**Controls on the stratigraphic framework and paleoenvironmental change within a Holocene
estuarine system: Pamlico Sound, North Carolina, USA.**

Nicholas Zaremba¹, David J. Mallinson^{1*}, Eduardo Leorri¹, Stephen Culver¹, Stanley Riggs¹,
Ryan Mulligan², Eric Horsman¹, Siddhartha Mitra¹

*1. Department of Geological Sciences, 101 Graham Building, East Carolina University, Greenville, NC
27858, USA*

*2. Department of Engineering and Applied Science, Queens University, Ellis Hall 58 University Avenue,
Kingston, ON K7L3N6, Canada*

* Corresponding Author: mallinsond@ecu.edu

Keywords: Pamlico Sound, Holocene stratigraphy, paleotopography, rapid climate change, coastal
geology

<http://ees.elsevier.com/margo/default.asp>

Abstract

This study examines the Holocene stratigraphic record and paleoenvironmental evolution of a large estuarine system, at high temporal and spatial resolution, in the context of changing climate, sea level, and hydrodynamics. New data are used to examine two time periods of increased marine influence within Pamlico Sound in northeastern North Carolina interpreted to be the result of extensive barrier island segmentation synchronous with periods of rapid climate change during the late Holocene. The study reveals the controls on the stratigraphic development and the highly dynamic character of the coastal system in response to climate, and sea-level change as it interacts with paleotopography. These findings can be used to inform projections of future environmental changes.

Estuarine waters occupied paleovalleys in the Pamlico Sound region as early as *ca.* 7500 cal BP and Pleistocene interfluves separated the paleovalleys from the Atlantic Ocean until *ca.* 5500 cal BP, when they were flooded by rising sea-level forming the broad, shallow Pamlico Sound. Initial barrier islands and shoals likely formed sometime between 5500 and 5000 cal BP, providing the geomorphic setting for continued estuarine conditions behind the barriers. At *ca.* 4000 cal BP, an increase in marine influence and sand content is detected in multiple cores, and is correlated to seismic data within the northern Pamlico Sound basin. This change is interpreted to be the result of increased segmentation of barrier islands (thus a greater number of inlets, or wider inlets), which is consistent with a rapid transgression seen in other areas of the U.S. east coast. The segmentation may have been partially facilitated by a rapid increase in lagoonal area and tidal prism by overtopping of interfluves. Greater barrier island continuity is evident from 3500 to 1200 cal BP, as indicated by muddy deposits with low brackish estuarine foraminiferal assemblages. At *ca.* 1200 cal BP, seismic, sedimentological and micropaleontological data suggest an increase in wave and current energy and marine influence throughout southeastern

Pamlico Sound. These changes are interpreted to represent extensive segmentation of the barrier islands during the Medieval Climate Anomaly (MCA). Since *ca.* 500 cal BP, the Pamlico Sound system has returned to a more restricted state, as inlets have closed. Currently only three major inlets segment the Outer Banks, the barrier island system fronting Pamlico Sound, but warming climate and increasing rates of sea-level rise suggest another episode of barrier island segmentation began about a half century ago and appears that it may extend into the near future.

1. Introduction

Coastal systems are influenced by numerous factors including tectonic setting, climate conditions, relative sea-level change, storm frequency and intensity, sediment supply and flux, and the antecedent geology. More specifically, the geomorphic configuration of a barrier island coastal system (whether it is prograding, retrograding, highly segmented by inlets, etc.) is fundamentally forced by climatic conditions. Changes in the geomorphology of barrier islands fronting a drowned river valley will likely be recorded in the infill of that basin as a result of hydrodynamic adjustments, which affect erosion and deposition. The stratigraphy of the lagoon will also be affected by sea-level rise as it inundates the paleotopography, changing the area and volume, and shifting the locations of sediment sources and sinks (Rodriguez et al., 2005). The changes in the stratigraphic record can be constrained by age estimates (radiocarbon, OSL, etc.) and correlated to sea-level and paleotopographic elevations, and past climatic fluctuations, including periods of rapid climate change (RCC; i.e., changes in regional to global meteorological conditions occurring within a few hundred years; Mayewski et al., 2004; Leorri et al., 2006; Culver et al., 2007; Sorrel et al., 2009; Timmons et al., 2010; Sorrel et al., 2010; Grand Pre et al., 2011; Mallinson et al., 2011; Simkins et al., 2012; Tessier et al., 2012; Traini et al., 2013).

Understanding how periods of RCC impact coastal systems over a large geographical area can provide insight into how oceanographic and meteorological phenomena will affect coastal regions of the world in the future. Furthermore, the characteristics of the changing depositional environments can be compared to local sea-level curves and Holocene climate studies to better understand the mechanisms of change, and the magnitude of the RCC required for the reorganization of a particular coastal system. Holocene climate records and the coeval response of barrier island systems to those conditions may be used to better constrain the response of barrier islands and associated estuarine or lagoonal systems to future climate conditions. Given the current and projected future rates of sea-level rise (IPCC, 2013) and the possibility of future increases in storm frequency and/or intensity (Emanuel, 2005), this information is essential for establishing responsible coastal management policies.

The Albemarle-Pamlico estuarine system (APES), of eastern North Carolina (Fig.1), is ideally suited to studies of past climate-related environmental change due to its large areal extent (second largest estuarine system in the contiguous USA), its well preserved stratigraphic record, and its variety of geologic, geomorphic, hydrodynamic and biologic characteristics (Culver et al., 2008; Culver et al., 2011). Previous investigations of Pamlico Sound suggested two periods of extensive barrier island segmentation, from approximately 4000 to 3500 and 1200 to 500 cal BP (Culver et al., 2007; Metger, 2009; Grand Pre et al., 2011; Mallinson et al., 2011). Culver et al. (2007) first postulated that segmentation of the barrier islands from 1200 to 500 cal BP was a result of an increase in storm intensity or frequency. This interpretation is supported by the data of Mann et al. (2009), who suggest an interval of increased hurricane intensity or frequency within the Atlantic during the Medieval Climate Anomaly (MCA) from *ca.* 1100–900 cal BP. Further, proxy sea-level data derived from salt marsh foraminifera in the APES suggest sea level

was stable for a period of time prior to *ca.* 1000 cal BP followed by an increase in the rate of rise to *ca.* 0.6 mm/yr from *ca.* 1000 to 600 cal BP (Kemp et al., 2011).

Previous work has provided extensive datasets on foraminiferal assemblage changes, barrier island segmentation, and back-barrier shoal development associated with the 4000 to 3500 cal BP and 1200 to 500 events (Culver et al., 2007; Metger, 2009; Grand Pre et al., 2011; Mallinson et al., 2011, Peek et al., 2013). These datasets, however, are not placed within a regional stratigraphic framework and thus do not provide for a full understanding of the geologic evolution of the Sound. This study integrates previous work and new data into a regional synthesis of the evolution of the Pamlico Sound using high-resolution geophysical data, bulk sediment magnetic susceptibility data, radiocarbon age estimates, and sediment analyses. The comprehensive dataset defines the Holocene stratigraphy within the Pamlico basin and the response to the inferred changes in geomorphology of the barrier islands and flooding of the paleo-topographic landscape.

2. Regional Setting

The APES has multiple estuarine/lagoonal, components with different geomorphic characteristics (a large open basin; narrow, linear shore parallel basins; and funnel-shaped drowned trunk river and tributary valley estuaries). The Pamlico Sound system is isolated from the Atlantic Ocean to the east by a wave-dominated barrier island chain, the Outer Banks, currently segmented by three major inlets (active for >100 years) (Fig. 1a). Three low to moderate brackish water estuaries (Pamlico River Estuary, Neuse River Estuary and Croatan Sound) drain into Pamlico Sound, providing fine-grained, organic-rich sediment (Wells and Kim, 1989). Astronomical tides are small (10 cm or less) within the estuary; wind tides (up to 1 m) are

the primary mechanism driving circulation of estuarine waters (Wells and Kim, 1989; Luettich et al., 2002).

The modern geologic processes and Holocene evolution of the northeast North Carolina coastal system are strongly influenced by the antecedent geology of the area (Riggs et al., 1995; Mallinson et al., 2010). The Albemarle Embayment, which includes Pamlico Sound, contains up to *ca.* 90 m of Quaternary deposits that record multiple transgressions and regressions (Mallinson et al., 2010). During periods of lower sea level, drainage systems incised into older Quaternary sediments, segmenting the coastal plain and forming fluvial valleys and interfluves (Fig. 1c) (Riggs et al., 1995; Mallinson et al., 2005; Mallinson et al., 2010). The modern Pamlico Sound is composed of a northern and southern basin that occupy the Pamlico Creek Paleo-Valley (PCRVC), Pamlico River Paleo-Valley (PRVC) and Neuse River Paleo-Valley (NRPV) (Fig. 1c). Late Pleistocene to early Holocene fluvial sediments accumulated in the paleovalleys until rising seas flooded the Pamlico Sound area initiating estuarine conditions (Riggs et al., 1992, Culver et al., 2007). The interfluves associated with these paleovalleys formed topographic highs that have influenced the geomorphology and hydrodynamics of Pamlico Sound throughout the Holocene (Riggs et al., 1995; Mallinson et al., 2005, Mallinson et al., 2010).

