Geologic framework of the northern North Carolina, USA inner continental shelf and its influence on coastal evolution ☆

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ABSTRACT

The inner continental shelf off the northern Outer Banks of North Carolina was mapped using sidescan sonar, interferometric swath bathymetry, and high-resolution chirp and boomer subbottom profiling systems. We use this information to describe the shallow stratigraphy, reinterpret formation mechanisms of some shoal features, evaluate local relative sea-levels during the Late Pleistocene, and provide new constraints, via recent bedform evolution, on regional sediment transport patterns. The study area is approximately 290 km long by 11 km wide, extending from False Cape, Virginia to Cape Lookout, North Carolina, in water depths ranging from 6 to 34 m. Late Pleistocene sedimentary units comprise the shallow geologic framework of this region and determine both the morphology of the inner shelf and the distribution of sediment sources and sinks. We identify Pleistocene sedimentary units beneath Diamond Shoals that may have provided a geologic template for the location of modern Cape Hatteras and earlier paleo-capes during the Late Pleistocene. These units indicate shallow marine deposition 15–25 m below present sea-level. The uppermost Pleistocene unit may have been deposited as recently as Marine Isotope Stage 3, although some apparent ages for this timing may be suspect. Paleofluvial valleys incised during the Last Glacial Maximum traverse the inner shelf throughout the study area and dissect the Late Pleistocene units. Sediments deposited in the valleys record the Holocene transgression and provide insight into the evolutionary history of the barrier-estuary system in this region. The relationship between these valleys and adjacent shoal complexes suggests that the paleo-Roanoke River did not form the Albemarle Shelf Valley complex as previously proposed; a major fluvial system is absent and thus makes the formation of this feature enigmatic. Major shoal features in the study area show mobility at decadal to centennial timescales, including nearly a kilometer of shoal migration over the past 134 yr. Sorted bedforms occupy ~1000 km^2 of seafloor in Raleigh Bay, and indicate regional sediment transport patterns between Capes Hatteras and Lookout that help explain long-term sediment accumulation and morphologic development. Portions of the inner continental shelf with relatively high sediment abundance are characterized by shoals and shoreface-attached ridges, and where sediment is less abundant, the seafloor is dominated by sorted bedforms. These relationships are also observed in other passive margin settings, suggesting a continuum of shelf morphology that may have broad application for interpreting inner shelf sedimentation patterns.

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1. Introduction

The inner continental shelf links the subaqueous portion of the continental margin and the subaerial coast. Sedimentation on the inner shelf influences coastal evolution at a variety of timescales, from hours to millennia (Swift, 1976; Wright, 1995). Understanding inner shelf geologic setting, morphology, and processes can improve models of coastal evolution (Cowell et al., 2003; Fagherazzi and Overeem, 2007) as well as provide a basis for evaluating resource availability (Finkl et al., 2007) and marine species habitat (Woodland et al., 2012).

Geophysical surveys of the inner continental shelf provide a basis for understanding the geologic history of the coastal system (Anderson et al., 2004), furnish insight into coastal sediment flux (Schwab et al., 2000; Denny et al., 2013), and can be used to identify sand resources and potential implications for mitigating erosion hazards through beach nourishment (Lazarus et al., 2011). Coastal areas with limited sediment supplies, such as North Carolina, are significantly influenced by the geologic framework of older stratigraphic units that occur beneath and seaward of the shoreline (Riggs et al., 1995). In this area, as with much of the eastern United States, rivers no longer introduce significant quantities of new sand to the coastal system. The sediment available to maintain modern beaches is derived from erosion and

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transport of sediment from either the adjacent coast or the inner continental shelf (e.g., Schwab et al., 2013). Thus, antecedent geology of the marine and subaerial portions of the coastal zone can determine the morphology of the nearshore zone and can strongly influence modern coastal change (McNinch, 2004; Miselis and McNinch, 2006).

Here we present a synthesis of new geophysical and geologic data that describes the regional geologic framework of the North Carolina inner continental shelf from False Cape, Virginia to Cape Lookout, North Carolina (Fig. 1) in high detail. This portion of the U.S. Atlantic margin has a long history of study that yielded several foundational concepts in shelf morphology, stratigraphy, and coastal evolution (e.g., Duane et al., 1972; Swift et al., 1972; Field and Duane, 1976; Swift, 1976; McBride and Moslow, 1991) that have informed the understanding of modern and ancient passive margin sedimentation worldwide (e.g., Franks, 1980; Hassouba, 1995; Cattaneo and Steel, 2003; Dillenburg and Hesp, 2009). This includes issues such as how Late Quaternary sea-level change and sedimentation can create geologic templates for modern coastal features (Riggs et al., 1995), the role of sediment availability in determining inner continental shelf morphology and coastal evolution (Schwab et al., 2000; 2013), and

the interpretation of bedform characteristics to understand sediment transport patterns, sources, and sinks (Goff et al., 2005). Using a large-scale, high-resolution dataset, we review and test existing interpretations of seafloor features, and offer different and alternative explanations for their origin and evolution; present new stratigraphic data to evaluate local relative sea-levels during the Late Quaternary; and interpret seafloor bedforms to provide new constraints on inner shelf sediment transport that influences coastal evolution.

2. Regional setting

The northeastern North Carolina coastal system (Fig. 1) is located within the Albemarle Embayment and contains a ~90 m thick, well-preserved Quaternary stratigraphic record (Mallinson et al., 2005; Mallinson et al., 2010, hereafter referred to as M2010). The Albemarle Embayment is a structural basin bounded by the Norfolk Arch to the north and the Miocene Cape Lookout High to the south (Brown et al., 1972). During the latest Quaternary, the embayment has been bounded to the east by a relict inter-stream divide, which is now occupied by the Outer Banks barrier islands (Mallinson et al., 2005). Pliocene and
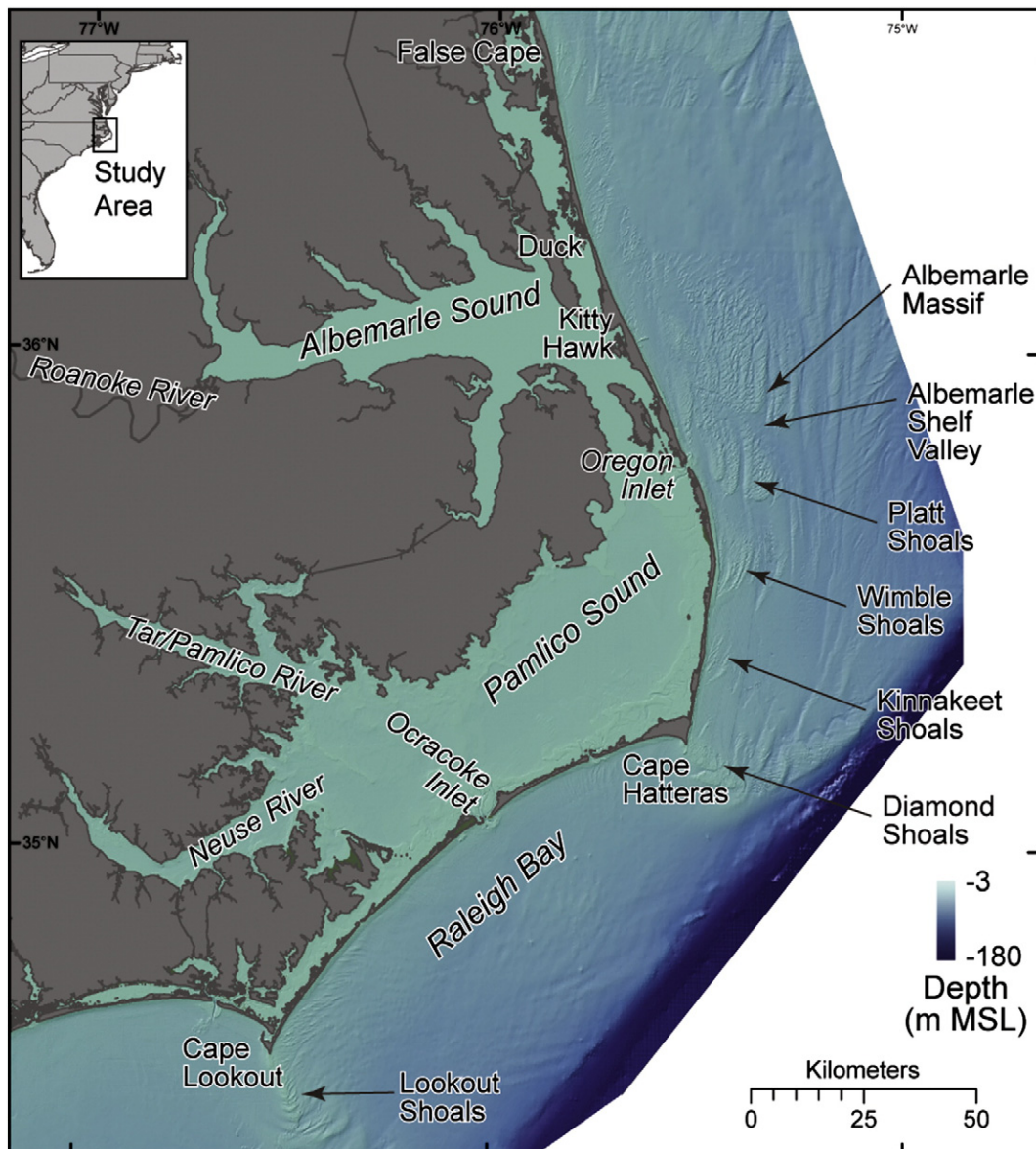

Fig. 1. Map of the study area in northeastern North Carolina. Bathymetry data is from the NOAA NGDC Coastal Relief Model (www.ngdc.noaa.gov/mgg/coastal/startcrm.htm) and this study.

Quaternary sequences dip and thicken toward the center of the basin, beneath northern Pamlico Sound. At the southern end of Pamlico Sound, the sequences thin onto an older antecedent high. Eighteen seismic sequences can be defined within the Quaternary section (Mallinson et al., 2005; M2010). M2010 mapped sequence boundaries and flooding surfaces to provide a three-dimensional perspective on the evolution of the basin fill.

The late Pleistocene stratigraphic units constitute the underlying geologic framework that the modern coastal system has inherited. Many coastal features, including inner shelf shoals, shore-oblique bars, and barrier islands reflect the influence of this framework (Riggs et al., 1995; McNinch, 2004; M2010). Barrier island segments, for example, have evolved in response to sediment supplied from three principal sources in the nearshore and inner continental shelf: paleofluvial channels, shoal complexes, and sand-rich Pleistocene sedimentary deposits. High and wide barrier island segments result from a large sediment supply. Barrier island segments lacking significant sediment supplies typically occur as simple overwash barriers (Riggs et al., 2009). Studies of the nearshore zone suggest a relationship between partial exposure of pre-modern, non-sandy substrates in the surf zone and bar morphodynamics, leading to the repeated occurrence of shoreline change hotspots (McNinch, 2004; Browder and McNinch, 2006; Miselis and McNinch, 2006; Schupp et al., 2006) and thus provide a direct link between the inner shelf geologic framework and coastal evolution.

The physical processes that characterize the study area are well known. Tides are semidiurnal with a mean range of ~1 m throughout the study area (Birkemeier et al., 1985; see also http://tidesandcurrents. noaa.gov/). Mean significant wave height over the period 1997–2012 was 1.0 ± 0.6 m, and mean period was 8.7 ± 2.8 s (http://www.frf. usace.army.mil/). Wave directions vary seasonally (Ashton and Murray, 2006). Currents and mean flows are an important component of the shelf circulation (Csanady, 1976; Lentz, 2008), including the Gulf Stream (Pietrafesa et al., 1985). Storms are most prevalent during the fall, winter, and spring (Birkemeier et al., 1985). Both extratropical (Wright et al., 1994; Kim et al., 1997) and tropical (e.g., Wren and Leonard, 2005) storms mobilize significant amounts of shelf sediment.

