as clearly seen in the modern geomorphology of the system (Fisher, 1967) (Fig. 7). Progradation continued until at least ~1.35 ka, and created a ~6.5 km-long spit complex over ca. 400 years (Fig. 7) at a spit progradation rate of ~16 m/yr, a rate similar to those found at modern inlets of the Outer Banks (Riggs and Ames, 2011). Foraminiferal assemblages in several Bogue Sound cores (BS-08-01, -02, -03, and -04) suggest flood-tide delta deposition and normal marine salinity conditions prevailed in Bogue Sound from ~1.7 ka to at least ~1.2 ka, at least behind Pine Knoll Shores. Thus, the geomorphology and paleoenvironmental data make it clear that west Bogue Banks and east Bogue Banks were two separate islands, with a rapidly migrating inlet between them in the Pine Knoll Shores area. Timmons et al. (2010) showed that the beach ridges on the western end of Bogue Banks (Emerald Isle) and on Long Island in Bogue Sound (Fig. 7) also yield ages of ~2.10 to 1.76 ka, indicating that these ridges, although interrupted by inlets, represented coeval deposition along a shore that was ~1.1 km north of the present ocean shoreline.

At 1.18 ± 0.17 ka, normal marine salinity conditions continued in Bogue Sound (Fig. 7). Salter Path represents one of the narrowest and most vulnerable places for overwash and sea-level rise flooding on Bogue Banks (Fig. 7). The suggested increase in storm activity resulting from warm ocean temperatures at this time (Cronin et al., 2003; Culver et al., 2007; Mann et al., 2009) likely contributed to island breaching as a result of increased fetch developing in the expanding Bogue Sound at this location (Timmons et al., 2010). The development of a dune system on Bogue Banks was interrupted by an erosional period in this location (also described by Timmons et al., [2010]), effectively segmenting the island and allowing for normal marine

salinity conditions to persist in Bogue Sound at this location (BS-08-05; Figs. 1B, 6B, 7). This is the same timing as the segmentation of the southern Outer Banks (Culver et al., 2007; Grand Pre et al., 2011), which resulted in normal marine salinity conditions in southern Pamlico Sound for ca. 500 years. As the southern Outer Banks barriers reformed, spit progradation on Bogue Banks continued seaward and westward, eventually filling the central portions of the Banks and resulting in the current high energy back-barrier estuarine conditions in Bogue Sound (Fig. 7).

Sedimentological and foraminiferal data from this study indicate large sections of flood-tide delta deposits along the eastern portion of Bogue Sound, directly behind the Pine Knoll Shores area of Bogue Banks (Fig. 7). Adjacent to Pine Knoll Shores is the Atlantic Beach area (Fig. 7), which was developed over the flood tide delta of Cheeseman's Inlet, a paleo-inlet which was open ca. 1850 (Cleary and Pilkey, 1996). Beaufort Inlet, which separates Bogue Banks from Shackleford Banks, is one of the most stable inlets in North Carolina (Fig. 1A; Cleary and Pilkey, 1996). This inlet lies over an antecedent fluvial drainage pattern, which has kept this inlet stationary for at least the past 300 years (Stick, 1958). The persistent presence of an inlet in this area could suffice to explain the extensive flood-tide delta deposits found in Bogue Sound.

5.3 Sequence Stratigraphic Framework

The sequence stratigraphic framework of the study area reflects its development over one complete base-level cycle (MIS6 to MIS2 - late Pleistocene) and one partial cycle (MIS1 - the Holocene). The base of the CBRC system (Unit 1; Figs 1 and 8) is marked by a transgressive ravinement surface, which was imaged in the GPR data (Figs 5 and 8). The age of this reflection is constrained by the overlying beach ridge sediments (*ca.* 80 ka in CR-08-GP3 and CR-08-GP5). Seaward progradation of the CBRC, with no corresponding offlap of the ridges (elevation

is consistent at ~10m), suggest that these represent a normal regression and highstand systems tract (Catuneanu, 2006). A lower elevation system (Unit 2; Figs. 1 and 8) occurs along the mainland perimeter of Bogue Sound and is tentatively interpreted as a falling stage systems tract (forced regressive deposits), based on the offlapping character of the ridges relative to the CBRC. The surface separating Unit 1 from Unit 2 is tentatively interpreted as a basal surface of forced regression (BSFR; Fig. 8).