3. Materials and Methods

3.1. Geophysical Data

Approximately 470 km of seismic data (Fig. 1b) were collected using an Edgetech SB216 (2 to 16 kHz) chirp sub-bottom profiler and Discover acquisition software. The sensor package was towed at 2 m water depth at a speed of 3 to 4 knots using the R/V *Stanley R. Riggs*. Navigation was acquired using a wide area augmentation system (WAAS)-enabled Garmin GPS. Seismic surveys were designed to cross 40 existing vibracore locations. Seismic horizons were

digitized and gridded using Seismic Micro-Technology (SMT) Kingdom Suite software (version 8.6) to produce depth to horizon maps. Correlations of seismic data to core data indicated that 1600 m/s was an accurate acoustic velocity within sediments for the conversion of two-way travel time (twtt) to depth in meters.

3.2. Core Acquisition and Storage

Fifty-two vibracores (8.9 cm in diameter and 2 m to 8 m in length) previously collected throughout Pamlico Sound by East Carolina University researchers (Fig. 1b) were supplemented with five vibracores collected during 2011 and 2012 specifically to target horizons and facies noted in chirp seismic data. Vibracores were cut into 1.5 m long sections in the field and split in two longitudinal halves in the laboratory. One half of the cores were graphically logged following the methodology of Farrell et al. (2012), then photographed, bagged, sealed, and archived. The other halves of the cores were sampled at 1 cm or 2 cm continuous increments for the entire length of the core, or sampled at discrete intervals based on lithological changes.

3.3. Granulometry and Lithofacies Analysis

Approximately 600 samples for grain-size analysis were dried at 40° C, weighed, and soaked in a measured volume of 0.05% sodium metaphosphate [$\text{Na}_2[\text{Na}_4(\text{PO}_3)_6]$ solution for a minimum of 24 hours to disaggregate the sediments. Each sample was wet-sieved to remove the mud fraction. The sand fraction was placed in the oven at 40° C to dry for 24 hours. The grain-size distribution of the sand fraction was calculated by means of dry sieve analysis (ro-tap for 15 minutes) using sieves ranging from -2 phi to 4 phi at 0.5 phi intervals. The mean, mode, median, skewness, and kurtosis of each sample was calculated using Gradistat software version 4 (Blott and Pye, 2001). Grain-size data and other sedimentary characteristics (structures, organics, color, etc.) were used to inform lithofacies classifications using the technique of Farrell et al. (2012).

The only deviation from this textural classification method is the distinction of the gravel component into shell material or quartz grains.

3.4. Radiocarbon Age Estimates

Samples for radiocarbon age estimates were targeted near seismic horizons to help constrain the age of seismic reflections and their formative events. Criteria for selecting the samples were based on evidence of the sample being in situ (e.g., articulated bivalve shells when available). Sample preparation followed the guidelines described by the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) Facility webpage. Samples were analyzed at NOSAMS and BETA Analytic, and calibrated using CALIB 7.00 software (Stuiver and Reimer, 1993). Marine13 and Intcal13 calibration curves were used for radiocarbon age estimates. Previously analyzed samples were re-calibrated for this study. A marine reservoir effect calculated from samples obtained from Bogue Sound, North Carolina, USA of 102 ± 70 yrs (Thomas, 2008) was applied to all carbonate age estimates.

3.5. Bulk Sediment Magnetic Susceptibility

Nine cores were analyzed at 5 cm intervals to provide bulk sediment magnetic susceptibility (BMS) data that were used for correlation purposes. Samples were dried in an oven at *ca.* 40° C to avoid alteration of magnetic properties. Once dry, the samples were disaggregated with a mortar and pestle to ensure uniform volume and grain-size. BMS was analyzed on 4.5 cm³ aliquots at East Carolina University using a multi-function Kappabridge MFK1-A by Advanced Geoscience Instruments Company (AGICO) operating at a field intensity of 200 amperes/meter and frequency of 976 hertz. Before samples were analyzed the instrument was calibrated using a standard provided by AGICO with a known BMS value; this sample was measured once at the beginning of every session. BMS values for the sample holder (plastic cylinder) were measured

three times, averaged, then subtracted from the BMS value for each sample; subtraction was executed by the instrument. To ensure reproducibility and to estimate the analytical uncertainty, each sample was measured five times. This allowed for an estimation of the BMS error, which was 1% or less.

3.6 Paleobathymetric Estimates

Knowledge of sea level for specific time slices was necessary for developing the Holocene evolution of the Pamlico Sound region. For this purpose the Kopp et al. (2015) relative sea-level curve was used. This curve was developed using index and limiting points from the study area (Horton et al., 2009; Kemp et al., 2011). To develop the paleobathymetry of the Pamlico Sound region at specific times, gridded seismic horizon depths, constrained by radiocarbon ages, were subtracted from the temporally equivalent relative sea level.

4. Results

4.1. Lithofacies

Lithofacies are presented in Table 1. Holocene sediments are predominantly homogenous mud to muddy sand, and often contain burrow-fill structures and bivalve shell material. Interbedded mud and sand are rare in the Holocene stratigraphy. Millimeter to centimeter thick laminae or beds of shell material composed primarily of *Ensis* sp., *Mulinia* sp., *Tellina* sp., and *Crassostrea virginica* fragments and valves commonly occur within muddy or sandy lithofacies.

The majority of the Pleistocene deposits recovered in this study vary from muddy shell hash to sandy gravel and are sometimes stained red or orange; burrows are common. Shell material varying in size from less than 1 mm to *ca.* 5 cm, are unidentifiable fragments or often highly abraded valves or fragments of *Terebra* spp., *Mulinia* sp., *Mercenaria* sp., *Tellina* sp.

4.2. Radiocarbon

Radiocarbon results are summarized in Table 2. Sixty-eight radiocarbon age estimates were used to establish chronostratigraphic control. Holocene age estimates ranged from ca. 8000 cal BP to modern values (some samples returned Pleistocene ages). Age estimates were used to constrain the ages of units and timing of boundary formation (Table 3)

4.1. Seismic Surfaces and Units

Seven late Pleistocene to late Holocene seismic reflections were characterized and digitized. These reflections form the boundaries for six seismically-defined units and two subunits of variable spatial extent. The characteristics of these reflections and units are presented in Table 3 and are described below.

4.1.1 Pleistocene last glacial maximum (P_{lgm})

This reflection is of high to low amplitude with high continuity and is imaged from 3 to 17 mbsl (0 to 11 meters below seafloor - mbsf). This reflection represents the division between post-LGM (mainly Holocene) units above and Pleistocene units below and is often identified by fluvial incisions or variable relief (Figs. 2, 3, 4). The deeper portions of this reflection are rarely imaged due to attenuation of the seismic signal by gas (Fig. 2a).

4.1.2 Unit 1

The lower and upper bounds of Unit 1 are P_{lgm} and H_{RS1} , respectively. This unit is thin (< 1.5 m), shows no internal structure, and is constrained to the base of channels. It is imaged only in a few locations as a result of gas attenuation associated with channel-fill sediments.

4.1.3 Holocene ravinement surface 1 (H_{RS1})

This reflection is of medium amplitude and low continuity and is imaged from 11 to 16 mbsl (5 to 10 mbsf). H_{RS1} is only found in a few small paleo-tributaries (Fig. 3), and is poorly

imaged in the deeper paleovalleys due to attenuation of the seismic signal by gas (Fig. 3a). This surface is generally observed on the eastern side of the Pamlico Creek paleovalley (Fig. 1).

Surface H_{RS1} is not temporally constrained, although based on the surface elevation, and the Kopp et al. (2015) relative sea-level curve, it must be younger than ca. 8000 cal y BP.

4.1.4 Unit 2

The lower and upper bounds of Unit 2 are H_{RS1} and H_{RS2} , respectively. Like Unit 1, this unit is thin (< 1.5 m) and is constrained to the base of channels. Clinoforms occur within this unit in the western area of the Pamlico Sound northern basin (Fig. 3a).

4.1.5 Holocene ravinement surface 2 (H_{RS2})

This is a high amplitude seismic reflection which is imaged from 4 to 16 mbsl (0 to 10 mbsf) (Figs. 2, 3). This surface is often amalgamated with P_{lgm} . It terminates against shoals such as Bluff Shoal (Fig. 1a), and extends to the present perimeter of the estuary where wave ravinement is occurring. Holocene sediments onlap this surface.

4.1.6 Unit 3

The lower and upper bounds of Unit 3 are H_{RS2} and H_{4000} , respectively. This unit varies from 0 to 4 m thick, and exhibits greatest continuity in paleovalleys. It thins and becomes discontinuous across the Hatteras Flats Interfluvial, and is absent from the Bluff Shoal Interfluvial (Fig. 1c). Radiocarbon ages constrain this unit to ca. 7000 to ca. 4000 cal BP.

4.1.7 Holocene reflection ca. 5000-3000 cal BP (H_{4000})

H_{4000} is characterized by medium to high amplitude and medium continuity averaging approximately 9 to 10 mbsl (3.3 to 5 mbsf) (Figs. 2-5). This reflection is imaged best within the paleovalleys of the northern basin (Fig. 1c). Over the interfluvials, H_{4000} often amalgamates with H_{RS2} and P_{lgm} and separates from these reflections when encountering paleovalleys. The age of

H₄₀₀₀ is poorly constrained, but generally occurs between ca. 5000 and 3000 cal BP based on radiocarbon age estimates of foraminifera in vibracore PS11-03, and bivalve shells in PS-05 (Fig. 4).