3. Materials and methods

We acquired approximately 9250 km of seismic, sidescan sonar, and bathymetric data along the inner shelf of North Carolina from False Cape, Virginia to Cape Lookout, North Carolina during eight research cruises between 1999 and 2008 (Fig. 2). The total surveyed area is 3100 km² and ranges in water depth from 6 m on the barrier island shoreface and across Diamond Shoals, to 38 m offshore of Cape Hatteras. For most of the study area, this includes the region from approximately 500 m seaward of the shoreline to 10 km offshore. Surveys were extended up to 19 km offshore to include Wimble Shoals and Diamond Shoals. Shore-parallel tracklines were generally spaced 300–325 m apart in the cross-shore direction, with shore-perpendicular ("tie") lines spaced approximately every 5 km in the alongshore direction. All navigation utilized differential GPS with an horizontal accuracy of 1–3 m. Details on most of these datasets are available in Thieler et al. (2013) or other published resources noted below and are summarized briefly here.

3.1. Seismics

Both chirp and boomer high-resolution subbottom profilers were used to map the shallow geologic framework (Fig. 2A). Chirp systems included a Teledyne Benthos (Datasonics) SIS-1000 north of Cape Hatteras and an Edgetech 512i offshore and south of Cape Hatteras. Boomer seismic reflection data were acquired using a Geopulse source, and ITI or Benthos hydrophone. These systems provided up to 100 m penetration at ~1 m vertical resolution. SIOSEIS software was used to process the seismic data for sea surface heave and water column noise. Further processing (e.g., bandpass filtering) utilized ProMAX
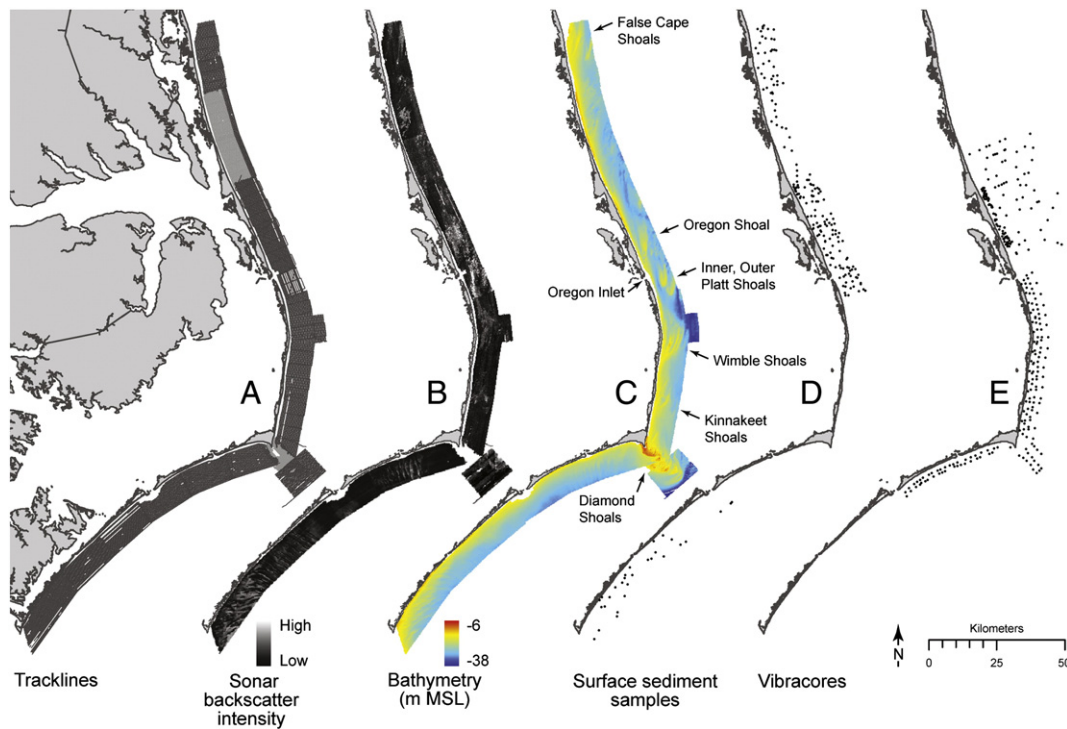

Fig. 2. Maps showing data used in this study. A) Tracklines for chirp and boomer seismic systems, sidescan sonar, and bathymetry systems. Dark gray indicates swath bathymetry, light gray indicates single-beam fathometer (off Duck and inner portion of Diamond Shoals). B) Sidescan sonar mosaic, depicting low acoustic backscatter (fine-grained sediments) as dark tones, and high acoustic backscatter (coarse-grained sediments) as light tones. C) Bathymetry compiled from swath and single-beam sources, with shoal features described in text identified. D) Locations of Van Veen surface sediment samples used to ground truth acoustic backscatter data. E) Locations of sediment cores collected by other studies, and made available by the North Carolina Geological Survey for this study.

and SeismicUnix software. Digitizing of seismic horizons and interpretations were done by using SeisWorks software.

3.2. Sidescan sonar

High-resolution sidescan sonar was used to provide complete acoustic backscatter coverage of the seafloor in the study area (Fig. 2B). Sidescan sonar systems included a Teledyne Benthos (Datasonics) SIS-1000 (100–120 kHz) north of Cape Hatteras and a Klein 3000 (100/500 kHz dual frequency) offshore and south of Cape Hatteras. These systems were towed behind the research vessel and used an acoustic ranging system and/or manual layback measurement to determine vehicle location relative to a shipboard GPS receiver. Sidescan-sonar data were logged digitally at a sample rate resulting in a 0.18-m pixel size in the across-track direction and approximately 0.14-m in the along-track direction following the methodology outlined in Danforth et al. (1991). Sidescan data were processed using a median filtering routine, and corrected for towfish altitude, slant range, and beam pattern artifacts (Danforth, 1997). Digital sidescan-sonar mosaics at a resolution of 2 m/pixel were created using PCI Geomatica software.

3.3. Bathymetry

Single-beam 200 kHz bathymetry data were collected in an 18.5 km^2 area offshore of Duck, North Carolina, and a 48 km^2 area across the inshore portion of Diamond Shoals (Fig. 2A). For the rest of the study area, swath bathymetry data were collected using a SEA, Ltd. SwathPLUS 234 kHz bathymetric sonar. Motion of the vessel (heave, pitch, roll) was recorded with a TSS DMS 2-05 motion sensor mounted directly above the SwathPLUS transducers. Trackline spacing resulted in roughly 30–40% areal coverage of the study area by the swath bathymetric sonar. Bathymetric data were corrected for variations in the speed of sound through the water column; sound velocity profiles were acquired throughout the survey area using an Applied MicroSystems SVPlus sound velocimeter. All soundings were processed and edited using SwathEd multibeam processing software. Water level variations due to tides were modeled and removed using the ADCIRC circulation model (Luettich, et al., 1992; Mukai et al., 2002). Offshore of Cape Hatteras, water levels were measured directly during the survey using real-time kinematic GPS. Tie lines were used to confirm tide corrections during post-processing. The processed data were interpolated to generate a continuous bathymetric surface at 40 m horizontal resolution and 0.1 m vertical resolution using GRASS (Geographic Resources Analysis Support System) GIS software (Fig. 2C).

3.4. Surface grab samples

To aid in the interpretation of acoustic datasets, surface sediment samples were collected at 202 stations on the inner shelf (Fig. 2D) by using a Van Veen grab sampler. Standard grain size analyses were conducted for size fractions and percent carbonate, following Poppe et al. (2005).

3.5. Sediment cores

Sediment cores from the inner shelf (Fig. 2E) were made available by the North Carolina Geological Survey from previously published studies (Hoffman and Brooks, 2001; Hoffman et al., 2001). Fifty-six cores were collected in 1996 on the inner and mid-shelf between Duck and just north of Oregon Inlet, of which 18 are located within our study area. Seventy-three cores were collected in 1995 on the inner shelf between Kitty Hawk and just north of Oregon Inlet. An additional 156 cores were collected in 1995 on the inner shelf from Oregon Inlet to Ocracoke Inlet, including Diamond Shoals. Cores were obtained by vibracoring using a 10 cm diameter barrel. Core lengths range from 0.5 to 6.15 m. Cores were logged for lithology and used to correlate with the seismic data.

Cores were also subsampled for radiocarbon age dating and amino-acid racemization analyses; some of these data are reported by Wehmiller et al. (2010).

Age assignments for seismic stratigraphic units, where possible, draw on initial correlations between seismic and core data by M2010. We also use amino-acid racemization (AAR) results from Wehmiller et al. (2010) to constrain the ages of seismic stratigraphic units. Using calibrations of AAR data with 87Sr/86Sr analyses, Wehmiller et al. (2012) confirmed the validity of the "non-linear model ages" proposed by Wehmiller et al. (2010; their Table 8 (column 1)), allowing more confident age assignments than those proposed in M2010.

4. Results

Our seismic interpretations follow the sequence stratigraphic terminology of Catuneanu et al. (2009). Designations for regionally continuous acoustic reflections follow complementary work in northeastern North Carolina by M2010. The descriptions in Sections 4.1 and 4.2 below are confined to the inner continental shelf study area. M2010 provide extensive discussion of the character of the reflections and seismic stratigraphic units, and correlations with sediment core and age data. Depths are given relative to mean sea level. Thicknesses of the seismic stratigraphic units are mapped in Thieler et al. (2013) and summarized here.

4.1. Regional geologic framework of the inner shelf

Four regionally-extensive seismic reflections were mapped across the inner continental shelf and the adjacent estuarine system (Fig. 3). M2010 presents these reflections and their interpretations for the estuarine system. We focus here on the inner continental shelf portion of the data set. The deepest reflection is designated Q0, and on the basis of micro- and macro-fossils sampled above and below the reflection, represents the Pliocene–Pleistocene boundary (see M2010 for discussion). On the inner shelf, the Q0 reflection dips southward from a depth of 45 m at False Cape toward the center of the Albemarle Embayment near Cape Hatteras (Figs. 3 and 4) and is recognized as a distinct angular unconformity. The reflection is 80 m deep just south of Kitty Hawk, and is deeper than our seismic data penetrates from just south of Kitty Hawk to near Cape Hatteras. At the southern end of the study area, the reflection shoals from a depth of about 70 m adjacent to Cape Hatteras to 20 m at Cape Lookout. M2010 interpreted Q0 as a submarine unconformity. The seismic stratigraphic unit overlying Q0 is designated SSU I by M2010. Fig. 4 shows that on the inner continental shelf north of Oregon Shoal, this unit is 30–60 m thick and is present at or near the sea floor. South of Cape Hatteras, SSU I decreases in thickness from 70 m near Cape Hatteras (A' in Fig. 4), to about 1 m just north of Cape Lookout (A in Fig. 4), and again is present at or near the sea floor. SSU I sediments are early Pleistocene in age (Wehmiller et al., 2010, 2012).

Reflection Q30 is mappable on the inner shelf from Kitty Hawk southward to just north of Cape Lookout (Fig. 3), and where present bounds the top of SSU I. This reflection dips eastward, from a depth of 14 m near Cape Lookout to a maximum of 60 m off the seaward end of Wimble Shoals. M2010 interpreted Q30 as a subaerial unconformity, with numerous incised valleys. One of these valleys is prominent on the inner shelf to the southwest of Cape Hatteras (designated Q30su on Fig. 4). A large cut-and-fill sequence penetrates Q30 just south of Ocracoke Inlet. SSU IV overlies Q30, and on the inner shelf reaches a maximum thickness of about 50 m beneath the inner portion of Wimble Shoals. This unit contains at least three distinct subdivisions of Pleistocene aminozone AZ3 (Wehmiller et al., 2010), which range in age from 170 to 770 ka.