Channels were imaged beneath Bogue Sound (Fig. 4), and are interpreted as fluvial, as they appear to correspond to the Holocene-Pleistocene boundary. Fluvial channels were also imaged seaward of Bogue Banks by Hine and Snyder (1985) and Timmons et al. (2010). Fluvial fill within the base of these channels is part of the lowstand systems tract (LST; Fig. 8). Sea-level rise associated with the last deglaciation (Termination 1) resulted in a transition (across the maximum regressive surface - MRS) to estuarine sediments associated with the transgressive systems tract. A transgressive ravinement surface (TRS; Fig. 8) formed as the shoreface moved landward. Maximum transgression (maximum flooding) associated with development of the Holocene HST occurred at ca. 6 to 4 ka as the proto-Bogue Banks barrier islands occurred north (landward) of the present location (Timmons et al., 2010). This was accompanied by initial emplacement of flood tide delta deposits beneath Bogue Sound (Fig. 7), and associated tidal ravinement which continues in some areas today depending on proximity to inlets. The Holocene maximum flooding surface marks the maximum landward position of the early barrier island, and occurs beneath southern Bogue Sound within the Holocene coastal sand prism (Fig. 8). By ca. 3000 y BP, barrier regression began (Timmons et al., 2010) and bay ravinement removed the subaerial portion of the early islands (Fig. 8).

The coastal sand prism has characteristics of a highstand systems tract as it is underlain by a TRS/MFS and exhibits normal regression. This highstand systems tract began to form at ca. 4 to 3 ka in response to decreased rates of sea-level rise; from 5 mmy⁻¹ to approximately 0.8 mmy⁻¹ (Horton et al. 2009; Timmons et al., 2010; Kopp et al., 2015). However, acceleration of sea-level rise over the last century (Church and White, 2011; Kemp et al., 2011), to the present global rate of 3.2 ± 0.4 mmy⁻¹ (Church and White, 2011) has contributed to the development of a transgressive ravinement surface at the base of the modern shoreface. As sea-level rise continues, the shoreface will move landward, and the present highstand systems tract will likely erode to form a transgressive barrier system, which may weld onto the CBRC.

5.4 Regional Controls on the Geomorphic Evolution

Sediment flux from the north, and glacio-isostatic adjustment (GIA) appear to be important factors in the evolution of this system. During the sea-level highstand of MIS5a, the study area was characterized by the initiation and rapid progradational growth (over shallow inner shelf sediments) of a complex eolian beach ridge system (the CBRC) at the southern end of the north-south trending Suffolk Shoreline (Mallinson et al., 2008; Parham et al., 2013; Fig. 9). This suggests that shoreface ravinement along the Suffolk Shoreline and sediment transport to the south, provided the sediment to build this system. The approximately 60 beach ridges formed attached to the low-lying mainland. To the east of this coastal system was a broad, shallow, low gradient inner shelf (Parham et al., 2013). To the south of the CBRC, as it is today, was Onslow Bay, a sediment-starved embayment characterized by seabed outcrops of several Cenozoic stratigraphic units of varying lithology (Riggs et al., 1996). During the succeeding sea-level lowstand, the upper sand of the CBRC underwent eolian reactivation, and fluvial channels were

incised into the study area (Hine and Snyder, 1985; Timmons et al., 2010), forming the antecedent topography that has been inundated during the mid- to late-Holocene (Fig. 9). The current sea level has interacted with the last glacial maximum topography and has led to the formation of the Outer Banks barrier islands perched upon a late Pleistocene interstream divide (Riggs et al., 1995; Mallinson et al., 2010). The MIS5a inner shelf deposits and falling stage tidal deposits currently occur beneath the broad, shallow back-barrier Pamlico Sound. These data indicate a significant transition in sediment availability occurring in the vicinity of the study area (sediment-starved to the south, sediment-rich to the north).