4.1.8 Unit 4

The lower and upper bounds of Unit 4 are H₄₀₀₀ and H₁₀₀₀, respectively. However, a discontinuous reflection (H₂₅₀₀) occurs within the middle of this unit, dividing it locally into lower (4a) and upper (4b) subunits (Fig. 4a, b). Unit 4 ranges from 3 to 5 m thick and is continuous throughout both basins, but does not occur on the Bluff Shoal interfluvial. The unit is seismically transparent in areas overlying paleo-valleys; however, discontinuous back-stepping parallel reflections are found within the unit above interfluvials (Fig. 2a, b).

4.1.9 Holocene reflection ca. 1000 cal BP (H₁₀₀₀)

This reflection is of low to medium amplitude has low continuity, and occurs from 7 to 8.3 mbsl (0.9 to 1.8 mbsf) in the northern basin, but deepens to >9 meters in the southern basin (Figs. 2-5). The reflection is poorly imaged in the paleo-Neuse and paleo-Pamlico river valleys (Fig. 1c) as a result of attenuation of the seismic signal by gas. H₁₀₀₀ is temporally constrained by multiple radiocarbon age estimates in cores PS-03 (Culver et al., 2007; Grand Pre et al., 2011), PS11-03, PS-05, PS11-VC1, and PS-09 (Figs. 4 and 5).

4.1.10 Unit 5

The lower and upper bounds of Unit 5 are H₁₀₀₀ and H₅₀₀, respectively. This unit is continuous throughout both basins, but does not occur on the Bluff Shoal interfluvial. It ranges from ca. 1 to 1.6 m thick and shows no significant internal structure. The age of the unit is constrained to ca. 1200 to 500 cal BP (Table 3).

4.1.11 Holocene reflection ca. 500 cal BP (H₅₀₀)

Characteristics of this reflection vary between the southern and northern basins. The reflection occurs from 6 to 8.2 mbsl (0.50 to 1.20 mbsf) and is characterized in the northern basin by high continuity and medium amplitude (Figs. 2, 4, 5). However, in the southern basin the reflection is characterized by low amplitude with low continuity. The surface occurs over valleys and interfluvies, and is temporally constrained by multiple radiocarbon age estimates in cores PNP-5, PNP-2, OCK-5, PS-05, PS-06, and PS-09.

4.1.12 Unit 6

The lower and upper bounds of Unit 6 are H_{500} and H_{sf} (Holocene seafloor reflection), respectively. This unit is typically <0.5 m thick and occasionally show some discontinuous parallel low-amplitude reflections. The unit is constrained to ca. 500 cal BP to modern based upon radiocarbon ages. H_{sf} ranges in depth from 3 to 7 mbsl within the data collected for this study and varies from high to low amplitude, indicating greater or lesser sand/mud, respectively.

4.2 Bulk sediment magnetic susceptibility

The BMS data from seven cores are presented in Fig. 6. Absolute values of BMS data are highly variable between cores; the difference between the maximum and minimum values in PS11-03 is 11.6×10^{-5} K(SI) while PNP-2 only varies by 4.5×10^{-5} K(SI). The Holocene BMS values range from 16.2×10^{-5} K(SI) in core PS-13 at 0.15 mbsf to 1.4×10^{-5} K(SI) in core PS-07 at 0.5 mbsf.

Trends in BMS values were found to be useful for core correlation purposes. Most notably, the low BMS values which occur at 1.8 to 0.70 mbsf in cores PNP-2, PS11-03, PS-05, PS-07 and PS-10 correspond to Unit 5, and are statistically significant and unique (in magnitude) within Holocene sediments. The sediments recording this minimum have been constrained by radiocarbon age estimates and seismic correlation to between 1200 and 500 cal BP (Fig. 6). This

age-range approximates the timing of the Medieval Climate Anomaly (Mayewski et al., 2004; Cronin et al., 2010). The abrupt increase in BMS values at *ca.* 3 m in PS11-VC1 is constrained by radiocarbon ages to *ca.* 4000 cal BP and correlates to the H₄₀₀₀ reflection, and BMS excursions, in several other cores. BMS trends in cores can be explained by various sediment parameters, with percent mud being one of the main controls; however, multiple other sediment parameters can affect BMS values (Simkins et al., 2012). A discussion of this is beyond the scope of this paper as BMS trends are used exclusively as a correlation tool in this investigation.

5. Discussion

5.1 Holocene Evolution - Early Infill History (>7500 Cal BP)

The late Pleistocene to Holocene evolution of the Pamlico Sound region likely began with the transition of fluvial-dominated processes that deposited Unit 1 (the lowstand systems tract; Catuneanu, 2006), to estuarine-dominated processes (the transgressive systems tract; Catuneanu, 2006) within flooded paleovalleys during the early Holocene (Fig. 7a). This transition has been documented in eastern Albemarle Sound north of Pamlico Sound, within the Roanoke River paleovalley, where fluvial channel deposits are overlain by bayhead delta sediments (Mallinson et al., 2005; Culver et al., 2006). The initial flooding of the Pamlico system created fetch-limited estuaries, thus limiting wave energy and making tidal processes dominant. Reflection H_{RS1} is likely a tidal ravinement surface resulting from this process. The surface exhibits a high amplitude acoustic response (Figs. 4 and 5), suggesting the concentration of a coarse lag deposit (although it was not recovered in any cores). The unit bounded by H_{RS1} and H_{RS2} (Unit 2) exhibits multiple thinly bedded layers, and clinoforms up to *ca.* 1 m height (Fig. 3) suggesting deposition under alternating energy levels and current flow. These deposits suggest the occurrence of moderate currents associated with either tidal flow (suggesting tidal-

dominance during early stages of flooding), or bayhead delta lobe deposition. Either interpretation is consistent with sequence stratigraphic models (Allen and Posamentier, 1993; Cattaneo and Steel, 2003; Catuneanu, 2006).

5.2 7500 to 4000 cal BP

Relative sea level at 7500 cal BP was at ca. -11 to -9 m, and rising at a rate of ca. 3.6 mm/y (Kopp et al., 2015). Radiocarbon data from *Crassostrea virginica* specimens from cores in the southern basin (PNP-2, PNP-6, and PNP-8; Table 3), provide marine limiting points that agree with the Kopp et al. (2015) curve, and indicate that estuarine conditions occupied portions of the paleovalleys in the southern Pamlico basin as early as ca. 7500 cal BP (Table 4). Under this scenario, marine waters would have flooded portions of the paleovalleys creating narrow, fetch-limited, estuarine systems (Fig. 7b). H_{RS2} marks the base of deposition for this time interval, and is interpreted to represent bay ravinement, primarily from wave energy, similar to that occurring today along the eroding estuarine shoreline of Pamlico Sound. The relief associated with H_{RS2} is controlled by the Pleistocene topography (interfluves and channels) and differential erosion and subsidence (above mud-dominated channel-fill), and in turn controls the thickness and character of the overlying Holocene units. Unit 3 exhibits a fining-upward sequence in cores PNP-2, PS-03 and PS11-VC1 and occurs as a muddy deposit in cores PS-10, PS-06, PS-09 (Fig. 7), PNP-5, OCR-07-S203, PNP-6 and PNP-8 (Fig. 1). Previous investigations also indicate estuarine foraminiferal and diatom assemblages as early as 7000 cal BP in the Pamlico Sound region (Foley, 2007; Culver et al., 2007; Metger, 2009; Grand Pre et al., 2011).

High-resolution chirp data from this study, combined with the relative sea level data (Kopp et al., 2015) suggest that emergent interfluves provided sufficient barriers to marine water until ca. 5000 cal BP. By ca. 5000 cal BP, the estuaries expanded beyond the confines of the

paleovalleys, and ravinement of interfluves was occurring (Fig. 7b). Between 5000 and 4000 cal BP, the interfluves were submerged (except for large portions of the Bluff Shoal Interfluve), thus barrier islands would need to have been in existence to maintain estuarine conditions (Fig. 7). Grand Pre et al. (2011) attributed the presence of estuarine conditions from *ca.* 7000 to 4000 cal BP to possible barrier islands separating the paleovalleys from the Atlantic Ocean. Timmons et al. (2010) also show the formation of barrier islands in the Bogue Banks area (Fig. 1) at *ca.* 6000 cal BP. Seismic data suggest that Bluff Shoal (Fig. 1) provided a subaerial barrier, at least 20 km in width, between the northern and southern basins of the Pamlico Sound region until *ca.* 4000 cal BP (Fig. 7b).

In the southern basin, interfluves such as Bluff Shoal and Brant Island Shoal (Fig. 1a,c) provided shelter from high energy waves originating from the north (along the long axis of the Pamlico Sound) and the east (Atlantic Ocean). Buried peat platforms occur along the western profile of Bluff Shoal, indicating that portions were not completely eroded by wave ravinement (Fig. 8), and suggesting a lower energy system than the northern basin. This is consistent with the dominant wave energy associated with the maximum fetch to the northeast. Waves produced by a southerly wind, typical of summer, would be restricted in size as a result of the limited fetch.