Reflection Q50 extends from about 15 km north of Oregon Inlet, to just southwest of Ocracoke Inlet (Fig. 3), and dips eastward. On the inner shelf, Q50 is 15 m below sea level near Ocracoke Inlet, and 30–33 m deep at the seaward limit of the study area. North of Cape
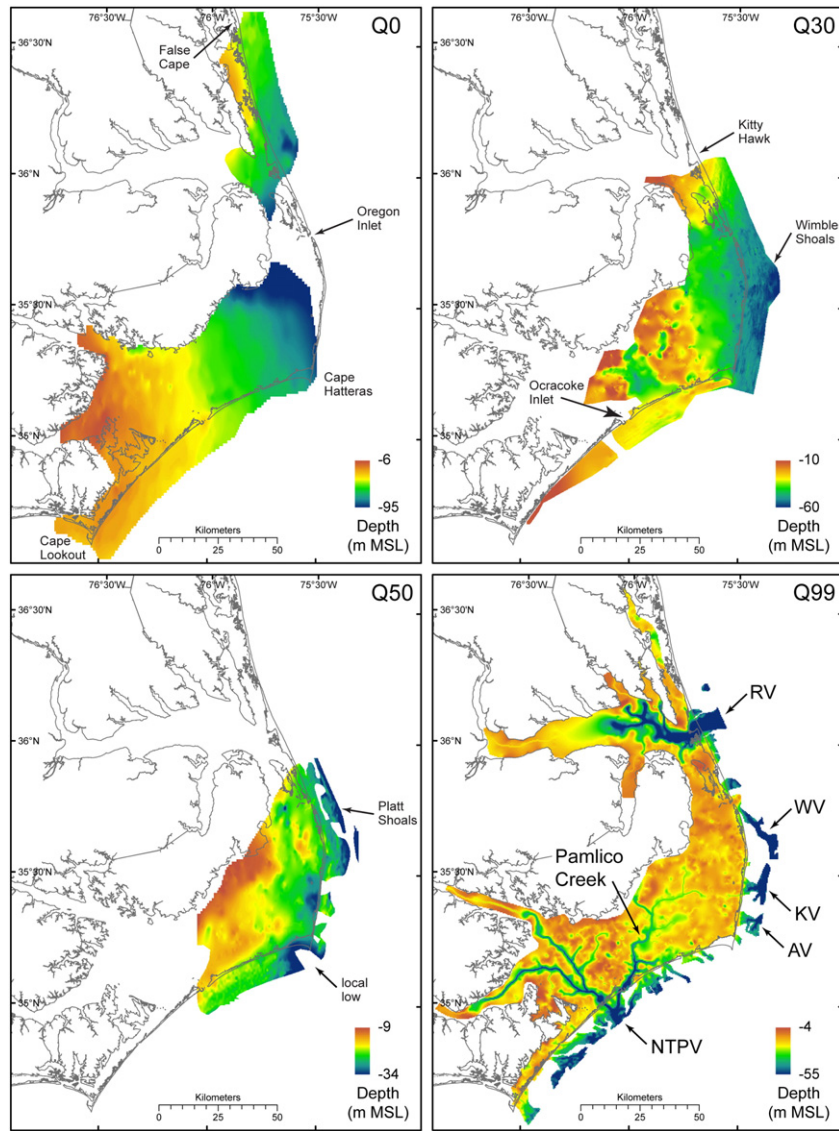
Fig. 3. Maps showing the depth of regional seismic reflections mapped in this study and by Mallinson et al. (2010). In Q99 panel, major paleofluvial valleys discussed in text are identified: RV = Roanoke Valley, WV = Wimble Valley, KV = Kinnakeet Valley, AV = Avon Valley, NTPV = Neuse-Tar-Pamlico Valley.

Hatteras, the areal continuity of Q50 is interrupted by several major incisions from overlying cut-and-fill sequences. Just west of Cape Hatteras, the Q50 reflection forms a local low that appears to open to the southeast (see arrow on Fig. 3), to the seaward limit of our data. M2010 interpreted Q50 as a transgressive ravinement surface. SSU V overlies Q50, and on the inner shelf its maximum thickness occurs beneath Diamond and Platt Shoals (Fig. 4). This seismic stratigraphic unit is characterized by extensive horizontally-bedded sediments, which cores indicate are estuarine and shelf sediments (M2010; Culver et al., 2011). Multiple fluvial incisions are also present within SSU V. Sediments in SSU V are late Pleistocene in age, ranging from 80 ka to ~160 ka.

The Q99 reflection (Fig. 3) is the most regionally extensive in the study area, and can be mapped from the upper reaches of the Albemarle–Pamlico estuarine system to the seaward limit of our study area. This reflection defines the base of the major paleo-fluvial valleys in the study area and is interpreted by M2010 as a subaerial unconformity. The depth of the reflection deepens seaward across the study area, and ranges from 5 m to 55 m. SSU VI overlies the Q99 reflection. These sediments have been studied extensively and are the basis for a detailed paleoenvironmental history from the Last Glacial Maximum

to the present (e.g., Mallinson et al., 2005; Culver et al., 2008). These valley systems are described in more detail below.

4.2. Shallow stratigraphy of Diamond Shoals

Geophysical data (Fig. 5) suggest that Diamond Shoals consists of unconsolidated modern sediment up to 8 m thick overlying a high-amplitude, continuous reflection that we interpret as a transgressive unconformity. The unconformity has variable relief, and is up to several meters shallower than the sea floor on the adjacent continental shelf; the transgressive unconformity thus defines a local high on top of which the modern sediment is deposited. Seismic profiles show extensive, well-layered sediments with an apparent dip to the southwest beneath the transgressive unconformity (Fig. 5, lines A-A', B-B', and C-C'). An additional layered unit with an apparent dip to the northeast (Fig. 5, lines A-A' and B-B') unconformably overlies these sediments. This unit is only intermittently visible across the middle portion of the shoal, due principally to being obscured by sea floor multiples.

The acoustic signature of these sediments is similar to those mapped as Pleistocene on the inner shelf, but their elevation lies well above the prominent Pleistocene Q50 surface (Fig. 3) described above. Due to the
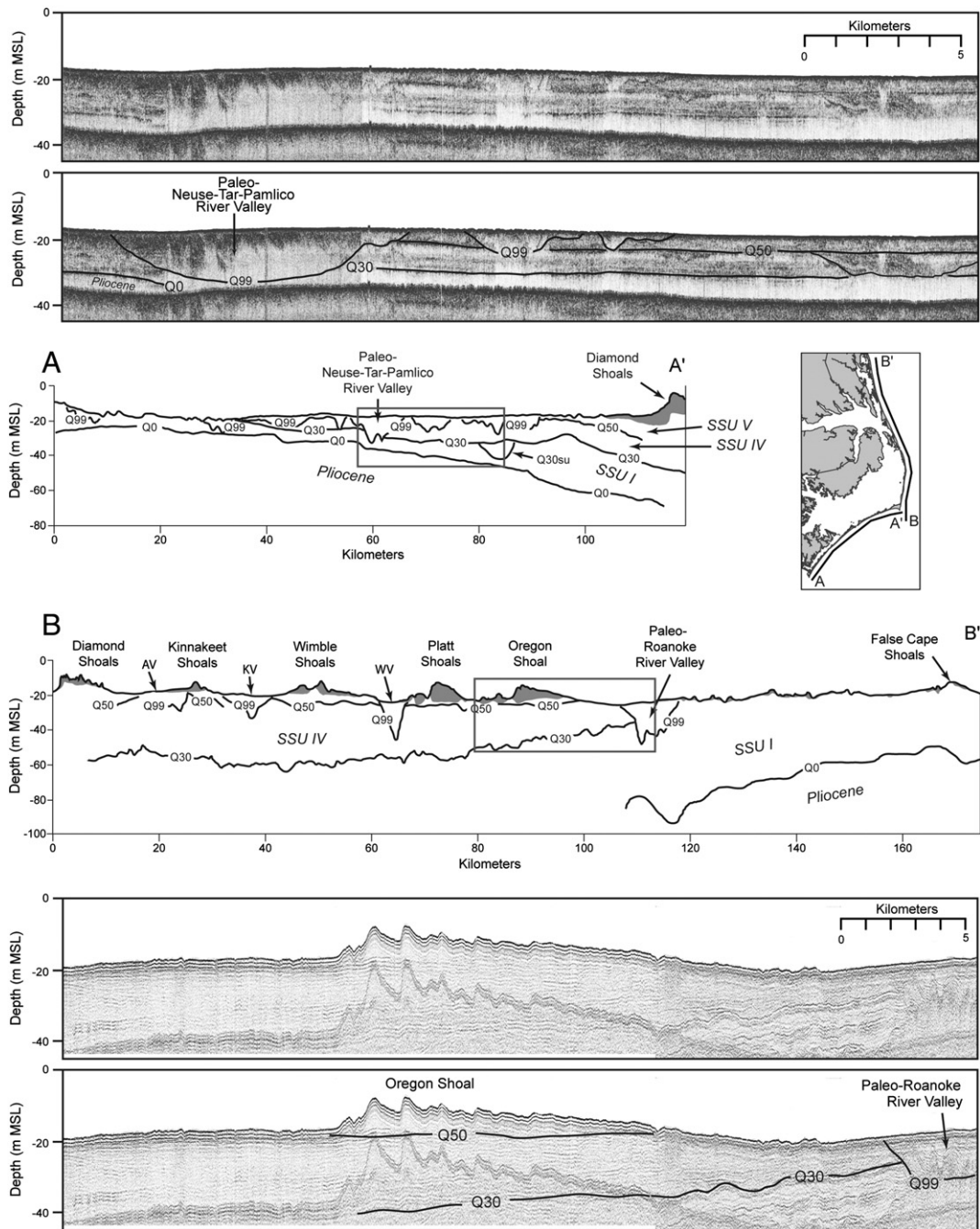
Fig. 4. Interpreted seismic sections (A-A', B-B') for the inner shelf study area, showing major seismic reflections and names of seismic stratigraphic units following Mallinson et al. (2010). Gray shaded areas in interpreted sections indicate Holocene sand bodies. On section B-B', AV = Avon paleo-fluvial valley, KV = Kinnakeet paleo-fluvial valley, WV = Wimble paleo-fluvial valley. Seismic data above interpretations is chirp data for boxed area shown in A-A'. Seismic data below interpretations is boomer data for boxed area shown in B-B'.

lack of seismic data that would link Diamond Shoals to the rest of the inner shelf study area, we are unable to confidently assign these sediments to existing mapped seismic stratigraphic units.

4.3. Major paleo-fluvial valley systems

The major paleo-fluvial valleys in the study area are associated with the Roanoke, Tar-Pamlico, and Neuse Rivers. Of these, the Roanoke is the largest and the only Appalachian-sourced river; the others originate in the Piedmont. The paleo-Roanoke (hereafter, Roanoke Valley, RV) is the largest valley system in the study area. The RV passes beneath and orthogonal to the modern barrier islands at Kitty Hawk (Boss et al., 2002; Mallinson et al., 2005; Browder and McNinch, 2006; this study).

The valley ranges in width from 8 to 9 km as it crosses the inner shelf, and is incised to up to 55 m below sea level at the seaward limit of our study area. Cores from the inner shelf and adjacent barrier island contain a wide variety of fluvial and estuarine sediments that have been used to reconstruct the Holocene rise of sea-level in this region (Horton et al., 2009) and related climatic changes (Culver et al., 2008).