The current sea-level highstand has not seen a return to a coast line with a geomorphology similar to that during MIS5a (Fig. 9). Modern relative sea level in North Carolina is very similar to the MIS5a relative sea level (Wehmiller et al., 2004; Mallinson et al., 2008; Parham et al., 2013) as a result of glacio-isostatic processes in the region (Peltier, 2004); however, late Pleistocene deposition (tidal, fluvial, eolian) east of the Suffolk Shoreline, with sediments provided by the major rivers (Neuse, Tar, Roanoke) has produced the modern mainland north and east of the study area (Mallinson et al., 2008; Parham et al., 2013), and the Suffolk shoreline has not (yet) been reoccupied (Fig. 9). The deposition of these sediments east of the Suffolk shoreline was likely facilitated by the occurrence of large drainage systems combined with the northward increase in subsidence rates due to GIA (Engelhart et al., 2011; Van de Plassche et al., 2014), which produced accommodation space for these sediments. The CBRC was a cusped foreland that marked a north-south to east-west change in shoreline which now occurs further east at the modern Cape Lookout (Fisher, 1967). The MIS5a shoreface likely remained as a significant paleotopographic break south of the CRBC following the late Pleistocene sea-level fall and subsequent rise (Termination 1). Thus, as sea-level rose, the

shoreline transgressed rapidly to form a coast-parallel barrier island near the relict MIS5a shoreface just south of the CBRC (Fig. 9), separated from the mainland by Bogue Sound, while north and east of the study area the shoreline steps eastward in response to the antecedent topography, sedimentation and GIA processes discussed above.

6. CONCLUSIONS

This study looks at coastal change in North Carolina over two major late Quaternary sea-level cycles and demonstrates the importance of processes operating at various temporal and spatial scales, including climate-related sea-level rise, wave energy, sediment flux, antecedent topography and glacio-isostatic adjustment in affecting the local- to regional-scale coastal geomorphic development. The Pleistocene development of the CBRC was a function of sediment transport from the north associated with longshore currents and the prevalence of large drainage systems to the north which provided sediment to the system. The large-scale Pleistocene and Holocene morphology of the coastline is dictated by differences in rates of subsidence due to GIA combined with sediment availability, and the resulting antecedent topography. Accommodation space development to the north, and fluvial valley incisions, allowed for the deposition of late Pleistocene units and formation of interstream divides that control the modern shoreline position north of Cape Lookout. Lack of deposition in Onslow Bay and a relative lack of fluvial systems likely preserved the MIS5a shoreline as a significant topographic break that was subsequently rapidly reoccupied during the Holocene sea-level rise. The Bogue Banks barrier island system has transgressed then regressed through time and has undergone climate-related barrier island segmentation coeval with similar events along the southern Outer Banks

(Culver, et al., 2007; Grand Pre et al., 2011). These more recent changes are dictated by changing rates of sea-level rise combined with the antecedent topography, and changes to wave climate.

ACKNOWLEDGMENTS

We thank J. Watson, J. Woods, S. Mahan, K. Peek, P. Parham, M. Mann, D. Lagomasino, R. Camp, and A. Dietsche for their help in the field and the laboratory. This research is part of the North Carolina Coastal Geology Cooperative Program (NCCGC) and was funded by the USGS pursuant to cooperative agreement 02ERAG0044. Partial funding was also provided by the National Science Foundation OCE-11308. Seismic Micro-Technology, Inc. provided support in the form of an educational software grant.