5.3 4000 to 3500 cal BP

Horton et al. (2009) and Kopp et al. (2015) suggested that relative sea-level rise slowed (to *ca.* 1.6 $\pm$ 0.5 mm/yr) *ca.* 4000 cal BP when sea level was *ca.* 4 m below its modern level. At this time, a change in the depositional environment occurred as suggested by an increase in sand content, and the occurrence of seismic horizon H₄₀₀₀ (base of Unit 5) (Fig. 4). H₄₀₀₀ can be correlated throughout much of the northern basin, and some areas of the southern basin, and is

typically associated with a decrease in percent mud (Figs. 5 and 9). Several cores near PS-03 (and including PS-03) contain normal marine salinity benthic and planktonic foraminifera with ages of *ca.* 4000 cal BP (Metger, 2009; Grand Pre et al., 2011). The interpretation of highly segmented Holocene barrier islands *ca.* 4000 cal BP by Grand Pre et al. (2011) is based upon these foraminiferal assemblages. Seismic surface H₄₀₀₀, imaged near cores PS-09 and PS-10, indicates that there was no deposition or preservation of sediments on the majority of interfluves before 4000 ± 500 years cal BP (Fig. 2a,b; 9).

An increase in marine influence within Pamlico Sound is possibly a result of increased hurricane frequency or intensity (Culver et al., 2007; Donnelly and Woodruff, 2007; Grand Pre et al., 2011). The overtopping of interfluves at this time, particularly Bluff Shoal, and rapid expansion of fetch, likely created the H₄₀₀₀ reflector throughout the region via an increase in wave energy and deepening of the wave base. Furthermore, rapid expansion of open water areas also likely created a greater tidal prism, which may have facilitated an increase in the number of inlets and island segmentation (Oertel, 1985).

5.4 3500 to 1200 cal BP

An increase in mud content within the majority of cores correlates to the upper part of Unit 5 and suggests a decrease in energy within Pamlico Sound from *ca.* 3500 to 1200 cal BP (Fig. 7). This agrees with previous work indicating a return to estuarine conditions (Culver et al., 2007; Metger, 2009; Grand Pre et al., 2011). This trend was briefly interrupted by a marine incursion at *ca.* 2500 cal BP, which is indicated by a seismic reflection (H₂₅₀₀) localized to the region of the western sound (both north and south of BSI) and near Ocracoke Inlet (Fig. 9), and associated with normal marine salinity foraminifera in sediments behind Portsmouth Island (Grand Pre et al., 2011). The presence of barrier islands along the North Carolina coast during

this time interval is also supported by data from Mallinson et al. (2008, 2011) and Peek et al. (2013). Optically stimulated luminescence age estimates from relict beach ridges in northern Pamlico Sound (Kitty Hawk; Fig. 1a) indicate a prograding barrier shoreline was present *ca.* 4500 to 2000 cal BP (Mallinson et al., 2008; Moran et al., 2015). Inlet-fill sediments from portions of the Outer Banks date to approximately 2000 cal BP (Mallinson et al., 2011). Beach ridge sediments on the northern portion of the Buxton beach ridge complex at Cape Hatteras provide an OSL age of 1635 ± 200 cal BP (Peek et al., 2013). The increased continuity (healing) of barrier islands following segmentation at *ca.* 4000-3500 cal BP was likely the result of reduced climatic forcing (e.g. decrease in storm frequency or intensities) and a relatively stable sea level with a rate of relative rise of 1.0 ± 0.3 mm/yr (from 3500 to 1200 cal BP). Alternatively, a reduction in the number of inlets may have been a result of a decrease in the M_2 tidal component, which was 75% larger than today at *ca.* 5000 cal BP, and was declining (Hill et al., 2011). Progradation may have been in response to a decrease in tidal prism due to basin shoaling or declining M_2 tides, and a corresponding decrease in inlet activity and onshore migration of eroding ebb-tidal delta sediments (Fitzgerald et al., 1984), providing a source of sand to the islands.

5.5 1200 to 500 cal BP

An abrupt change in the depositional environment of Pamlico Sound is suggested by a general increase in sand content in Unit 5 (constrained to *ca.* 1200 to 500 cal BP), significant decreases in BMS data, and the occurrence of seismic reflection H_{1000} corresponding with the increase in the sand (Fig. 5). These data agree with previous work that indicates an increase of marine influence in Pamlico Sound from *ca.* 1200 to 500 cal BP based on the occurrence of normal marine salinity benthic foramineral taxa, and Gulf Stream planktonic foraminifera

(Culver et al., 2007; Grand Pre et al., 2011). The expansion of marine influence into the Sound has been interpreted as the result of extensive segmentation of the southern Outer Banks, possibly as a result of an increase in storm activity during the MCA (Culver et al., 2007; Mann et al., 2009; Metger, 2009; Grand Pre et al., 2011; Mallinson et al., 2011; Peek et al., 2013).

Geomorphic features within Pamlico Sound appear to be related to barrier segmentation during the MCA. Seismic and core data from this study suggest that Gull Shoal and East Pamlico Shoals (Fig. 9) formed between ca. 1200 and 500 cal BP. East Pamlico Shoals are part of an extensive sand sheet associated with Unit 5 that varies in thickness from ca. 0.5 m (between shoal ridges) to 3 m (Fig. 9) in eastern Pamlico Sound. Seismic horizon H_{500} amalgamates with the modern seafloor over these shoals, suggesting little to no deposition since ca. 500 cal BP across the shoal areas. An estuarine mud unit occurs above the sand sheet (above H_{500}) in the bathymetric lows between the shoals (see PS-07 location, Fig. 9). The shoals show a high amplitude seismic response and signal attenuation, suggesting coarse sediments, and high-energy deposition relative to modern conditions. Gull Shoal to the northwest of the MCA Shoals, is oriented in the same NW-SE direction, and is bounded by H_{1000} and H_{500} (Fig. 9). Chirp data are not as clear in the East Pamlico Shoals area, but age data from PS-07 suggest that the base is bounded by H_{1000} , similar to Gull Shoals (Fig. 9). The East Pamlico Shoals are far too large to be typical barrier island overwash deposits. Larger scale processes such as intense and or multiple hurricane impacts, a tsunami, or a substantial increase in the tidal regime must be invoked to explain the existence of these shoals. Greater hurricane activity during this time interval has been proposed by others (Donnelly and Woodruff, 2007; Mann et al., 2009).

Bogue Banks to the south of the study area (Fig. 1a), and Delaware Bay to north both contain transgressive deposits or an increase in marine influence dated to ca. 1000 cal BP (Leorri

et al., 2006; Timmons et al., 2010). The spatial distribution of the bay ravinement surface in Bogue Banks suggests that the transgression was caused by an increase in storm activity and not a result of sea-level rise (Timmons et al., 2010). Both of these studies provide examples of other estuaries where the depositional environment was altered during the MCA.

5.6 500 cal BP to Present

Unit 6 is delineated by seismic horizons H_{500} and H_{sf} . Unit 5 and Unit 6 are differentiated by the net increase in mud content and increases in BMS values above H_{500} . Previous studies (Culver et al., 2007; Metger 2009; Grand Pre et al. 2011; Peek et al., 2013) indicated that Pamlico Sound returned to full estuarine conditions (compared to the MCA unit) at *ca.* 500 cal BP as a result of the reformation of the southern barrier islands, and progressive decrease in the number of inlets along the Outer Banks since *ca.* 500 cal BP (Mallinson et al., 2011; Peek et al., 2013). However, cores PS-05, PNP-2, and PS11-03 indicate fluctuations in the sand/mud ratio after *ca.* 500 cal BP, as opposed to a simple fining-upward trend (Fig. 5). This might be the result of an increase in inorganic sediment from land clearance during initial European settlement of the region. Studies of the lower Hudson Valley and Chesapeake Bay correlated increases in inorganic sediments to fluctuations in pollen types that suggest an increase in land clearance (Ward et al., 1998; Pederson et al., 2005) and Willard et al. (2011) found evidence of land clearance within the Roanoke River valley *ca.* 300 cal BP. Other anthropogenic effects are detected in this paper's datasets. The rise in BMS values within the top 30 to 40 cm of a few cores (Fig. 7) is likely from metal pollution. Previous studies have found a significant increase in trace metals within sediments recovered from nearby estuaries (e.g., Riggs et al., 1993; Cooper et al., 2004; Corbett et al., 2009). Additional anthropogenic changes are beyond the scope of this study as they require higher resolution analysis.

5.7 Synthesis

The datasets summarized in this paper illustrate the importance of the antecedent topography, as well as climate conditions, in determining the character and timing of the formation of lithostratigraphic and seismic stratigraphic boundaries and units. The initial flooding of the fluvial valleys produced reflections (H_{rs1} and H_{rs2}) that conform with existing stratigraphic studies (e.g., Dalrymple et al., 1992; Foyle and Oertel, 1997; Dabrio et al., 2000; Anthony et al., 2002), and are driven by rising sea level and associated changes to hydrodynamics within the flooding valleys. Subsequent boundary and unit formation, beyond the confines of the valleys, was influenced by various autogenic and allogenic processes.

