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Late Quaternary development of the Croatan Beach Ridge Complex, Bogue Sound, Bogue Banks, NC, USA and implications for coastal evolution

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

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

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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 1900 CE (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 (Fig. 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 cuspate foreland (Fig. 1C). This beach ridge complex is morphologically very similar to the beach ridges present in the Cape Hatteras (North Carolina, USA) cuspate 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 than 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 (2–16 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 ~±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-μm (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