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	Biofacies					
	A	B	C	D	E	F
<i>Ammonia</i> cf. <i>A. beccarri</i>	0.00	0.00	0.00	0.00	0.00	0.38
<i>Ammonia parkinsoniana</i>	1.89	6.30	10.89	20.87	36.18	23.45
<i>Ammonia tepida</i>	0.06	0.00	0.00	0.50	0.61	0.00
<i>Ammotium salsum</i>	0.00	0.00	0.00	0.00	0.00	4.94
<i>Bolivina lowmani</i>	0.66	1.08	0.19	0.24	0.25	0.06
<i>Bolivina paula</i>	0.12	0.87	0.11	0.18	0.00	0.17
<i>Buccella inusitata</i>	0.07	0.38	0.71	0.84	0.37	0.32
<i>Buliminella elegantissima</i>	0.41	0.34	0.00	0.63	0.35	0.62
<i>Cibicides lobatulus</i>	0.00	0.13	1.34	1.66	0.12	0.18
<i>Cibicides</i> sp.	0.00	0.00	0.33	0.09	0.00	0.00
<i>Elphidium excavatum</i>	93.93	76.61	54.71	54.40	39.15	41.26
<i>Elphidium galvestonense</i>	0.00	0.83	0.54	0.30	0.46	6.81
<i>Elphidium gunteri</i>	0.13	0.30	0.51	1.28	3.83	4.05
<i>Elphidium mexicanum</i>	0.73	1.99	1.46	7.51	7.96	13.88
<i>Elphidium poeyanum</i>	0.00	0.00	0.07	0.06	0.57	0.66
<i>Elphidium transluscens</i>	0.42	1.11	1.13	1.78	1.35	0.75
<i>Eponides repandus</i>	0.00	0.42	2.50	0.28	0.00	0.00
<i>Gavelinopsis praegei</i>	0.56	1.84	0.29	0.66	0.12	0.18
<i>Hanzawaia strattoni</i>	0.11	1.23	6.15	2.84	0.49	0.19
<i>Haynesina germanica</i>	0.00	0.21	0.11	0.44	6.95	1.05
<i>Nonionella atlantica</i>	0.07	0.71	1.54	1.26	0.12	0.13
<i>Quinqueloculina bosciana</i>	0.27	0.08	0.07	0.00	0.00	0.56
<i>Quinqueloculina jugosa</i>	0.00	0.04	1.45	0.32	0.12	0.12
<i>Quinqueloculina lamarckiana</i>	0.00	0.13	2.37	0.14	0.00	0.00
<i>Quinqueloculina seminula</i>	0.14	2.58	12.75	0.50	0.00	0.18
<i>Rosalina floridana</i>	0.29	1.54	0.11	1.07	0.00	0.00
<i>Textularia</i> cf. <i>T. gramen</i>	0.00	0.08	0.63	0.23	0.00	0.00
<i>Trifarina angulosa</i>	0.07	0.13	0.04	0.69	0.00	0.00
<i>Trochammina inflata</i>	0.00	0.30	0.00	0.00	0.00	0.00
<i>Trochammina</i> sp.	0.00	0.78	0.00	0.00	0.24	0.00
Fossil <i>Cibicides</i>	0.00	0.00	0.00	0.74	0.00	0.06
Fossil <i>benthic</i>	0.07	0.00	0.00	0.48	0.75	0.00

Core Location ^a	Core	Sample Depth above MSL (m)	% Water Content ^b	K (%) ^c	Th (ppm) ^c	U (ppm) ^c	Cosmic dose ^d additions (Gy/ka)	Total Dose Rate (Gy/ka)	Equivalent Dose (Gy)	n ^e	Age (ka) ^g
CBRC	CR-08-GP1a	3.80–3.87	23 (34)	0.47 ± 0.05	0.91 ± 0.12	0.36 ± 0.07	0.14 ± 0.01	0.64 ± 0.04	11.0 ± 0.61	20 (25)	18.3 ± 1.60 ^f
CBRC	CR-08-GP1b	1.30–1.38	29 (36)	0.78 ± 0.03	1.66 ± 0.18	0.74 ± 0.08	0.10 ± 0.01	0.89 ± 0.05	44.9 ± 2.45	23 (25)	50.4 ± 3.80 ^f
CBRC	CR-08-GP3	3.95–4.06	5 (42)	0.52 ± 0.02	1.62 ± 0.13	0.85 ± 0.09	0.19 ± 0.01	0.77 ± 0.06	62.2 ± 4.91	20 (21)	80.8 ± 9.00
CBRC	CR-08-GP4	7.14–7.19	6 (40)	0.23 ± 0.01	1.66 ± 0.24	0.57 ± 0.11	0.17 ± 0.09	0.52 ± 0.05	49.5 ± 3.86	25 (25)	95.2 ± 9.25
CBRC	CR-08-GP5	4.45–4.53	15 (41)	0.33 ± 0.02	2.47 ± 0.32	1.06 ± 0.18	0.16 ± 0.01	0.70 ± 0.06	58.8 ± 5.23	24 (25)	83.4 ± 8.92
		below MSL (m)									
BB	BB08-GP1	0.15–0.25	21 (31)	0.56 ± 0.02	4.90 ± 0.43	2.66 ± 0.26	0.19 ± 0.01	1.38 ± 0.07	2.37 ± 0.15	19 (20)	1.72 ± 0.14
BB	BB08-GP2	0.80–0.89	22 (31)	0.54 ± 0.02	1.01 ± 0.19	0.69 ± 0.11	0.18 ± 0.09	0.77 ± 0.08	1.04 ± 0.05	21 (22)	1.35 ± 0.15
BS	BS-08-01	5.67–5.77	23 (35)	0.71 ± 0.03	1.51 ± 0.25	1.02 ± 0.15	0.18 ± 0.09	0.96 ± 0.08	2.40 ± 0.14	26 (28)	2.49 ± 0.25
BS	BS-08-03	7.96–8.06	24 (39)	0.61 ± 0.01	2.00 ± 0.19	1.67 ± 0.10	0.16 ± 0.01	0.99 ± 0.06	40.6 ± 2.31	19 (20)	41.0 ± 3.78
BS	BS-08-04	7.61–7.71	20 (44)	0.69 ± 0.03	1.67 ± 0.24	0.88 ± 0.19	0.18 ± 0.01	0.88 ± 0.07	4.56 ± 0.26	28 (28)	5.18 ± 0.53
BS	BS-08-05	3.30–3.40	22 (27)	0.40 ± 0.01	0.93 ± 0.20	0.72 ± 0.11	0.19 ± 0.01	0.69 ± 0.08	0.81 ± 0.06	17 (20)	1.18 ± 0.17
aCore location abbreviations: CBRC = Croatan Beach Ridge Complex; BB = Bogue Banks; BS = Bogue Sound											
bField moisture, with figures in parentheses indicating the complete sample saturation %. Ages calculated using 90% of saturation values (below water table)											
cAnalyses obtained using laboratory Gamma Spectrometry (low resolution NaI detector).											
dCosmic doses and attenuation with depth were calculated using the methods of Prescott and Hutton (1994).											
eNumber of replicated equivalent dose (De) estimates used to calculate the mean. Figures in parentheses indicate total number of measurements made including failed run with unusable data											
fDose rate and age for fine-grained 250–180 um quartz sand. Linear + exponential fit used on age, errors to one sigma.											
gDose rate and age for fine-grained 150–90 um quartz sand. Linear + exponential fit used on age (only linear for De < 1 Gy), errors to one sigma.											