The hypsography of the basins and interfluves within the Pamlico Sound region created a stepped change in the expanse of open water (the fetch) in the northern basin as some interfluves were overtopped between ca. 5000 and 4000 cal y BP (Fig. 7b). The preservation of sediments younger than this age on the Hatteras Flats interfluve (elevation of ca. 7 mbsl), but not on shallower interfluves (e.g. Bluff Shoal interfluve) demonstrates the interaction between elevation, sea level, and base level (as dictated by storm wave base). Rapid estuarine shoreline transgression between ca. 5000 and 4000 cal y BP, due to the low slope on the top of interfluves, increased the estuary size, fetch, wave energy and tidal prism (Fig. 7b). Increased wave energy resulted in deeper wave base, and increased wave ravinement resulting in accelerated seafloor and shoreline erosion within the system and creating H_{4000} . A similar process of fetch-driven wave energy increase and accelerated shoreline erosion was suggested by Timmons et al. (2011) for the rapid erosion of the estuarine shoreline surrounding Bogue Sound, NC at ca. 1100 cal y BP. In the Pamlico Sound, rapid expansion of the system and associated tidal prism caused an increase in salinity. A similar mechanism is invoked for an increase in salinity in the

Chesapeake Bay at ca. 7.6 ka (Bratton et al., 2003). The increase in tidal prism also likely facilitated a more segmented barrier island system allowing for greater marine influence, as evidenced by normal marine salinity foraminiferal taxa in the eastern Pamlico Sound (Culver et al., 2007; Grand Pre et al., 2011).

Interfluvial erosion contributed sands to the formation of Unit 4 above H_{4000} until sea-level rise raised the base level such that preservation was possible across interfluvial, and shorelines became more distal. This resulted in a fining-upward unit. In more basinal areas (e.g., PS-09; Figs. 1, 2, 4, 5), the amplitude of H_{4000} is greater than in areas above the interfluvial, reflecting the greater acoustic contrast between basinal muds of Unit 3 and the sands of Unit 4, as opposed to the minimal contrast between sandier sediments of both units above the interfluvial.

Backstepping reflections can be seen overlying the Hatteras Flats interfluvial (Fig. 2) suggesting episodic event boundary formation during storm conditions as sea level continued to rise and Unit 4 onlapped and overtopped interfluvial.

Rodriguez et al. (2005) demonstrated a similar process of flooding surface and parasequence formation in Galveston Estuary (Texas, USA) where successive inundation of fluvial terraces forced rapid transgressions. However their data differ from the Pamlico Sound in that flooding surfaces in Galveston Estuary are characterized by an abrupt transition from delta plain facies to central basin facies (abrupt upward-fining). In the Pamlico Sound, H_{4000} is most commonly marked by an increase in sand content. This difference between the two areas may be a function of the sediment type on eroding terraces, with Pamlico Sound interfluvial characterized by Pleistocene sands. Alternatively, it may be due to an increase in tidal regime in Pamlico Sound, resulting in higher current velocities and winnowing of fines, and sands being advected into the system through large inlets.

The influence of climate on the formation of Unit 4 is not entirely clear. The time period of 4200 to 3800 cal BP is indicated as a period of rapid climate change (RCC) by Mayewski et al. (2004). This period is characterized by greater Trade Wind and Westerlies strength (Bradbury et al., 1993; Haug et al., 2001), and decreased North Atlantic Deep Water (NADW) flow (Bianchi and McCave, 1999). Levermann et al. (2005) demonstrated that a decrease in NADW formation would cause a rise in sea level along the North American east coast. A sea-level rise along the east coast, and greater wind and wave energy, may have contributed to the segmentation of the barrier system and increase in salinity in the Pamlico Sound. Leorri et al. (2006) recognize a transgressive facies contact in sediments of Delaware Bay at this time, and suggest the influence of a rapid sea-level rise related to conditions associated with the RCC period presented by Mayewski et al. (2004).

The formation of H₁₀₀₀ and Unit 5 during the Medieval Climate Anomaly appears to have been in response to an increase in barrier island segmentation. However, this was not facilitated by antecedent topographic control, but likely by climate conditions. The characteristics of Unit 5, including the apparent association with sand ridges (the East Pamlico Shoals) in eastern Pamlico Sound, indicate normal marine salinity and higher energy conditions (relative to today) within the eastern portion of the sound. The western and southern Pamlico Sound continued to exhibit low energy brackish conditions (Foley, 2007; Metger, 2009). By the time of deposition of Unit 5, the extent of Pamlico Sound was similar to today, and interfluves were submerged. An increase in salinity could have occurred as a result of sustained drought conditions, but that would not explain the characteristics of Unit 5. Sargasso Sea surface waters were characterized by relatively high temperatures (ca. 24°C; Keigwin, 1996) at this time, and temperatures in the eastern North Atlantic were also at a peak (de Menocal et al., 2001). Chesapeake Bay water

temperatures were also ca. 2°C warmer than the pre-20th century average (Cronin et al., 2003). An increase in hurricane activity in the North Atlantic, as a result of these warm conditions, was proposed by Mann et al. (2009), and is considered the likely cause of barrier island segmentation (Culver et al., 2007; Grand Pre et al., 2011). Notably, MCA conditions in the eastern North Atlantic indicate a decrease in winter storm conditions, and better preservation of coastal sediments (Sorrel et al., 2010) resulting from a multidecadal persistence of a negative phase of the North Atlantic Oscillation (NAO; Proctor et al., 2000; Meeker and Mayewski, 2002). Xie et al. (2005) showed that the negative phase of NAO favors an increase in the number of hurricanes making landfall along the east coast of the United States.

Segmentation of the barrier islands during the MCA must have been substantial in order to allow normal marine salinity conditions in eastern Pamlico Sound. Widespread erosion of the barriers to form subtidal shoals and wide inlets likely caused a rapid increase in tidal influence within the Sound, advection of sand into the system, and tidal reworking of deposits to form the sand sheet and East Pamlico Shoals of Unit 5.

H₅₀₀ marks the decrease in tidal energy as the barriers islands became more continuous. Unit 6 represents deposits formed during and since the Little Ice Age. Mallinson et al. (2011) showed that many more inlets were open during the LIA than today. Many of these may have remained from the MCA segmentation, but were slowly shutting down. Salinity conditions within Pamlico Sound during the LIA became more brackish, similar to modern salinities (Culver et al., 2007; Grand Pre et al., 2011). Episodic segmentation may have been sustained by an increase in North Atlantic storminess during the LIA (Mayewski et al., 2004; Sorrel et al., 2010; Mallinson et al., 2011). Since the peak of the LIA, the barriers have gradually become more continuous, with only three large active inlets in the modern system. However, the last

century has been characterized by a substantial increase, *ca.* 2.2 mm/yr, in the rate of relative sea-level rise (Kemp et al., 2009; Horton et al., 2011) and significant increase in barrier island erosion (Riggs and Ames, 2003). Based on the history of the Pamlico Sound region over the past millennium and the current increased rate of sea-level rise, as well as possible future hurricane intensification, it is likely that the Outer Banks will become severely segmented once more in the decades to come.

6. Conclusions

This study provides a high resolution interpretation of the stratigraphic and paleoenvironmental evolution of a large estuarine and barrier island system, in response to rising sea level, antecedent topography, and geomorphic changes to the barrier island system. The coastal system evolved through several distinct stages and modes of operation (e.g, tidal or wave dominance, restricted or open-ocean connected, etc.) in response to sea-level rise interacting with the antecedent topography and controlling the hydrodynamics, and depositional and erosional processes. In this setting, during topographically-controlled rapid expansion of the estuary at *ca.* 4000 cal BP, a ravinement surface formed as a result of the rapid increase in fetch and wave energy. As base-level rose, fining-upward deposits and back-stepping surfaces were produced. An initial increase, and subsequent decrease, in tidal energy due to barrier island segmentation and subsequent healing may have also contributed to the fining-upward unit.

North Atlantic basin-wide climate conditions influenced barrier island conditions and estuarine hydrodynamics, and are recorded in the later stages of estuarine fill within Pamlico Sound. Rapid reorganization of the system occurred during the MCA, likely as a result of severe hurricane impacts, wide-spread barrier island segmentation, and a resulting increase in tidal

currents and salinity within Pamlico Sound. This is recorded by the occurrence of a ravinement surface (likely tidal in origin) and sand sheet deposit containing normal marine salinity foraminiferal taxa.

This study provides a basis for understanding future coastal changes as a result of continued sea-level rise and climate change. Increased rates of sea-level rise and increases in storminess altered the hydrodynamics of Pamlico Sound during the MCA. Modern rates of sea-level rise are substantially higher than during the MCA, while hurricane intensity is predicted to increase with increasing temperatures. The barrier islands are gradually narrowing, potentially setting the stage for a new cycle of wide-spread segmentation (Riggs and Ames, 2003) and returning the system to hydrodynamically energetic conditions last seen ca. 1000 years ago.

Acknowledgements

We would like to thank John Woods and Jim Watson for their technical assistance. Financial support was provided by the National Science Foundation OCE-11308. Seismic Micro-Technology, Inc. provided support in the form of an educational software grant.

References

- Allen, G.P., Posamentier, H.W., 1993. Sequence stratigraphy and facies model of an incised valley fill: the Gironde estuary, France. *Journal of Sedimentary Petrology* 63, 378–391.
- Anthony, E.J., Lucien, M.O., Lang, J., 2002. Sedimentation in a fluvially infilling, barrier-bound estuary on a wave-dominated, microtidal coast: Oueme River estuary, Benin, West Africa. *Sedimentology* 49, 1095–1112.
- Bradbury, J.P., Dean, W.E., Anderson, R.Y., 1993. Holocene climatic and limnologic history of the north-central United States as recorded in the varved sediments of Elk Lake, Minnesota: a synthesis. *Special Paper - Geological Society of America* 276, 309–328.
- Bianchi, G.G., McCave, I.N., 1999. Holocene periodicity in North Atlantic climate and deep-ocean flow south of Iceland. *Nature* 397, 515–517.
- Bratton, J., Colman, S., Thielert, E., Seal II, R., 2003. Birth of the modern Chesapeake Bay estuary between 7.4 and 8.2 ka implications for global sea-level rise. *Marine Geology Letters* 22, 188–197.
- Blott, S.J., Pye, K., 2001. Grain-size Statistics Program. *Earth Surface Processes and Landforms* 26, 1237–1248.