At least three well-defined paleo-fluvial valleys exist between Oregon Inlet and Cape Hatteras (Fig. 3). These valleys originate beneath the modern barrier islands, and deepen seaward, dissecting the underlying seismic stratigraphic units described above and defining the seaward perimeter of Wimble Shoals, Kinnakeet Shoals, and the northern flank of Diamond Shoals. The valley on the northern side of Wimble Shoals (hereafter, Wimble Valley, WV) averages
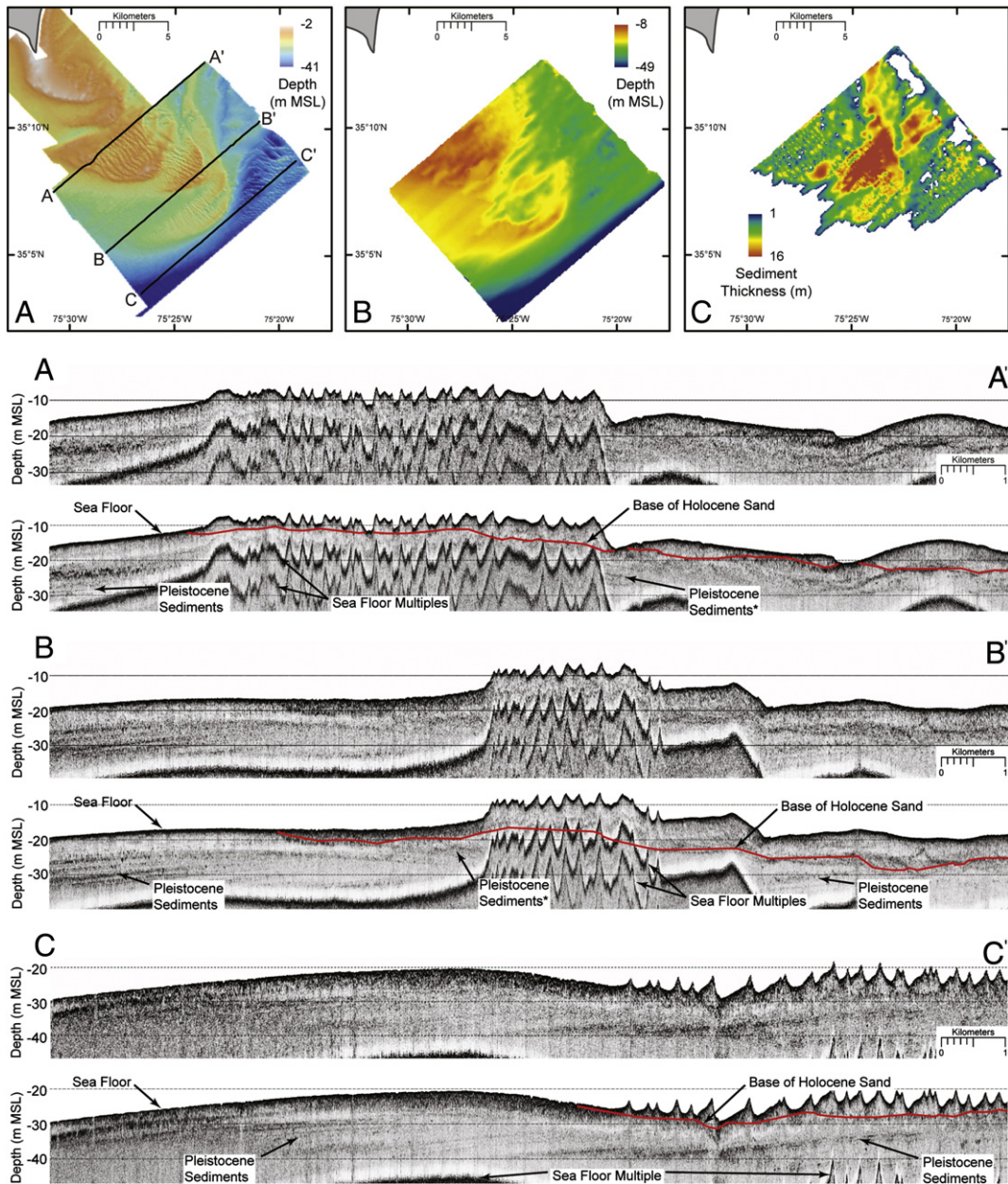
Fig. 5. Maps and seismic data for Diamond Shoals. A) Bathymetry of Diamond Shoals and locations of representative chirp seismic data shown below. B) Map showing depth to the top of the interpreted Pleistocene–Holocene unconformity at the base of the Holocene sand. The surface has variable relief. C) Map showing interpreted thickness of Holocene sand above the Pleistocene unconformity. Sand thickness is not determined solely by the depth to the unconformity (i.e., the modern shoal is a depositional feature with positive relief). Seismic lines show interpreted Holocene–Pleistocene unconformity as a red line. Inferred Pleistocene sediments marked with an asterisk (*) have an apparent dip to the northeast. See text for discussion.

3 km in width, and traces to the southeast, then to the south around the seaward end of the shoals. The base of the WV is up to 43 m below sea level. The valley located between Wimble Shoals and Kinnakeet Shoals (hereafter Kinnakeet Valley, KV) bifurcates about 6 km offshore of the modern barrier islands, with 2.5–3.5 km wide valleys up to 34 m below sea level tracing northward toward the WV at the seaward end of Wimble Shoals, and to the south. The valley on the southern side of Kinnakeet Shoals (hereafter Avon Valley, AV) meanders to the northeast, and is joined on its southern side by a broad tributary valley that also traces to the northeast.

Seismic data from the WV, KV and AV clearly show fluvial incisions and backfill with estuarine facies (Fig. 6), consistent with seismic facies from similar incised valley systems elsewhere on the U.S. Atlantic margin (Nordfjord et al., 2006) and the estuary facies models of Dalrymple

et al. (1992) and Reinson (1992). The estuarine fill is acoustically laminated and up to 5 m thick. Core data (Fig. 7) show interlaminated estuarine sandy mud, muddy sand, mud, and oyster (*C. virginica*) bioherms. Radiocarbon ages on oyster specimens sampled from the bioherms range from ~9800 to 6700 cal yr BP, with age decreasing up-section. These data indicate the former presence of emerged lands seaward of the WV, KV, and AV that provided a protected estuarine environment, although our data do not allow us to distinguish between fronting barrier islands or mainland coast.

Several small valley systems originate just landward of the modern barrier island between Cape Hatteras and Ocracoke Inlet. These valleys are 2–3 km wide, and deepen seaward up to 34 m below sea level.

A drainage system defined by the Q99 reflection in central Pamlico Sound is termed Pamlico Creek by M2010. Fig. 3 shows the Pamlico Creek valley coalescing with the Tar-Pamlico and Neuse valleys on the
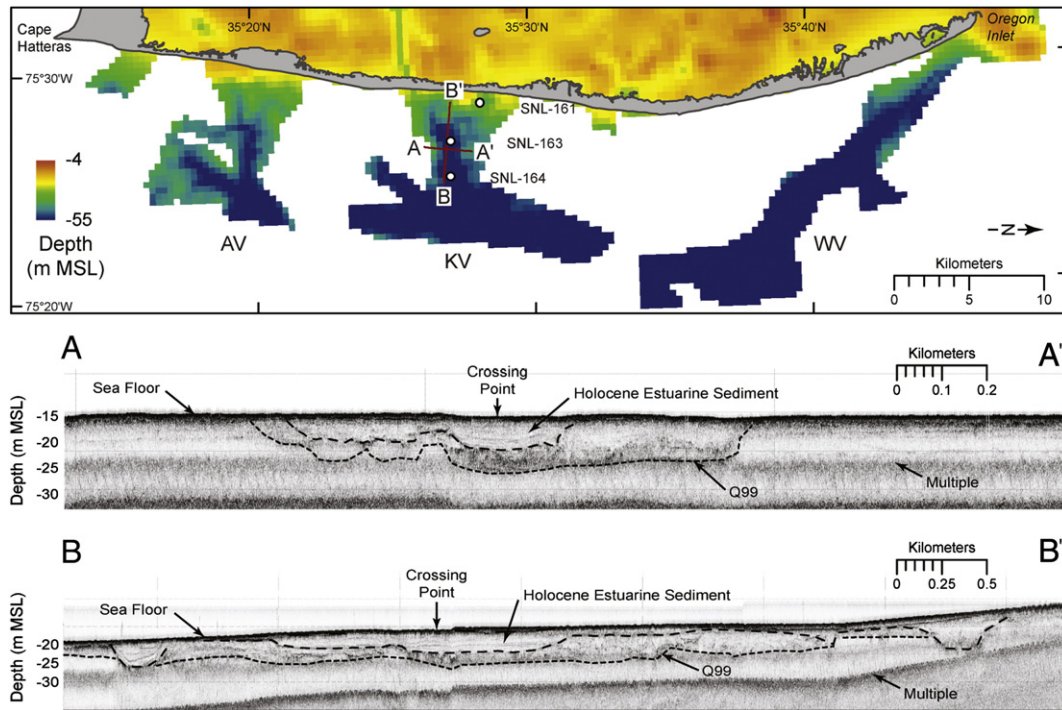
Fig. 6. Map and interpreted chirp seismic data showing the depth of fluvial incision and fill of the three major paleovalley systems off Hatteras Island. AV = Avon paleo-fluvial valley, KV = Kinnakeet paleo-fluvial valley, WV = Wimble paleo-fluvial valley. Location of seismic lines A-A' and B-B' are shown on the map.

inner shelf to the southwest of Ocracoke Inlet. An additional small valley that originates on the inner shelf joins at the northeastern side of the confluence of the Neuse, Tar-Pamlico, Pamlico Creek valleys (hereafter Neuse-Tar-Pamlico Valley, NTPV). The NTPV system is 6–7 km wide and deepens to 38 m below sea level at the seaward edge of the study area. The northern of the two valleys traces to the east, towards the NTPV. The southern valley appears to bifurcate and deepens up to 32 m below sea-level both to the northeast and the southwest.

Two additional valley systems, comparable in size to those between Cape Hatteras and Oregon Inlet, traverse the study area offshore of Core Banks. Fig. 3 shows these valleys originating just landward of the barrier island, meandering and becoming wider (2.5–3.5 km) and deeper (up to 32 m below sea level) seaward.

The southernmost paleo-fluvial valley system we mapped is just north of Cape Lookout (Fig. 3). This valley is poorly defined, but appears to originate to the west of Core Banks in Back Sound. The valley traces a 5–6 km wide path to the southeast and deepens to 26 m below sea level.

4.4. Sea floor sediment texture, morphology, and Holocene marine sediment distribution

Based on broad relationships between sonar image intensity and surficial sediment grab samples, the sidescan sonar imagery of the study area (Fig. 2) shows high acoustic backscatter as light to white-colored (image intensity values greater than about 155 on an 8-bit
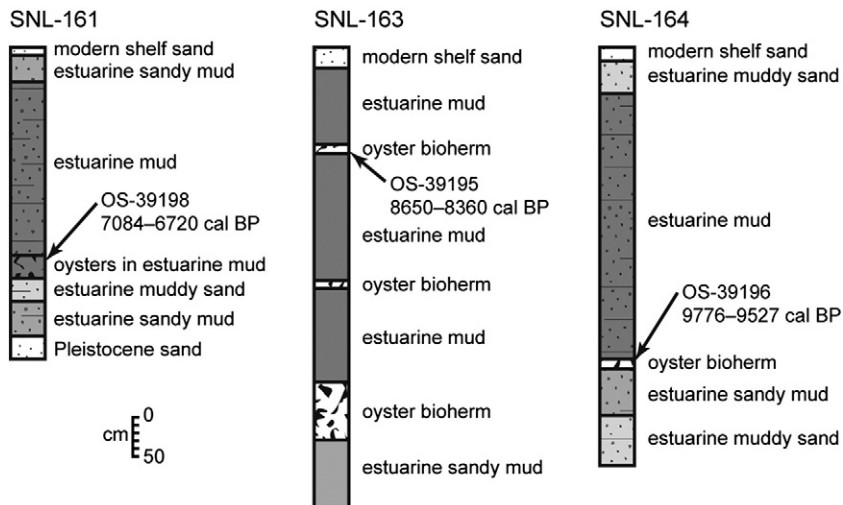

Fig. 7. Interpretive diagrams for three vibracores from the Kinnakeet paleo-fluvial valley off Hatteras Island. Core locations are shown on Fig. 6. The cores show typical estuarine sequences that comprise the valley fill.

scale from 0 to 255 where 0 is black and 255 is white), which generally corresponds to medium sand and coarser, as well as rock outcrops. Low acoustic backscatter is depicted as dark gray to black (image intensity values less than about 95), and corresponds to fine-grained sand and mud. VanVeen grab samples (Fig. 2; Thieler et al., 2013) provide ground-truth for the backscatter patterns. Bathymetry across the inner shelf varies regionally, and is used to define prominent morphologic elements of the inner shelf. Chirp seismic data allow the delineation of sediment deposits greater than 1 m in thickness. Fig. 8 shows the interpreted thickness of Holocene marine sediment throughout the study area.

Large-scale bedforms are present over broad areas of the inner shelf, including both the tops of the shoals and the intervening swales. The bedforms have wavelengths of 10–300 m, heights of 1–2 m, and reflect the energetic physical oceanographic regime of this region (Swift and Freeland, 1978). Two deep swales trending roughly N-S are present between Kitty Hawk and Oregon Inlet. The swales are floored with coarse-grained sediment. Bedforms are also present in the swales, including a field of well-organized sand waves lining the seaward edge of the swale off Wimble Shoals (Figs. 2 and 8).