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Lazar – Table 3

Bogue Sound Core Location	Lab Sample #	Sample Depth (m below MSL)	Material	Conventional Radiocarbon Age	¹³C/¹²C Ratio	2σ Calibration
BS-08-02	261208	3.24	oyster	3500 ± 40 BP	0	3.39 ± 0.07 ka
BS-08-03	261209	4.59	angel wing clam	3990 ± 40 BP	1.9	3.92 ± 0.10 ka
BS-08-03	261210	7.075	foraminifera	5650 ± 50 BP	-5.1	6.05 ± 0.13 ka

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APPENDIX CAPTIONS

Appendix 1: Raw census data of foraminiferal assemblages; includes counts of all benthic foraminifera in 59 samples. Planktonic taxa were included; barren samples were not included.

TABLE CAPTIONS

Table 1: Average relative abundance calculations of each taxon in each biofacies. The three most abundant taxa in each biofacies are shown in bold.

Table 2: OSL age estimates and equivalent dose data of samples from the Croatan Beach Ridge Complex, Bogue Banks, and Bogue Sound, NC.

Table 3: AMS ^{14}C age estimates of samples from Bogue Sound, NC. Depositional abbreviations: HSE = high salinity, low energy estuary; LENMS = low energy normal marine salinity; FTD = flood tide delta. Dates were calculated using MARINE04 database (Hughen *et al.*, 2004) and calibrated with INTCAL04 radiocarbon age calibration (Reimer *et al.*, 2004), with no local reservoir correction applied.

FIGURE CAPTIONS

Figure 1: **A** LiDAR map of eastern North Carolina. The Suffolk Scarp extends from Norfolk, VA to Morehead City, NC. Geographic location of map is shown in black box on map of southeastern North America (inset). Study area is indicated by box on the LiDAR map. Map source: www.ncfloodmaps.com. **B** Map of study area showing core locations. The CBRC is dashed in white; the modern shoreline forming the northern boundary of Bogue Sound (Unit 2) is

dashed in black. **C** Morphology of the CBRC showing the beach ridge system, larger area map shown in inset. The Suffolk Scarp is depicted, with the approximate southern terminus in the study area dashed. Adapted from Fisher (1967), where this beach ridge system was named the Newport Group.

Figure 2: A Foraminifera of CBRC, Bogue Banks, and Bogue Sound. (Scale bars = 50 μ m) **1** *Elphidium excavatum*. **2** *Elphidium galvestonense*. **3** *Elphidium gunteri*. **4** *Elphidium mexicanum*. **5** *Elphidium translucens*. **6** *Elphidium poeyanum*. **7** *Haynesina germanica*. **8** *Ammotium salsum*. **9** *Textularia* cf. *T. gramen*. **10** *Buliminella elegantissima*. **11** *Bolivina lowmani*. **12** *Bolivina paula*. **13** *Quinqueloculina seminula*. **14** *Quinqueloculina lamarckiana*. **15** *Quinqueloculina jugosa*. **16** *Quinqueloculina bosciana*.