- Cattaneo, A., Steel, R.J., 2002. Transgressive deposits: a review of their variability. *Earth Science Reviews* 62, 187–228.
- Catuneanu, O., 2006. *Principles of Sequence Stratigraphy*. Elsevier, Amsterdam. 375 p.
- Church, J.A., Clark P.U., Cazenave A., Gregory J.M., Jevrejeva S., Levermann A., Merrifield M.A., Milne G.A., Nerem R.S., Nunn P.D., Payne A.J., Pfeffer W.T., Stammer D., Unnikrishnan A.S., 2013: Sea Level Change. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1137–1216.
- Conrad, C.P., Husson, L., 2009. Influence of dynamic topography on sea level and its rate of change. *Lithosphere* 1, 110–120.
- Cooper, S.R., McGlothlin, S.K., Madritch, M., Jones, D.L., 2004. Paleocological evidence of human impacts on the Neuse and Pamlico estuaries of North Carolina, USA. *Estuaries* 27, 617–633.
- Corbett, D.R., Walsh, J.P., Marciniak, K., 2009. Temporal and spatial variability of trace metals in sediments of two adjacent tributaries of the Neuse River Estuary, North Carolina, USA. *Marine Pollution Bulletin* 58, 1739–1747.
- Cronin TM, Dwyer GS, Kamiya T, Schwede S, Willard D.A., 2003. Medieval Warm Period, Little Ice Age and 20th century temperature variability from Chesapeake Bay. *Global and Planetary Change* 36:17–29
- Cronin, T.M., Hayo, K., Thunell, R.C., Dwyer, G.S., Saenger, C., Willard, D.A., 2010. The Medieval Climate Anomaly and Little Ice Age in Chesapeake Bay and the North Atlantic Ocean. *Palaeogeography, Palaeoclimatology, Palaeoecology* 297, 299–310.
- Culver, S.J., Ames, D.V., Corbett, D.R., Mallinson, D.J., Riggs, S.R., Smith, C.G., Vance, D.J., 2006. Foraminiferal and sedimentary record of late Holocene barrier island evolution, Pea Island, North Carolina. *Journal of Coastal Research* 22, 836–846.
- Culver, S., Grand Pre, C., Mallinson, D., Riggs, S., Corbett, D., Foley, J., Hale, M., Ricardo, J., Rosenberger, J., Smith, C.G., Smith, C.W., Snyder, S., Twamley, D., Farrell, K., Horton, B., 2007. Late Holocene Barrier Island Collapse: Outer Banks, North Carolina, U.S.A. *The Sedimentary Record* 5, 4–8.
- Culver, S.J., Farrell, K.M., Mallinson, D.J., Horton, B.P., Willard, D.A., Thieler, E.R., Riggs, S.R., Snyder, S.W., Wehmiller, J.F., Bernhardt, C.E., Hillier, C., 2008. Micropaleontologic record of Late Pliocene and Quaternary paleoenvironments in the northern Albemarle Embayment, North Carolina, USA. *Palaeogeography, Palaeoecology, Palaeoclimatology* 264, 54–77.
- Dabrio, C.J., Zazo, C., Goy, J.L., Sierro, F.J., Borja, F., Lario, J., Gonzalez, J.A., Flores, J.A., 2000. Depositional history of estuarine infill during the last postglacial transgression (Gulf of Cadiz, Southern Spain). *Marine Geology* 162, 381–404.
- Dalrymple, R.W.; Zaitlin, B.A., and Boyd, R., 1992. Estuarine facies models: Conceptual basis and stratigraphic implications. *Journal of Sedimentary Petrology* 62, 1130–1146.
- de Menocal P., Ortiz J., Guilderson T., Sarntheim M., 2000. Coherent high- and low-latitude climate variability during the Holocene warm period. *Science* 288, 2198–2202.
- Donnelly, J.P., and J.D. Woodruff, 2007, Intense hurricane activity over the past 5,000 years controlled by El Nino and the West African monsoon: *Nature* 447, 465–468.
- Emanuel, K., 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* 436, 686–688.

- Farrell, K., Harris, B., Mallinson, D., Culver, S., Riggs, S., Pierson, J., Self-Trail, J., Lautier, J., 2012. Standardizing texture and facies codes for a process-based classification of clastic sediment and rock. *Journal of Sedimentary Research* 82, 364–378.
- Fitzgerald, D.M., Penland, S., Nummedal, D., 1984. Control of barrier island shape by inlet sediment bypassing: East Frisian Islands, West Germany. *Marine Geology* 60, 355–376.
- Foley, J., 2007. Foraminiferal, sedimentological and geochemical indications of Holocene environmental change in Pamlico Sound, North Carolina: Master's Thesis, East Carolina University, 1–167.
- Foyle, A.M., Oertel, G.F., 1997. Transgressive systems tract development and incised-valley fills within a Quaternary estuary-shelf system: Virginia inner shelf, USA. *Marine Geology* 137, 227–249.
- Grand Pre, C., Culver, S.J., Mallinson, D.J., Farrell, K.M., Corbett, D.R., Horton, B.P., Hillier, C., Riggs, S.R., Snyder, S.W., Buzas, M.A., 2011. Rapid Holocene coastal change revealed by high-resolution micropaleontological analysis, Pamlico Sound, North Carolina, USA. *Quaternary Research* 76, 319–334.
- Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., Rohl, U., 2001. Southward migration of the Intertropical Convergence Zone through the Holocene. *Science* 293, 1304–1308.
- Hill, D.F., Griffins, S.D., Peltier, W.R., Horton, B.P., Törnqvist, T.E., 2011. High-resolution numerical modeling of tides in the western Atlantic, Gulf of Mexico, and Caribbean Sea during the Holocene. *Journal of Geophysical Research* 116, 1–16.
- Horton, B.P., Peltier, W.R., Culver, S.J., Drummond, R., Engelhart, S.E., Kemp, A.C., Mallinson, D., Thieler, E.R., Riggs, S.R., Ames, D.V., Thomson, K.H., 2009. Holocene sea-level changes along the North Carolina Coastline and their implications for glacial isostatic adjustment models. *Quaternary Science Reviews* 28, 1725–1736.
- Keigwin LD (1996) The Little Ice Age and Medieval Warm Period in the Sargasso Sea. *Science* 274, 1504–1508.
- Kemp, A.C., Horton, B.P., Donnelly, J.P., Mann, M.E., Vermeer, M., Rahmsdorf, S., 2011. Climate related sea-level variations over the past two millennia. *Proceedings of the National Academy of Sciences* 108, doi:10.1073/pnas.1015519108, 1–6.
- Kopp, R.E., Horton, B.P., Kemp, A.C., Tebaldi, C., 2015. Past and future sea-level rise along the coast of North Carolina, USA. *Climatic Change*, DOI 10.1007/s10584-015-1451-x.
- Leorri, E., Martin, R., McLaughlin, P., 2006. Holocene environmental and parasequence development of the St. Jones Estuary, Delaware (USA): Foraminiferal proxies of natural climatic and anthropogenic change. *Palaeogeography, Palaeoclimatology, Palaeoecology* 241, 590–607.
- Levermann, A., Griesel, A., Hofmann, M., Montoya, M., Rahmstorf, S., 2005. Dynamic sea level changes following changes in the thermohaline circulation. *Climate Dynamics* 24, 347–354.
- Luettich R.A., Carr, S.D., Reynolds-Fleming, J.V., Fulcher, C.W., McNinch, J.E., 2001. Semi-diurnal seiche in a shallow, micro-tidal lagoonal estuary. *Continental Shelf Research* 22, 1669–1681.
- Mallinson, D., Riggs, S., Thieler, E. R., Culver, S. J., Farrell, K., Foster, D.S., Corbett, D.R., Horton, B., and Wehmler, J.F., 2005. Late Neogene and Quaternary evolution of the northern Albemarle Embayment (mid-Atlantic continental margin, USA). *Marine Geology* 217, 97–117.