Modern sedimentary features in the study area show substantial mobility at decadal to centennial timescales. For example, Swift et al.
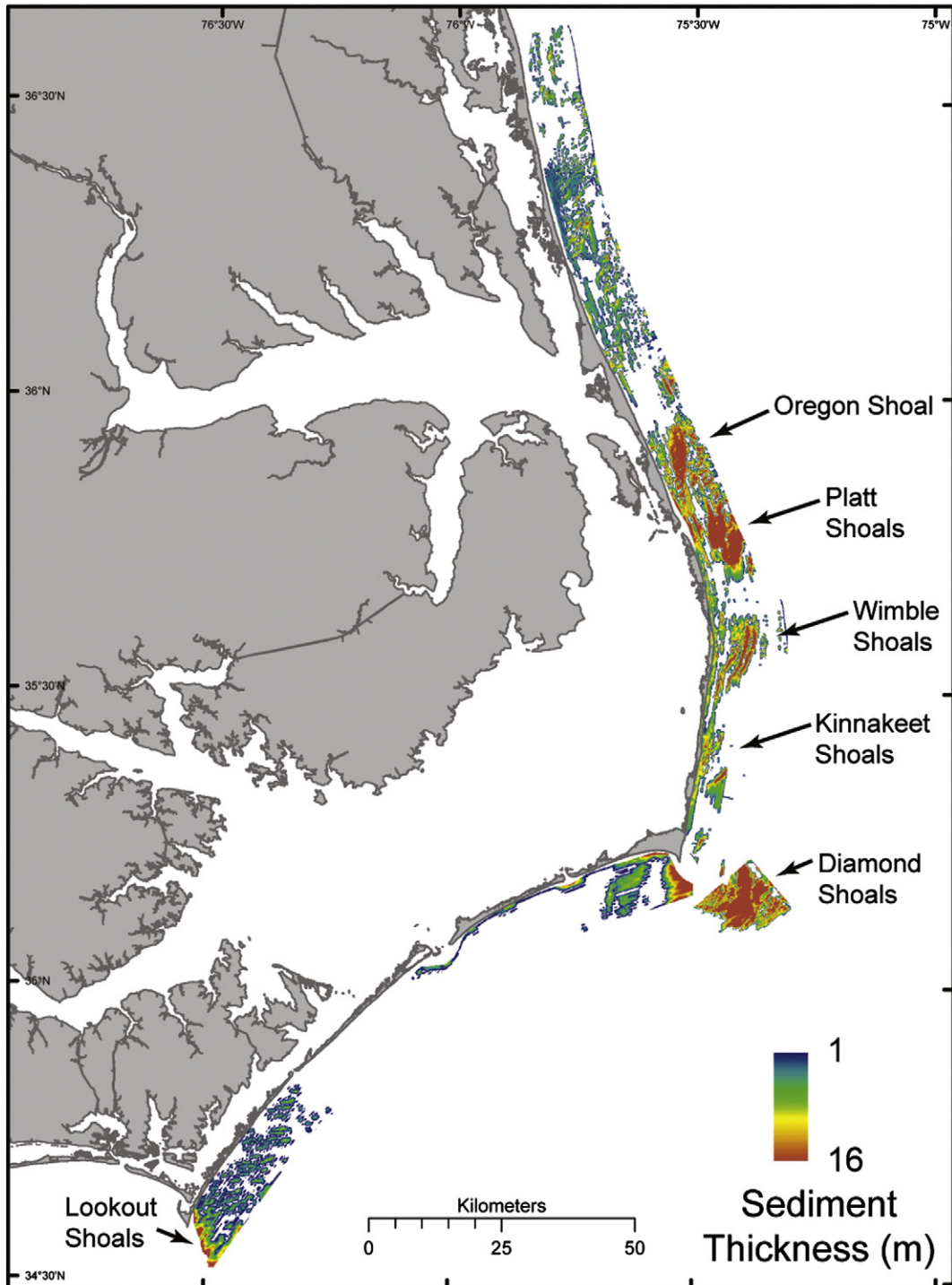

Fig. 8. Map showing the interpreted thickness of Holocene sand in the study area. Major shoal features discussed in text are identified.
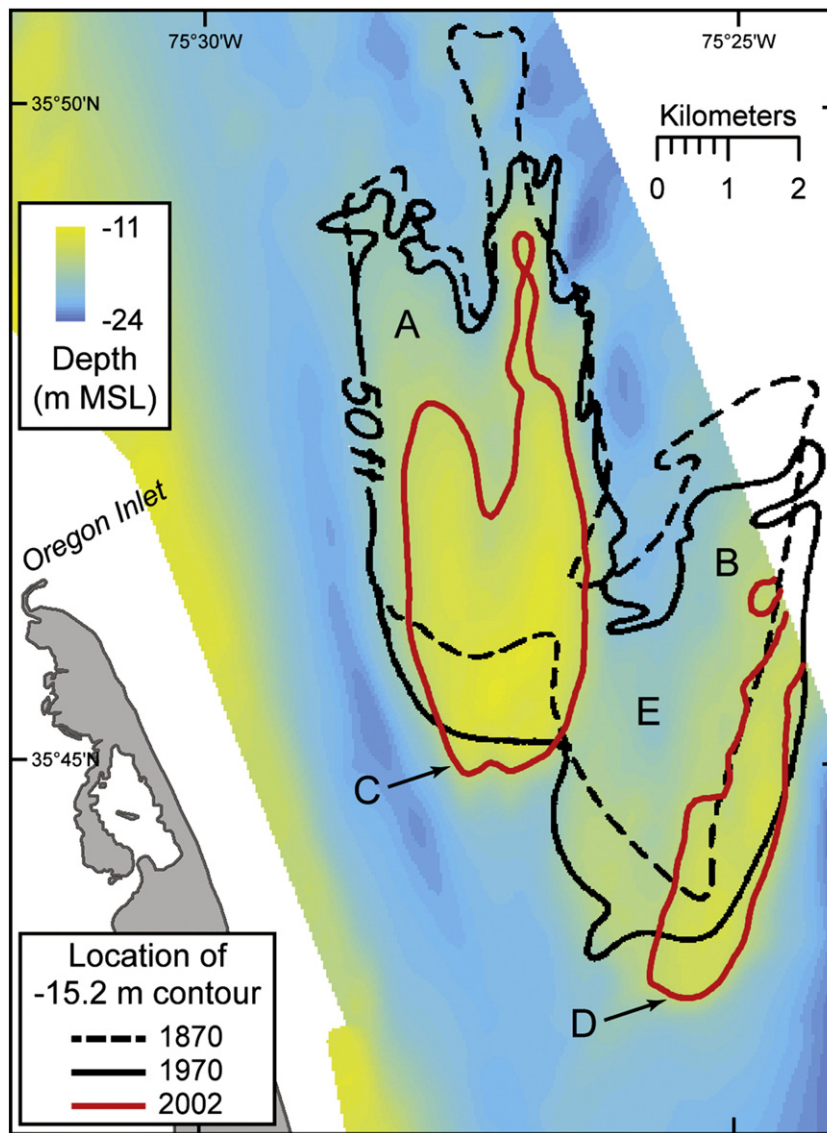
Fig. 9. Map showing bathymetry of inner and outer Platt Shoals and changes in the −15.2 m contour from 1870 to 2002. Distances of southward movement: A = 3 km; B = 2.5 km; C = 0.5 km; D = 0.75 km. E = 3 m of deepening (sea floor erosion). (1870 and 1970 contours from Swift et al., 1978.).

(1978) previously documented nearly a kilometer of southeastward extension of Platt Shoals over the period 1870–1970. Our data (Fig. 9) extends this record another 32 yr and indicates not only continued southward migration but also a potential loss of sediment volume from the shoals, as inferred by the reduced area enclosed by the −15.2 m depth contour. The central swale between inner and outer Platt Shoals also appears to have deepened by about 3 m and extended southward since 1970. Although there is substantial positional and depth uncertainty in the older bathymetric data, some of the changes greatly exceed even very conservative estimates (tens of meters) of mapping accuracy.

Similar patterns are evident on Wimble Shoals over the past 134 yr (Fig. 10). Based on movement of the 11 m depth contour, the shoreface here appears to have steepened, the inshore ridge has reduced in area, and an outer ridge has both shortened and migrated seaward about 500 m.

4.4.1. False Cape to Kitty Hawk

The sea floor from False Cape to Kitty Hawk can be characterized as a largely patchy veneer of fine-grained, Holocene sediment overlying Pleistocene sediments. Regions of high acoustic backscatter generally correspond to areally extensive outcrops of Pleistocene sediments (see

Fig. 4) or "windows" between Holocene fine sediment accumulations that expose the ancient sediments. Near the RV (Figs. 3 and 4), the coarse fraction of the sea floor sediments is dominated by river gravels (e.g., Schupp et al., 2006), and elsewhere by worn shell and rock fragments derived from the extensive Pleistocene units on the shelf.

The seafloor morphology in this region (Fig. 2) exhibits a series of shore-oblique ridges that seismic data indicate are composed largely of Holocene sand (Fig. 8). The ridges are best-defined at False Cape, where some are comprised at least in part of older sediments (Swift et al., 1972; Robinson and McBride, 2008), but are also present southward to Kitty Hawk. The ridges are irregularly-spaced, oriented to the NNE with opening angles from 35 to 50° relative to the average shoreline orientation, and are up to 4 m higher than the surrounding sea floor. The thickest accumulations of Holocene sediment in this region occur in the middle of the inner shelf study area, in two ridges located about 10 km northeast of Duck (Fig. 8).

4.4.2. Kitty Hawk to Cape Hatteras

This region of the seafloor contains the major shoal features in the study area, including Oregon Shoal (name following Swift et al., 1973), Platt Shoals, Wimble Shoals, Kinnakeet Shoals, and Diamond Shoals.
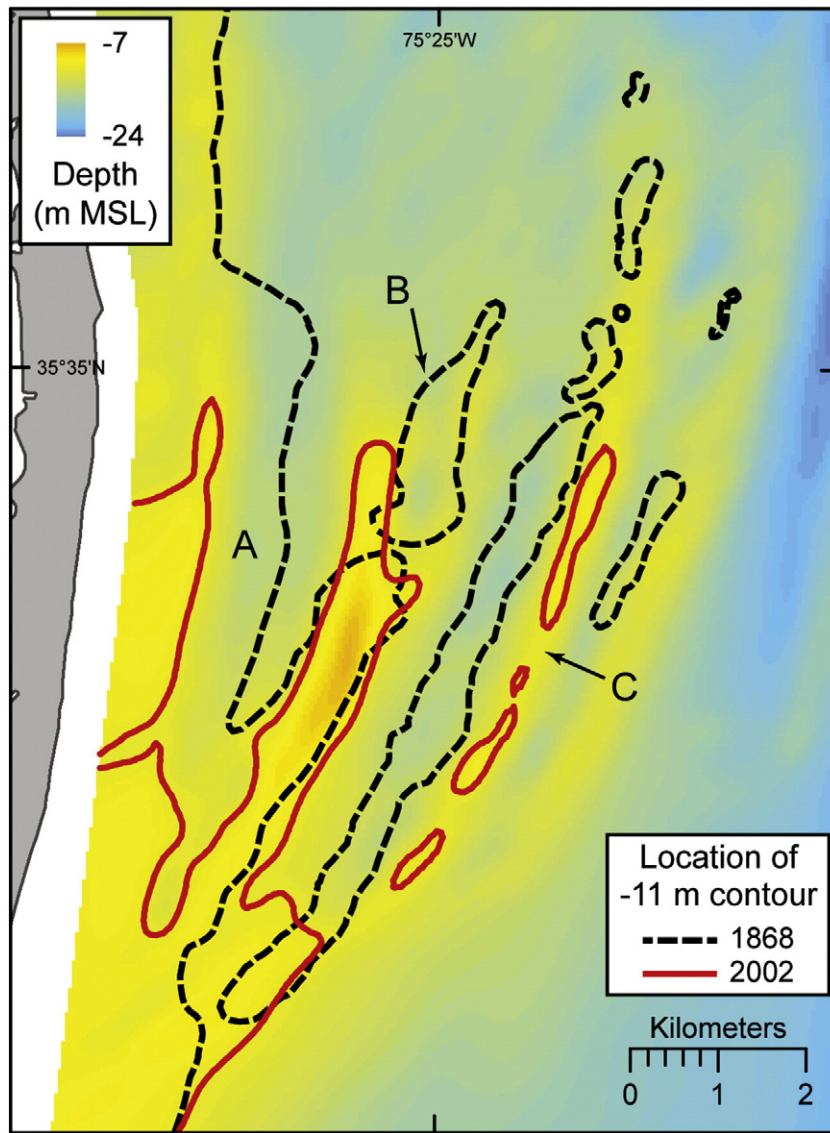
Fig. 10. Map showing bathymetry of Wimble Shoals and changes in the −11 m contour between 1868 and 2002. A = increase in shoreface steepness. B = 2 km reduction in shoreface-attached ridge length. C = 2.5 km reduction in shoreface-attached ridge length and seaward migration of 500 m. (1868 data from National Ocean Service.).