B Foraminifera of CBRC, Bogue Banks, and Bogue Sound. (Scale bars = 50 μ m) **1a,b** *Ammonia parkinsoniana*. **2a,b** *Hanzawaia strattoni*. **3a,b** *Eponides repandus*. **4a,b** *Nonionella atlantica*. **5a,b** *Cibicides lobatulus*. **6a,b** *Buccella inusitata*. **7a,b** *Ammonia tepida*. **8** *Ammonia* cf. *A. beccarii*. **9** *Trifarina angulosa*.

Figure 3: Dendrogram resulting from cluster analysis of foraminiferal abundance data, indicating biofacies and interpreted paleoenvironments. Abbreviations of lithofacies are as follows: sand (S); organic-rich sand (orgS); muddy sand (mS); shelly, muddy sand (shmS); shelly sand (shS); gravelly sand (gS); mud (M); sandy mud (sM); shelly mud (shM); shelly, sandy mud (shsM); interbedded mud and sand (I); interbedded mud and sand with shells (mI); large shell (Sh).

Figure 4: Chirp seismic data and interpretations from three locations in Bogue Sound (see inset map for locations of transects). Cores BS-08-03 and BS-08-04 are indicated on the A-A' transect, with interpreted paleoenvironmental facies shown.

Figure 5: Filtered and interpreted GPR data from Line 1840. Inset: All GPR lines collected in the CBRC shown in black; location of Line 1840 in the study area shown in white.

Figure 6: **A** Cross-section of depositional facies along Transect A. **B** Cross-section of depositional facies along Transect B. Location of approximate Holocene/Pleistocene Boundary hatched. Sample depths for foraminifera, OSL, and radiocarbon are indicated for each core.

Figure 7. Geologic evolution of Bogue Banks. Age of time slices (A-E) based on the OSL and ^{14}C age estimates of this study. (A) Initial formation of the island; (B-C) Seaward and westward spit progradation; (D) Normal marine salinity conditions persist in Bogue Sound; (E) Eventual closing of the island through spit progradation; present configuration of the island. Depositional facies of this study's Bogue Sound cores are shown at each time slice. Bogue Sound vibracores in the format BS-08-0X are shortened to B and Bogue Banks Geoprobe cores in the format BB08-GPX are shortened to G for this figure. Inset: Map of Bogue Banks, with locations referred to in text. LI, Long Island; EL, Emerald Isle; IB, Indian Beach; SP, Salter Path; PKS, Pine Knoll Shores. Adapted from Fisher (1967).

Figure 8. Generalized stratigraphic profile extending across the CBRC, Bogue Sound, and Bogue Banks based upon GPR, chirp, and core data. The surface morphology is linked to the

stratigraphic framework, and reflects formation over one complete (late Pleistocene), and one partial (Holocene) base-level cycle.

Figure 9. **A** Formation of the CBRC during MIS5a was facilitated by longshore sediment flux (Q) from the north along the Suffolk Shoreline. **B** During late MIS5a, or post MIS5a falling sea level conditions, tidal and alluvial deposition occurred east of the Suffolk Shoreline as a result of subsidence and fluvial sediment flux to the region, but no significant deposition occurred south of the CBRC. **C** During the late Holocene sea-level rise, the shoreline transgressed rapidly to near the MIS5a shoreface position south of the CBRC, then prograded seaward; however, transgression was slower east of the Suffolk Shoreline as a result of the falling stage deposition in the area.

Figure 1

Figure 2A

Figure 2B

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Generalized Stratigraphic Profile

Legend	
—	shoreface clinoform surface
- - -	maximum flooding surface (MFS)
- . - .	transgressive ravinement surface (TRS)
—	subaerial unconformity
~~~~~	basal surface of forced regression (BSFR)
.....	maximum regressive surface (MRS)
■	Holocene estuarine sediments
HST	highstand systems tract
FSST	falling stage systems tract
TST	transgressive systems tract
LST	lowstand systems tract
FTD	flood tide delta
MSL	mean sea level

Figure 9