- Mallinson, D., Burdette, K., Mahan, S., Brook, G., 2008. Optically stimulated luminescence age controls on late Pleistocene and Holocene coastal lithosomes, North Carolina, USA. *Quaternary Research* 69, 97–109.
- Mallinson, D.J., Culver, S.J., Riggs, S.R., Thieler, E.R., Foster, D., Wehmiller, J., Farrell, K., Pierson, J., 2010. Regional seismic stratigraphy and controls on the Quaternary evolution of the Cape Hatteras region of the Atlantic passive margin, USA. *Marine Geology* 268, 16–33.
- Mallinson, D.J., Smith, C.W., Mahan, S., Culver, S.J., McDowell, K., 2011. Barrier island response to late Holocene climate events, North Carolina, USA. *Quaternary Research* 76, 46–57.
- Mann, M., Woodruff, J., Donnelly, J., Zhang, Z., 2009. Atlantic hurricanes and climate over the past 1,500 years. *Nature* 460, 880–883.
- Mayewski, P.A., Rohling, E.E., Stager, D. J., Karlén, W., Maasch, K.A., Meeker, D. L., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., Steig, E.J., 2004. Holocene climate variability. *Quaternary Research* 62, 243–255.
- Meeker, L.D., Mayewski, P.A., 2002. A 1400-year high-resolution record of atmospheric circulation over North America and Asia. *The Holocene* 12, 257–266.
- Metger, L., 2009. Holocene Paleoenvironmental change in southern Pamlico Sound, North Carolina: Master's Thesis, East Carolina University, 1–178.
- Moran, K.L., Mallinson, D.J., Culver, S.J., Leorri, E., Mulligan, R.P., 2015. Late Holocene evolution of Currituck Sound, North Carolina, USA: Environmental change driven by sea-level rise, storms and barrier island morphology. *Journal of Coastal Research* 31, 827–841.
- Oertel, G.F., 1985. The barrier island system. *Marine Geology* 63, 1–18.
- Pederson, D.C., Peteet, D.M., Kurdyla, D., Guilderson, T., 2005. Medieval Warming, Little Ice Age, and European impact on the environment during the last millennium in the lower Hudson Valley, New York, USA. *Quaternary Research* 63, 238–249.
- Peek, K., Mallinson, D., Culver, S., Mahan, S., 2013. Holocene geologic development of the Cape Hatteras region, Outer Banks, North Carolina. *Journal of Coastal Research* 30, 41–58.
- Procter, C.J., Baker, A., Barnes, W.L., Gilmore, M.A., 2000. A thousand year speleothem record of North Atlantic climate from Scotland. *Climate Dynamics* 16, 815–820.
- Riggs, S.R., York, L.L., Wehmiller, J.F., Snyder, S.W., 1992. Depositional patterns resulting from high-frequency Quaternary sea-level fluctuations in northeastern North Carolina. In: Fletcher, C., Wehmiller, J. Eds., *Quaternary Coasts of the United States: Marine and Lacustrine Systems*. Society for Economic Paleontologists and Mineralogists Special Publication 48, 141–153.
- Riggs, S.R., Bray, J.T., Wyrick, R.A., Klingman, C.R., Ames, D.V., Hamilton, J.C., Lueck, K.L., 1993. Heavy Metals in Organic-Rich Muds of the Albemarle Sound Estuarine System: Albemarle-Pamlico Estuarine Study, U.S. Environmental Protection Agency and N.C. Dept. of Environment, Health, and Natural Resources 93-02, 1–173.
- Riggs, S.R., Cleary, W.J., Snyder, S.W., 1995. Influence of inherited geologic framework on barrier shoreface morphology and dynamics. *Marine Geology* 126, 213–234.

- Riggs, S.R., Ames, D.V., 2003. Drowning the North Carolina Coast: Sea-Level Rise and Estuarine Dynamics: North Carolina Sea Grant Program, Publication No. UNC-SG-03-04, Raleigh, NC.
- Rodriguez, A.B., Anderson, J.B., Simms, A.R., 2005. Terrace inundation as an autocyclic mechanism for parasequence formation: Galveston Estuary, Texas, U.S.A. *Journal of Sedimentary Research* 75, 608-620.
- Simkins, L.M., Simms, A.R., Cruse, A.M., Troiani, T., Atekwana, E.A., Puckette, J., Yokoyama, Y., 2012. Correlation of early and mid-Holocene events using magnetic susceptibility in estuarine cores from bays along the northwestern Gulf of Mexico. *Palaeogeography, Palaeoclimatology, Palaeoecology* 346–347, 95–107.
- Sorrel, P., Tessier, B., Demory, F., Delsinne, N., Mouazé, D., 2009. Evidence for millennial-scale climatic events in the sedimentary infilling of a macrotidal estuarine system, the Seine estuary (NW France). *Quaternary Science Reviews* 28, 499–516.
- Sorrel, P., Tessier, B., Demory, F., Baltzer, A., Bouaouina, F., Proust, J., Menier, D., Traini, C., 2010. Sedimentary archives of the French Atlantic coast (inner Bay of Vilaine, south Brittany): depositional history and late Holocene climatic and environmental signals. *Continental Shelf Research* 30, 1250–1266.
- Stuiver M., Reimer, P., 1993. Extended 14C data base and revised CALIB 3.0 14C Age calibration program. *Radiocarbon* 35, 215–230
- Thomas, D.H., 2008. Native American landscapes of St. Catherines Island, Georgia II. The Data, *American Museum of Natural History* 88, 343–831.
- Timmons, E.A., Rodriguez, A.B., Mattheus, C.R., DeWitt, R., 2010. Transition of a regressive to a transgressive barrier island due to back-barrier erosion, increased storminess, and low sediment supply: Bogue Banks, North Carolina, USA. *Marine Geology* 278, 100–114.
- Tessier, B., Billeaud, I., Sorrel, P., Delsinne, N., Lesueur, P., 2012. Infilling stratigraphy of macrotidal tide-dominated estuaries. Controlling mechanisms: Sea-level fluctuations, bedrock morphology, sediment supply and climate changes (The examples of the Seine estuary and the Mont-Saint-Michel Bay, English Channel, NW France). *Sedimentary Geology* 279, 62–73.
- Traini, C., Menier, D., Proust, J., Sorrel, P., 2013. Transgressive systems tract of a ria-type estuary: the Late Holocene Vilaine River drowned valley (France). *Marine Geology* 337, 140–155.
- Ward, L.G., Kearney, M.S., Stevenson, J.C., 1998. Variations in sedimentary environments and accretionary patterns in estuarine marshes undergoing rapid submergence, Chesapeake Bay. *Marine Geology* 151, 111–134.
- Wells, J.T., Kim, S.Y., 1989. Sedimentation in the Albemarle–Pamlico lagoonal system: synthesis and hypothesis. *Marine Geology* 88, 263–284.
- Willard, D., Bernhardt, C., Brown, R., Landarcre, B., Townsend, P., 2011. Development and application of a pollen-based paleohydrologic reconstruction from the lower Roanoke River Basin, North Carolina, USA. *The Holocene* 21, 305–317.
- Xie, L., Yan, T., Pietrafesa, L., Morrison, J., Karl, T., 2005. Climatology and interannual variability of North Atlantic hurricane tracks. *Journal of Climate* 18, 5370–5381.

Table Captions

Table 1. Lithofacies codes and descriptions.

Table 2. Radiocarbon age estimates used in this study.

Table 3. Summary of seismic reflections and stratigraphic units (SU); Interpretations based on seismic data combined with core logs, grain-size analysis and radiocarbon age estimates. (* Indicates that the reflection/ unit is not discussed in this paper.)

Figure Captions

Figure 1. Map of study area: (A) indicates bathymetry (reference datum NAVD 88) and location of important geographic features discussed in the paper; (B) shows the location of chirp seismic data and cores recovered from Pamlico Sound. (C) Map showing the paleotopographic surface formed during the late Pleistocene sea-level fall and lowstand, based upon seismic data (modified from Mallinson et al., 2010). Note the incised paleo-valleys associated with the Neuse River (NRPV) and Pamlico River (PRPV), and paleo-Pamlico Creek (PCPV), a completely submerged drainage system. Bluff Shoal Interfluvium (BSI) controls the modern position of Bluff Shoal and separates the northern and southern basins of Pamlico Sound. Hatteras Flats Interfluvium (HFI) underlies the Outer Banks barrier islands. Brant Shoal Interfluvium (BrSI) separates the Pamlico and Neuse Rivers.

Figure 2. A) High resolution chirp seismic profile and B) stratigraphic interpretation near vibracore PS-09 located in the northern Pamlico basin. Vertical Exaggeration = 7. C) High resolution chirp seismic profile and D) interpreted stratigraphic horizons (lower panel) across vibracore PS11-VC1. H_{1000} and H_{2500} are constrained by radiocarbon age estimates and occupy a paleovalley. The P_{lgm} reflection is poorly imaged in this profile due to attenuation of the seismic

signal by gas associated with peat (found in the bottom of PS11-VC1; Fig. 1b). Vertical Exaggeration = 7.

Figure 3. A) High resolution chirp seismic profile and B) interpretation of the in-fill of a paleovalley within Pamlico Sound. Data suggest tidal ravinement (H_{RS1}) of the Pleistocene topography followed by tidal deposition as suggested by the large clinoforms. The Holocene bay ravinement surface (H_{RS2}) occurring above the tidal deposits does not appear to truncate the clinoforms. H_{4000} occurs above H_{RS2} and is likely an erosional surface. The profile location is indicated by the small black box around the survey line shown in the inset. Vertical Exaggeration = 6.6. C) High resolution chirp seismic profile and D) interpretation of the transgressive surfaces in Pamlico Sound located south of vibracore PS-08 (Fig. 1b). The profile location is indicated by the small black box around the survey lines shown in the inset. Vertical Exaggeration = 7.

Figure 4. Chirp subbottom profiler data at core sites A) PS11-VC1, B) PS11-03, C) PS-09, and D) PS-05, showing the position of seismic reflections and corresponding radiocarbon ages (cal BP; Table 2) used to help constrain the age of the reflections. Note that not all reflections are present at all of the sites. See Figure 1b for the location of cores.

Figure 5. Structure contour maps of the H_{4000} , H_{1000} , and H_{500} surfaces in meters below present sea level. Note that reflections do not occur above Bluff Shoal Interfluvial (BSI) as it has been an eroding topographic high throughout the Holocene. The location of the associated mapped reflection, which was used to create the contour map, is also shown.