Oregon Shoal is an unconsolidated sand body located just north of Oregon Inlet (Fig. 2). The shoal forms a roughly elongate triangular to chevron shape that is 15 km long and 3 km wide, with the tip pointing southward. The shoal covers approximately 34 km² in water depths

from 19 up to 10 m below sea level, and slopes upward to the south. On its northwestern side, it is separated from the barrier island shoreface by a swale up to 19 m deep. Near its southern tip, the shoal merges with the shoreface on the northern side of Oregon Inlet as a
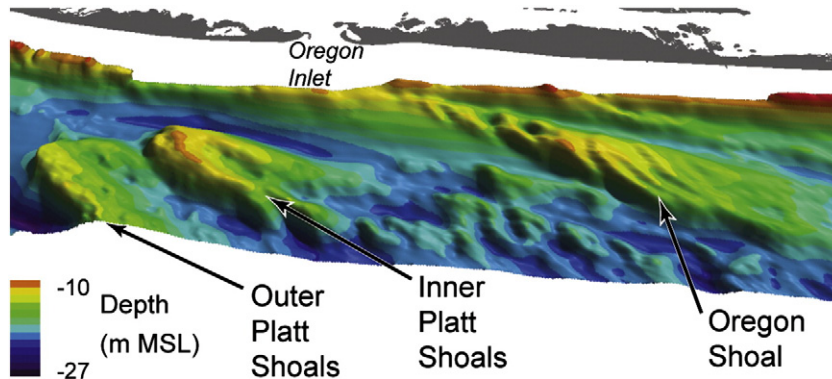

Fig. 11. Perspective view of shaded-relief bathymetric data for Oregon Shoal, and Inner and Outer Platt Shoals, looking west towards Oregon Inlet. The field of view is approximately 30 km wide, and the across-shore width of the data is 10 km. Vertical exaggeration is 100.

series of large sand waves (Fig. 11). The surface of the shoal is covered with 1–1.5 m high crescentic sand waves with wavelengths of 400–1000 m. Backscatter data shows surface sediments are generally coarse, although the southern tip is characterized by fine sediment.

Platt Shoals is a sand body that can be divided into inner and outer sections. Inner Platt Shoals (Fig. 2; Fig. 11) is chevron-shaped, 8.5 km long and 3 km wide, with the tip pointing southward. Its surface slopes upward to the south from 19 up to 11 m below sea level. Backscatter and bathymetry data indicate the presence of low-amplitude (<50 cm) sand waves with a wavelength of ~500 m on the surface of the shoal. Most of the shoal is covered by fine sediment. Outer Platt Shoals is similar in size and surficial morphology to Inner Platt Shoals, but is lower, and forms an asymmetric chevron shape that is shorter on its western side.

Wimble Shoals is a major morphologic element in the study area (Fig. 2), encompassing an area of approximately 150 km^2 that extends approximately 15–17 km alongshore and up to 10 km offshore. The shoal is five times larger than the adjacent shoals, and similar to Diamond Shoals (a major cape-associated shoal) in areal extent. The location of Wimble Shoals corresponds to a change in barrier island shoreline orientation and has been called a minor cape (Riggs et al. 1995). Seismic data (Fig. 4) suggest that the core of Wimble Shoals is composed of late Pleistocene sediments corresponding to SSU IV described above. This core provides a platform that rises several meters above the surrounding sea floor on which are five large, shore-oblique ridges (Fig. 12). Four inshore ridges appear to coalesce and originate from a ~5 km-long zone of shoreface attachment at the southern end of the shoal and have arcuate openings to the north-northeast. The seaward-most ridge is detached from the main body of the shoal. The ridges are 10–13 km long, ~500 m wide, and up to 7 m high. Seismic data indicate that the ridges are composed of unconsolidated Holocene sand (Fig. 8). The northern portion of the shoal is covered by coarse-grained sediment. The surface of the ridges is fine-grained, with coarse sediment predominating in the intervening swales.

Kinnakeet Shoals is comprised of four shore-oblique, shoreface attached ridges, overlying a rough topography that includes apparent rocky outcrops visible in the sidescan sonar backscatter (Thieler et al., 2013). The ridges are 4–8 km long, but are somewhat discontinuous. Crest heights vary from 2 to 5 m along and between ridges. The ridges appear to be composed predominantly of Holocene sand (Fig. 8), with swales dominated by coarse sand and apparent rock outcrops.

The area of Diamond Shoals that we surveyed (Figs. 2 and 5) is approximately 330 km^2 and extends from ~400 m seaward of the shoreline comprising the cape tip to 20 km offshore, where the shoal terminates in approximately 40 m water depth. The main body of the shoal consists of a 7 km^2 triangular central platform that extends 8 km southeast from the cape tip. The top of the platform is at a water depth of 2–5 m below sea level and is mantled by symmetrical sand waves with crest directions that trend NW-SE. The sand waves have a wavelength of ~300 m, and amplitudes up to 4 m. The central platform is bounded by two large lobate ridges and swales in water depths of 10–20 m. The ridges are ~5 m high, 1.5 km wide, and are more pronounced on the northern side of the shoal. As noted in Section 4.3, Holocene sediment is up to 8 m thick across the central portion of the shoals. The ridges on the northern side of the shoal are covered by coarse sediment. Sand waves similar to those on the central platform are superimposed on the ridges, but are asymmetrical and indicate northeastward-directed sediment transport over the ~10-day period of the survey in this area.

4.4.3. Cape Hatteras to Cape Lookout

The inner shelf in Raleigh Bay between capes Hatteras and Lookout can be characterized as an extensive field of sorted bedforms (Murray and Thieler, 2004), covering about 1000 km^2. The bedform field begins about 10 km west of Cape Hatteras and can be divided into four distinct regions based on bedform characteristics (Fig. 13). From 10 km west of Cape Hatteras to Ocracoke Inlet (Fig. 13, region A), the sorted bedforms are shore-perpendicular, have a wavelength of ~1.5 km, and heights of 0.75–1.5 m. They are moderately asymmetric, with the steeper, coarse-grained flanks facing to the southwest (Fig. 14B). In north-central Raleigh Bay (Fig. 13, region B), the presence of sorted bedforms is indicated by the backscatter data as the characteristic coarse and fine sediment domains with a slightly shore-oblique orientation, but the bedforms have very low amplitude (less than 50 cm) that is visible in raw acoustic data. These data indicate that the coarse sediment domains face to the northeast on a slightly steeper bedform flank than that of the fine sediment domains. In south-central Raleigh Bay (Fig. 13, region C), the sorted bedforms become larger and better-organized towards the southwest, converging on a wavelength of approximately 700 m and height of 0.5–1.5 m. They are also asymmetric with the steeper, coarse flank facing to the northeast. In southern Raleigh Bay (Fig. 13, region D), sorted bedform crests and troughs become less continuous, their orientation becomes increasingly shore-oblique towards Cape Lookout, and they have a morphologic expression consistent with shoreface-attached ridges. The sea floor in this region is also characterized by widespread coarse sediment. However, the sorted bedform morphology is still apparent, with coarse sediment present in bedform troughs and
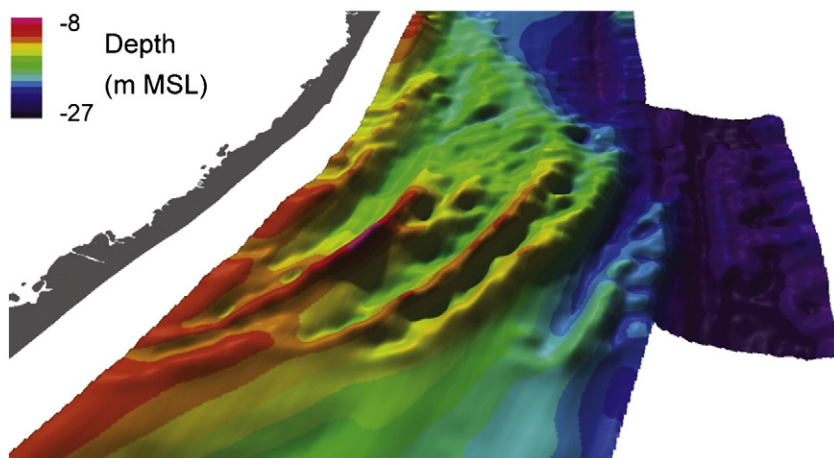

Fig. 12. Perspective view of shaded-relief bathymetric data for Wimble Shoals, looking north. Five distinct shore-oblique ridges are evident. The across-shore width of the data is 13.5 km. Vertical exaggeration is 100.
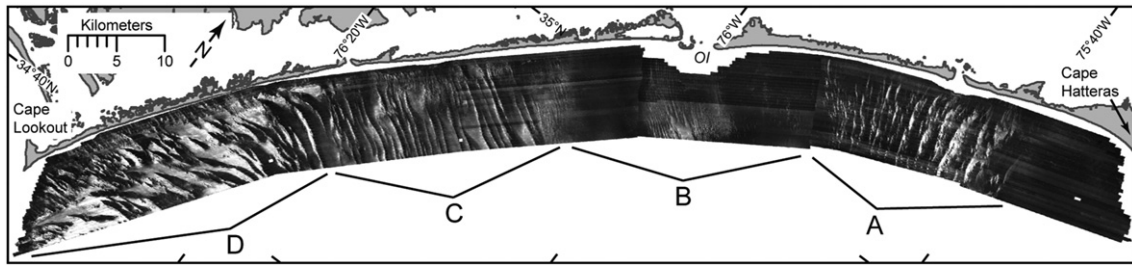
Fig. 13. Map showing sidescan sonar mosaic of Raleigh Bay, between Capes Hatteras and Lookout, and four distinct regions of sorted bedforms described in text. Low acoustic backscatter is depicted as dark tones and corresponds to fine-grained sediments; high acoustic backscatter is depicted as light tones and corresponds to coarse-grained sediments. OI = Ocracoke Inlet.

on northeast-facing flanks of the ridges. Fine sediment covers bedform/ridge crests and all southwest-facing flanks (Fig. 14A).

5. Discussion

The regional geologic framework of the northeastern North Carolina inner continental shelf substantially influences the evolution of coastal environments in the study area; the morphology of the shelf; the sources, composition, transport, and sinks of sediment; and the morphology of the adjacent barrier islands and cuspate forelands. Here we discuss aspects of the geologic framework that provide new insight into the late Quaternary evolution of this coastal system, and their implications for coastal evolution on passive margin barrier island coasts more generally.

5.1. Regional geologic framework of the inner shelf

In an early study of the seismic stratigraphy of this area, Shideler et al. (1972) mapped a regionally-extensive reflection surface (their R1) and proposed, in the absence of direct age control, that it represented the Miocene and post-Miocene boundary. We interpret their R1 as being the same reflection that we and M2010 mapped as Q0 (see Fig. 3), and determined through correlation with regional core data to correspond to the Pliocene–Pleistocene boundary (M2010; Culver et al., 2008; 2011). M2010 proposed relationships between regional Pleistocene stratigraphy and sedimentation that resulted from changes in the magnitude of sea-level fluctuations in the mid- to late-

Pleistocene, and represent the early Pleistocene eastward and vertical development of this portion of the continental margin, progressing from relatively deep outer shelf to coastal depositional environments. The geophysical interpretations we present here are consistent with M2010, and expand this information onto the inner continental shelf. M2010 also recognized additional reflections and units (Q10, Q20; SSU II and SSU III) that we are unable to delineate with confidence on the inner shelf. Thus, we focus principally on those elements of the stratigraphic record for which we have more complete information.

5.2. Pleistocene sediments underlying Diamond Shoals

We interpret the transgressive unconformity underlying the modern sand on Diamond Shoals (Fig. 5) as the Holocene ravinement unconformity. Sediments beneath this ravinement unconformity are presumably Pleistocene in age. One interpretation is that the sediments represent the uppermost portion of SSU V. M2010 suggested that SSU V is late Pleistocene in age and contains estuarine, shelf, and valley-fill sediments deposited during Marine Isotope Stage (MIS) 5. Due to the limits of areal coverage and seismic attenuation, correlating the Diamond Shoals sediments with those more landward on the inner shelf and those mapped in Pamlico Sound by M2010 is difficult. There is, however, an approximately 10 m thick section present between the top of the Q50 surface and the interpreted top of the Pleistocene sediments in Diamond Shoals (Fig. 4) that may represent SSU V.

The apparent dip of these sediments changes up-section, as described above. Fig. 5 (profile B-B') shows this change in apparent dip
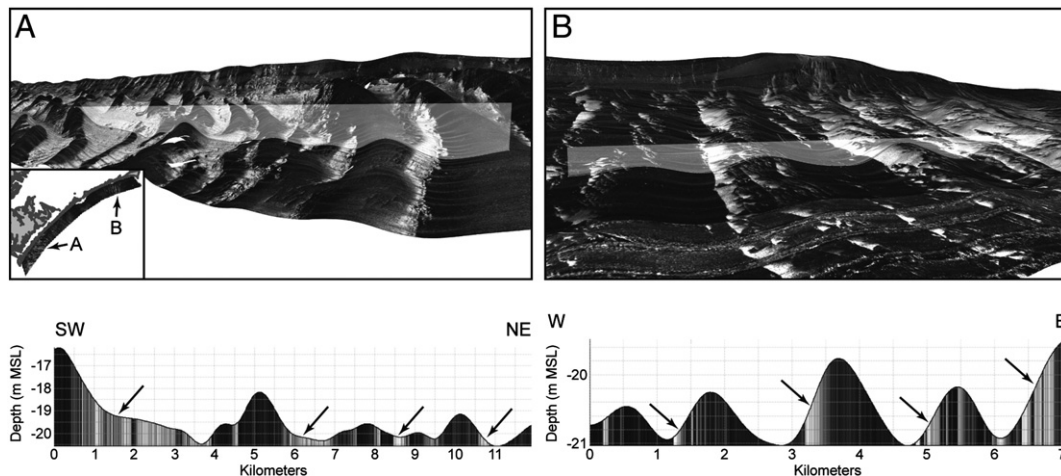

Fig. 14. Perspective views of bathymetry and sidescan sonar data, and bathymetric/backscatter profiles across sorted bedforms at the northern and southern ends of Raleigh Bay. Inset map shows location and look-direction of views in A and B. A) Portion of region D identified in Fig. 13, looking to the west from offshore. Vertical exaggeration is 200. Shaded area on perspective view is vertical section presented as profile below. The area under the profile shows the relative sea floor acoustic backscatter along the profile. Arrows indicate coarse sediments on the lower portions of the northeast-facing flanks of the sorted bedforms in this region. B) Portion of region A identified in Fig. 13, looking to the north-northeast from offshore. Vertical exaggeration is 200. Shaded area on perspective view is vertical section presented as profile below. The area under the profile shows the relative acoustic backscatter along the profile. Arrows indicate coarse sediments on the southwest-facing flanks of the sorted bedforms in this region.

from deeper sediments dipping southwestward, to shallower sediments dipping northeastward (in profile A-A', the contact at the dip change is obscured by the sea floor multiple). We interpret this change in apparent dip to reflect lateral shifting of the high beneath Diamond Shoals.

An alternative interpretation is that some or all of these sediments are younger than SSU V (late Pleistocene, MIS 5), and were deposited during MIS 3. Several pieces of information support this interpretation. In a core just west of Diamond Shoals on Cape Hatteras, two AMS ¹⁴C-dated marine bivalve specimens at depths of 19.6 up to 14.4 m below sea level (samples OS-45327 and OS-67832 reported in Culver et al., 2011, their Table 4) yield calibrated ages of 31.9–33.1 cal ka and 35.1–36.4 cal ka (2-sigma age range using CALIB 6.0 and marine09 dataset; Reimer et al., 2009). Paleoenvironmental interpretations by Culver et al. (2011) suggest deposition in a shallow shelf setting as indicated by foraminiferal assemblages. The depth of the dated samples, as well as the paleoenvironmental interpretation, is consistent with the depth of the mapped seismic units and the character of the internal stratigraphy in the Diamond Shoals sediments (Fig. 5). An MIS-3 time of deposition for emergent coastal deposits in the study area was proposed by Mallinson et al. (2008) using optically-stimulated luminescence (OSL). However, at least some of these units have molluscan amino acid racemization age estimates that place them in Pleistocene aminozone AZ2 (Wehmiller et al., 2010), which is calibrated to ~80 ka with associated U–Th coral ages in the study area. Some shells from AZ2 have finite radiocarbon ages in the 30–40 ka range (Wehmiller et al., 2010), suggesting that these apparent MIS 3 ages may be suspect.

MIS 3 was a time of intermediate global ice volume and sea-level fluctuations (Lambeck and Chappell, 2001; Siddall et al., 2008). The timing and amplitude of MIS 3 sea-level changes provide a viable explanation for observed changes in seismic character of the 10-m thick unit we identify beneath the Holocene ravinement unconformity in Diamond Shoals. Age control and paleoenvironmental interpretations from adjacent cores suggest a mid- to late-MIS 3 age of deposition, in an environment consistent with a shallow marine shoal. The depth of the deposit and the adjacent dated material suggest a ~10 m envelope for relative sea-level at an elevation about 15–25 m below present sea level. Comparison with relative sea-level records from around the globe (Siddall et al., 2008) suggests that this elevation is higher than observed elsewhere, and is at the upper bound of the errors used to compile those records (Siddall et al., 2008). Kopp et al. (2009), however, suggest that comparison of single sites from disparate locations can be misleading. Glacial isostatic adjustment (GIA) during MIS 3 might have contributed to a vertical difference from other Atlantic margin and global records. The magnitude of GIA would presumably have been muted due to intermediate ice volume, in contrast to GIA from the greater ice-load at the Last Glacial Maximum (LGM) (Peltier, 2004; Engelhart et al., 2011). Thus, it is reasonable for these sediments' depth and our inferred sea-level elevation envelope to vary from a global MIS 3 eustatic curve.

Regardless of an MIS 3 or MIS 5 age of deposition, the sediments underlying modern Diamond Shoals constitute a Pleistocene high. The presence of this remnant high demonstrates a geologic influence of antecedent geology on the location of the Cape Hatteras cuspate foreland that has been suggested for other time periods (e.g., Popenoe, 1990; M2010), but not for this late Pleistocene interval. The lack of this unit elsewhere in the study area also allows us to speculate that a cuspate foreland has existed here previously; the modern Cape Hatteras may have been preceded by one or more paleo-capes or sandy shoals during the late Pleistocene.

5.3. Paleo-fluvial valley systems

The major paleo-fluvial valley systems in the study area appear to be Late Pleistocene in origin. Through their influence on drainage basin development and sedimentation, the valley systems influenced the evolution of the modern barrier island system. They also contain an archive of

early- to mid-Holocene coastal sedimentation. The spatial relationships between the valleys and adjacent features on the inner continental shelf provide a basis for understanding estuary and barrier island development. The modern barrier islands from south of the RV to west of Cape Hatteras for the most part occupy an interstream divide and reflect the influence of the regional geologic framework.

Previous work by Boss et al. (2002), using relatively widely-spaced seismic lines, mapped several tributary valleys of the RV on the inner shelf. One valley is located on the south side of the RV and two on the north side: a smaller inshore valley and larger offshore valley. The denser network of high-resolution chirp data presented here, however, identifies only a single main Roanoke Valley channel as described in Section 4.3. Our interpretation places the southern and northern inshore tributary valleys of Boss et al. (2002) within SSU IV and/or SSU I, respectively. The relationship between the larger northern offshore channel mapped by Boss et al. (2002) and the main RV is unclear. The channel as mapped has similar dimensions to the RV itself, yet it does not obviously relate to a large fluvial system or drainage basin. Our seismic interpretations (Fig. 3) assign the portion of this valley that we mapped to SSU VI. This is also consistent with the sediments and facies interpretations in cores from both the RV and this channel (Boss et al., 2002; Culver et al., 2008; M2010). An intriguing possible interpretation is that this valley represents a slightly more southerly route of the paleo-James River than proposed by Swift et al. (1977). The James River enters the Atlantic Ocean at the mouth of the Chesapeake Bay about 40 km north of False Cape (see Fig. 1), and its paleo-valley was mapped by Swift et al. (1977) south-southeastward across the inner shelf towards False Cape, where it turned eastward. In this interpretation, the James and the Roanoke Rivers coalesced here off Kitty Hawk, and comprised a single fluvial system that traversed the shelf to the shelf break.

Our interpretations, combined with the offshore extension of data from Boss et al. (2002), identify the RV (and possibly the James River?) as routed eastward across the inner to inner-mid continental shelf (Fig. 15). Thus, the RV does not lie within the Albemarle Valley proposed by Swift et al. (1978). This interpretation has implications for the shoal-retreat massif model of Swift et al. (1978) for which we offer an alternative explanation in Section 5.4 below.

The three major valley systems between Oregon Inlet and Cape Hatteras (WV, KV, and AV) dissect older Pleistocene sediments, particularly SSU V. The valleys appear to originate on the interstream divide that separates them from the southward-draining Pamlico Creek valley mapped by M2010 (see Fig. 3). The AV, however, may have a landward extension into southeastern Pamlico Sound, where core data (Culver et al., 2011) identify a thin sequence of early Holocene estuarine sediments. The KV exhibits a seaward-branching morphology, which has been identified in other paleovalley systems (Greene et al., 2007) and attributed to a change in coastal plain gradient from steep to gradual. A similar circumstance may exist here, as the inferred interstream divide beneath the modern barrier islands lies just to the west and comprises the steepest portion of the inner continental shelf in this area.