Figure 6. A) Bulk sediment magnetic susceptibility data (black data points) with wt.% mud (red data points), seismic reflectors (grey lines), and age data (cal BP) for seven cores. The MCA minimum is a particularly prominent BMS low that was useful for correlating Unit 5 between H₁₀₀₀ and H₅₀₀. B) Modern bathymetric map, obliquely viewed, showing the location of cores.

Figure 7. Maps showing the flooding of the Pleistocene surface (based on seismic data from Mallinson et al., 2010), at three time intervals, disregarding Holocene sedimentation. Relative sea-level (RSL) elevations are from Kopp et al. (2015). These images reveal the timing of expansion of the Pamlico estuary system beyond the confines of the paleovalleys (A, and Fig. 1c), and the ultimate overtopping of interfluves. Rapid expansion of the system at ca. 5000 to 4000 cal BP resulted in the formation of H₄₀₀₀ and Unit 4 as interfluve sands were ravined and exported basinward. The thick black line in B and C indicates the likely shoreline position. The distribution of land at the present time is indicated by grey. No data is indicated by white. The probable location of barrier islands is indicated in B and C. Note the islands in Pamlico Sound in C.

Figure 8. Chirp subbottom profiler data illustrating reflections and a buried peat platform in the southern basin, suggesting low energy, sheltered conditions.

Figure 9. Geologic cross-sections of Pamlico Sound based upon integrated core data, seismic data, and age data. Vertical exaggeration = 1200x. The P_{LGM} surface is derived from Mallinson et al. (2010) with modifications using data from this study. A) Cross-section from the western side of the Pamlico Sound. B) Cross-section from the eastern Pamlico Sound. C) Bathymetric

853 map, viewed obliquely, showing transect locations. Note that the H₄₀₀₀, the H₁₀₀₀, and H₅₀₀
854 reflections are the most continuous throughout the region, whereas the H₂₅₀₀ reflection is only
855 seen in the area of PS11-VC1, PS-03, and PS-05. H₄₀₀₀ and H₁₀₀₀ are typically (but not
856 universally) associated with an increase in grain size, followed by a fining-upward trend. Age
857 data in the region of PS-13 and PS12-VC2 suggest an erosive event in eastern Pamlico Sound
858 between ca. 900 and 1500 cal BP.

859

860

figure 1abc.tif

figure 2abcd.tif

figure 3abcd.tif

figure 5.tif

figure 6.tif

A. *ca.* 9500 cal BP; RSL = *ca.* -15m

B. *ca.* 7500 cal BP; RSL = *ca.* -10m

C. *ca.* 5000 cal BP; RSL = *ca.* -5m

figure 8.tif

figure 9.tif

Table 1

Lithofacies	Code	Description and Sedimentary features
Sandy shell hash	sSH	Poorly sorted shell hash with medium-coarse sand; shell material consists of mm-cm scale bivalve fragments.
Muddy sandy shell hash	msSH	Poorly sorted shell hash with medium-coarse sand and mud, shell material consists of mm-cm scale bivalve fragments.
Muddy shelly sand	mshS	Poorly sorted medium-coarse sand with shell clasts and mud, shell material consists of mm-cm scale bivalve fragments.
Muddy gravelly sand	mgS	Poorly sorted medium-coarse sand with quartz granules and mud present, shell material is absent.
Sand	S	Moderate to poorly sorted, medium sand, with less than 5% mud, shell material common, occasionally interbedded.
Muddy sand	mS	Poorly sorted fine-to-medium sand with mud, shell material common, occasionally interbedded.
Sandy mud	sM	Mud with fine-grained sand composed of quartz, mica, and shell material, occasionally interbedded.
Mud	M	Mud with fine-grained sand composed of quartz, mica and shell fragments, in situ shell material common, occasionally interbedded.

Table 2

Core	mbsl (top of sample)	Depth in core (m)	Calibrated BP 2 sigma range	Conventional age	Age error	Material dated	$\delta^{13}C$
PS-03	7.58	1.08	257-521	860	40	Elphidium excavatum	-1.9
PS-03	8.18	1.68	776-1151	1510	40	Elphidium excavatum	-5.2
PS-03	10.02	3.52	3706-3311	3700	40	Elphidium excavatum	0
PS-03	10.84	4.34	3964-3538	3900	40	Elphidium excavatum	-3.2
PS-03	11.16	4.96	4112-3670	4010	35	Elphidium excavatum	-2.1
PS-03	12.24	5.74	4287-3825	4130	40	Elphidium excavatum	-3.1
PS-03	14.59	8.1	7415-7007	6290	70	organic sed	-25
PS-04	7.46	0.46	1 - 264	610	20	Mulinia	-1.61
PS-05	6.81	0.56	722-493	1130	30	Mulinia	-0.5
PS-05	7.04	0.79	1-238	550	25	Anadara	-1.99
PS-05	8.35	2.1	2564-2103	2730	30	Anadara	0.1
PS-05	9.7	3.45	4893-4505	4630	35	Shell Clast	-3.04
PS-05	10.05	3.8	42403-41669	38200	220	Mulinia	1.85
PS-05	11.35	5.1	44675-38086	37850	1760	mixed Mulinia and Ensis	N/A
PS-06	8.28	1.28	500-236	820	20	Mulinia	0.37
PS-06	9.16	2.16	1998-1612	2320	30	Mulinia	-0.4
PS-07	7.35	0.85	1948-1571	2280	30	Mulinia	-0.94
PS-07	7.73	1.23	modern	445	25	Mulinia	-0.97
PS-07	8.11	1.61	2340-1985	2620	25	Mulinia	0.14
PS-07	8.76	2.26	2140-1762	2430	25	Bruised Nassa	0.9
PS-08	7.11	0.51	280-post 1950	580	30	Gastropod	-0.6
PS-08	7.46	0.86	2732-2357	2930	30	Anadara	0.19
PS08	7.7	1.1	2061-2670	2740	80	Crassostrea virginica	N/A
PS-08	8.08	1.48	modern	0	30	Gastropod	0
PS-09	6.84	0.44	modern	345	35	Shell clasts	-2.14

Table 3

Reflection	Unit		Approximate age (cal BP)	Characteristics of Reflections and Units	Interpretation of Reflections and Units
H _{sf}			Modern		Modern sediment/water interface
	6		500–0	Transparent, delineated by H ₅₀₀ and H _{sf} , 1.2–0.4 m thick.	Increased barrier island continuity allowed for deposition of muddy deposits.
H ₅₀₀			ca. 500	Medium amplitude, high continuity within the northern basin, low amplitude low continuity within the southern basin.	Delineates top of the 500-1200 cal BP unit; acoustic impedance is a result of finer-grained mud deposits overlying the sandier Unit 5.
	5		1200–500	Transparent, delineated by H ₅₀₀ and H ₁₀₀₀ , 1.6–1 meter thick.	Extensive segmentation of barrier islands, increased hydrodynamics and sand content within the Sound.
H ₁₀₀₀			ca. 1200	Low to medium in amplitude, low continuity.	Delineates an increase in estuarine hydrodynamics/marine influence.
	4	4b	ca. 2500-1200	Generally transparent, but exhibiting a higher amplitude signal toward the top.	Restricted, reduced salinity lagoonal deposition (sM, M) within the Pamlico Sound.
H ₂₅₀₀			ca. 2500	Medium amplitude, medium continuity. Limited in extent to the southern basin, and western and southern regions of the northern basin. Locally separates Unit 4 into two subunits (4a and 4b).	A minor increase in estuarine hydrodynamics primarily within the southern basin.
		4a	ca. 4000–2500	Mostly transparent but sometimes containing multiple discontinuous reflections. Most prominent in the northern basin. 3-5 m thick.	Fining upward sequence. Initial increase in marine influence, followed by formation of barrier islands which decreased estuarine hydrodynamics and restricted the influx of sand into the Sound.
H ₄₀₀₀			ca. 5000-3000	High-medium amplitude, high continuity. Rarely occurs in the southern basin.	Erosional surface; represents an increase in estuarine hydrodynamics likely as a result of an increase in fetch and tidal energy as interflaves are overtopped.
	3		7000-4000	Varies in thickness from 0-4 m, however, thickest sections are not imaged due to gas attenuation.	Restricted, reduced salinity lagoonal deposition (sM, M) within the Pamlico Sound.
H _{RS2}			<8000-0	High amplitude, high continuity, variable relief, amalgamates with multiple surfaces.	Holocene bay ravinement surface, truncates the Pleistocene in most locations.
	2		<8000-7000	Rare in the stratigraphic record, thin deposit 0.5-1.5 m thick and confined to paleo-valleys; clinoforms in data are rare.	Tidal and/or bayhead delta deposition occurring within a fetch-limited system, before sea level rose above the interflaves (Figs. 4, 5).
H _{RS1}			<8000-7000	Medium amplitude; confined to paleo-valleys; rarely imaged.	Holocene ravinement, interpreted to be the result of tidal scour, truncates Pleistocene deposits (Figs. 4, 5).
	1		>8000	0.5-1.5 meters thick, transparent, rare in the stratigraphic record.	Fluvial channel deposits of the lowstand systems tract.
P _{lgm}			>8000	High to medium amplitude, high continuity.	Subaerial unconformity exhibiting incised fluvial valleys. Reworked Pleistocene shells and iron staining, or compacted blue-grey clay characterize the surface in cores.