Seismic data for the WV and KV do not provide continuous coverage that identify whether these two valleys coalesce. The WV follows a bathymetric low around the seaward end of Wimble Shoals, which continues to the south, apparently seaward of the KV. We infer, however, that the two valleys do coalesce, likely in the ~2.5 km-long region adjacent to our data (see Fig. 2). We speculate that the AV also coalesces with the WV and KV and that this single valley system may trace to the south, meeting the shelf break east of Cape Hatteras near the seaward end of Diamond Shoals. This speculation is consistent with both the WV following a bathymetric low, and with the north-south oriented ridge and swale bathymetric fabric that characterizes the continental shelf in the region from Kitty Hawk to Cape Hatteras (see Fig. 1). We surmise here that the shelf bathymetric fabric results at least in part from the influence of relict Pleistocene sedimentary units, such as observed in Wimble and Kinnakeet Shoals.
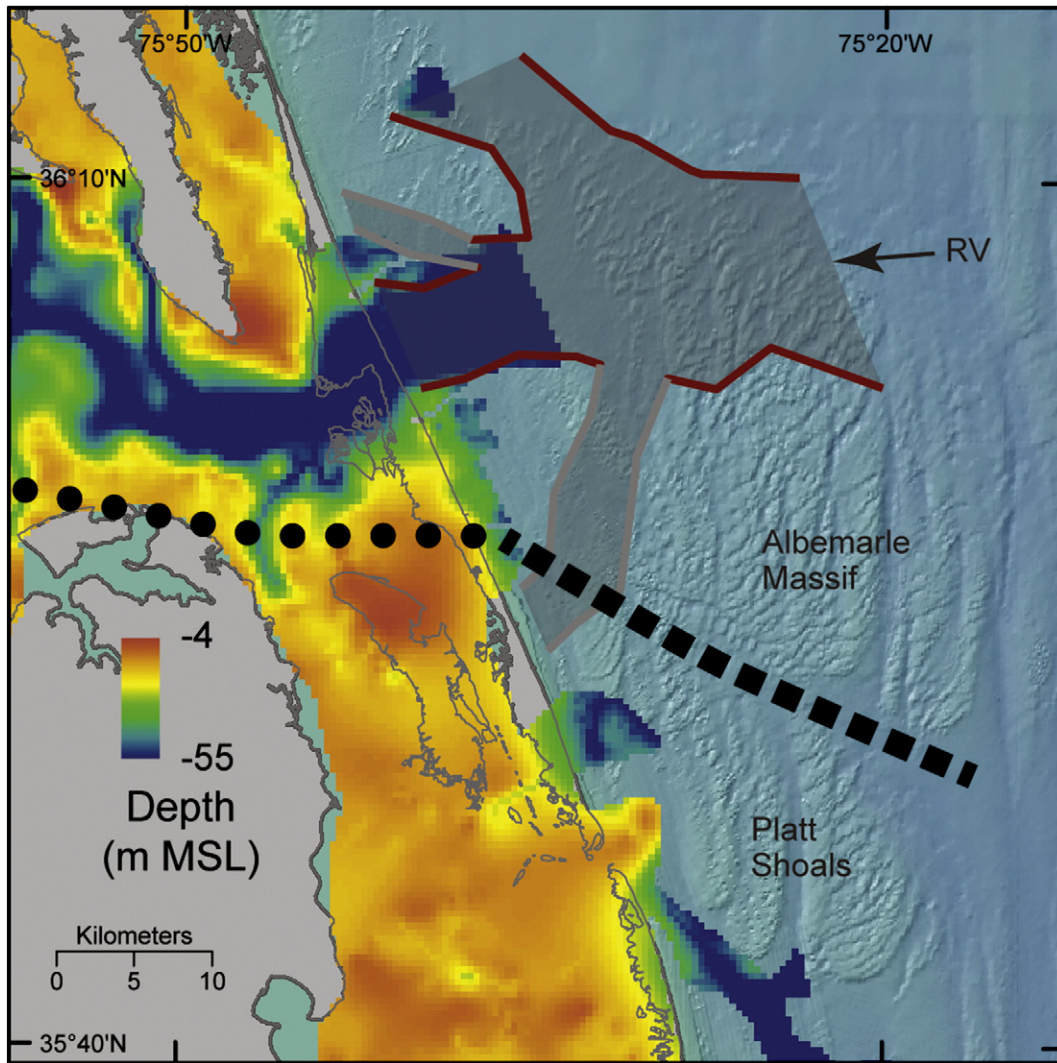
Fig. 15. Map showing the course of the paleo-Roanoke River valley (RV) through the study area, based on seismic data presented in this paper (color image of depth to the Q99 reflection) and by Boss et al. (2002) (red and gray lines with light gray shading), in relation to the course proposed by Swift et al. (1978) to explain the formation of the Albemarle shelf valley and adjacent shoal retreat massifs. Line symbology for Swift et al. (1978) interpretation follows the original work: circles indicate "subsurface valley", dashes indicate "surface valley". Gray lines with light gray shading indicate valley fills interpreted by Boss et al. (2002) as part of the RV, but which we assign to underlying Pleistocene units (SSU IV and/or SSU I; see text for discussion).

The NTPV system is the largest and most continuous valley system between Cape Hatteras and Cape Lookout. It is composed of three major North Carolina Piedmont-sourced rivers, plus the Pamlico Creek system. Thieler and Ashton (2011) proposed that this fluvial system may have formed a delta on the mid- to outer-shelf in Raleigh Bay, and contributed to the formation of a cuspate foreland that was an early- to mid-Holocene predecessor of the modern Carolina Capes.

Similar to the WV, KV, and AV north of Cape Hatteras, the paleo-valleys we mapped in Raleigh Bay originate under or near the modern barrier islands, both north and south of the NTPV (see Fig. 3). These valleys may also represent the upper reaches of paleofluvial systems near a former drainage divide. In this region there is little age control available from sediment cores (see Fig. 2E), but our interpretations are broadly consistent with other work (e.g., Heron et al., 1984) that identified Holocene backbarrier deposits beneath the modern Core and Portsmouth Banks barrier islands.

5.4. Origin of shoal/massif complexes

A series of papers (Swift et al., 1972; Swift and Sears, 1974; Swift, 1976) that comprise the first major syntheses of coastal and continental shelf evolution on the U.S. Atlantic coast proposed a model for shelf valley complexes found in the mid-Atlantic Bight that describes their origins as estuary-mouth or inlet-associated shoals that were subsequently modified by marine transgression and modern shelf oceanographic processes. Swift et al. (1978) applied this model to the Albemarle Shelf Valley, which is the topographic low between the shoals formed by the Albemarle Massif and Platt Shoals (see Figs. 1 and 15). An explicit assumption in this model is that the Roanoke (Albemarle) River valley (RV, as defined above), bisects these two shoals. Swift et al. (1978) inferred this from early seismic reflection surveys in southern Albemarle and Croatan Sounds (O'Connor et al., 1972). More recent data presented in M2010 and here, however, show the RV occupying the central portion of Albemarle sound and tracing east to east-northeast. On the inner continental shelf, our data and that of Boss et al. (2002) demonstrate that the RV is not associated with the Albemarle Massif and Platt Shoals. In the absence of a fluvial valley that satisfies the shoal-retreat massif model, alternative explanations are needed to explain the shoal deposits.

One alternative explanation is that, as both we and Swift et al. (1978) find, both the Albemarle Massif and Platt Shoals are eroded Pleistocene remnants with a modern (palimpsest) sand cap. This suggests a configuration analogous to the modern Wimble and Kinnakeet

Shoals and adjacent barrier islands, which would most likely have existed during lower sea level in the early Holocene (Horton et al., 2009; Thieler and Ashton, 2011).

A second alternative explanation is that the massif and shoals are abandoned and reworked shoreface or cape-associated shoal complexes. This explanation is consistent with the shoreface ridge model of McBride and Moslow (1991). Modern analogs include the shoreface-attached ridges at False Cape, Virginia (Robinson and McBride, 2008) and Wimble Shoals. Our reinterpretation of the Albemarle shelf valley complex does not invalidate the broad implications of the classic model of Swift et al. (1972). Rather, it highlights the multiple possibilities for shelf ridge and valley evolution, and creates new explanations of the early Holocene evolution of this shelf sector.

5.5. Sea floor sediment texture, morphology, and Holocene sediment distribution

As described in Section 4.4, the inner continental shelf in the study area is composed largely of palimpsest sediments. Modern sediments and sedimentary features are principally confined to ridges and shoals. In other words, there is not a continuous blanket of Holocene sediment (Fig. 8). The distribution of these sediments and features provides insight into the dominant process–response relationships shaping the inner shelf.

Migration and evolution of the shoals in this area is consistent with models of shoreface ridge evolution. Trowbridge (1995); Calvete et al. (2001) and Vis-Star et al. (2007) found that under oceanographic forcing comparable to our study area, sand body migration velocities on the inner shelf are 1–10 m yr^{-1}. Both the long-term data from the mid-1800 s and the more recent 30 yr period for Platt Shoals is consistent with these estimates.

Diamond Shoals represents the major regional sink for sediment in the study area. Processes that contribute to sediment accumulation at Diamond Shoals include littoral drift (Inman and Dolan, 1989), tidal currents (McNinch and Luettich, 2000), and convergence of alongshore sediment transport pathways (Dyer and Huntley, 1999). Ashton and Murray (2006) identified a strongly bi-modal distribution of the regional long-term wind and wave climatology, with major components from the southwest and northeast that favor deposition on the shoal. Direct observations of oceanographic processes at Diamond Shoals confirm that waves and near-bottom currents can drive sediment onto the shoal (List et al., 2011; Armstrong et al., 2013). Estimates of sediment flux and deposition rates, however, remain to be quantified.

The sorted bedforms that dominate the inner continental shelf in Raleigh Bay provide insight into sediment availability and transport between Capes Hatteras and Lookout. Sorted bedforms here are similar to but much more widespread and better developed than has been reported for other shelf locations (Murray and Thieler, 2004; Trembanis and Hume, 2011); the 1000 km^2 area of sorted bedforms is one to two orders of magnitude larger than others reported in the literature.

Sorted bedforms tend to be asymmetric with their coarser flanks facing updrift, into the direction of dominant suspended sediment transport (Murray and Thieler, 2004; Goff et al., 2005; Gutierrez et al., 2005). The orientation of sorted bedforms relative to local or regional sediment transport directions has been observed off Martha's Vineyard, Massachusetts, where sorted bedform orientation (inclination direction of coarse flank) changes in response to the dominant forcing along the island (Goff et al., 2005). In locations that lack a dominant current direction, sorted bedforms tend to be symmetric (e.g., Goff et al., 2005; Diesing et al., 2006). Applying these relationships to Raleigh Bay allows us to infer sediment transport towards both capes that reflects in part the directionally bimodal wave climate (Ashton and Murray, 2006), with a nodal zone in middle. In Fig. 13, region A indicates sediment transport towards Diamond Shoals, which is consistent with List et al. (2011). The broad area of fine sediment to the east of region A may

represent a zone of fine-grained sedimentation on the western flank of Diamond Shoals. Sorted bedform orientation in Regions C and D indicate sediment transport towards Lookout Shoals, which is consistent with the longshore transport direction identified by Park and Wells (2005). Symmetric sorted bedforms in Region B indicate a nodal zone of bimodal (?) or no preferred direction of sediment transport. The fine-grained sediment on the sea floor on either side of Ocracoke Inlet in region B may represent sedimentation resulting from long-term, inlet-related processes at this historically stable inlet, which has been open since at least AD 1585 (Fisher, 1962). Accumulation of fine-grained sediment around the ebb-tide delta may also indicate the lack of a preferential inner shelf sediment transport direction here.

The varied seafloor morphology and sediment distribution in our 3100 km^2 study area serve as the basis for a generic conceptual model that describes a continuum of inner shelf morphologies. Such a model may have broad application to other continental shelves. This includes describing the role of sediment availability in determining the nature of the inner shelf morphology and sediment cover. For example, on sediment-starved inner shelves with coarse and fine sediments such as Raleigh Bay, sorted bedforms are the dominant morpho-sedimentary feature. As sediment availability increases, the inner shelf morphology is characterized by shoreface-attached ridges (e.g., on the north side of Lookout Shoals; Fig. 14) and shelf sand bodies (e.g., Platt and Oregon Shoals; Fig. 11). In the former case, there is still evidence of coarse-fine sediment domains consistent with sorted bedforms. Similar observations have been made on the inner continental shelf south of Long Island, New York (Schwab et al., 2000) where sorted bedforms are found off eastern Fire Island and Long Beach. Both areas are characterized by relatively low sediment availability. The central portion of Fire Island, in contrast, lacks sorted bedforms and has well-developed shoreface-attached ridges, evidence of relatively higher sediment availability.

North of Cape Hatteras there are no sorted bedforms on the inner shelf. We interpret this as an indication of relatively high sediment availability, as well as the result of interactions between physical oceanographic processes, inner shelf topography and underlying geology that inhibit the development of sorted bedforms (Goldstein et al., 2011).

6. Conclusions

This study illustrates the broad application of regional-scale geophysical information to improve understanding of the influence of regional geologic framework on coastal and inner continental shelf evolution. Late Quaternary sedimentation patterns may have provided a geologic template for successive Pleistocene paleo-capes near modern Cape Hatteras. This includes a period of shallow marine sediment deposition during the Late Pleistocene that is supported by geophysical, geologic, geochronologic, and paleoenvironmental data. Regional to local-scale variations in the geometry and lithology of the northern North Carolina inner continental shelf dictate seafloor morphology and character of sediments. The large shoal complexes in the study area, False Cape, Platt, Wimble and Kinnakeet, are composed of both underlying indurated sediments and mobile sand bodies. Historical bathymetric comparisons indicate that large volumes of sediment in these complexes may move hundreds of meters in tens of years. Sediment transport patterns inferred from the analysis of modern bedforms in Raleigh Bay suggest sediment transport towards both Cape Hatteras and Cape Lookout, with a nodal zone midway between the capes. The distribution of modern sediment (above the Holocene ravinement surface) on the inner shelf suggests that sediment availability defines the morphologic character of the inner shelf. Where modern sediment is relatively abundant, the inner shelf contains shoreface-attached ridges and shoal complexes. Where modern sediment is lacking, the seafloor is characterized by sorted bedforms.

Acknowledgments

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