Appendix H

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Exhibit A

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

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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

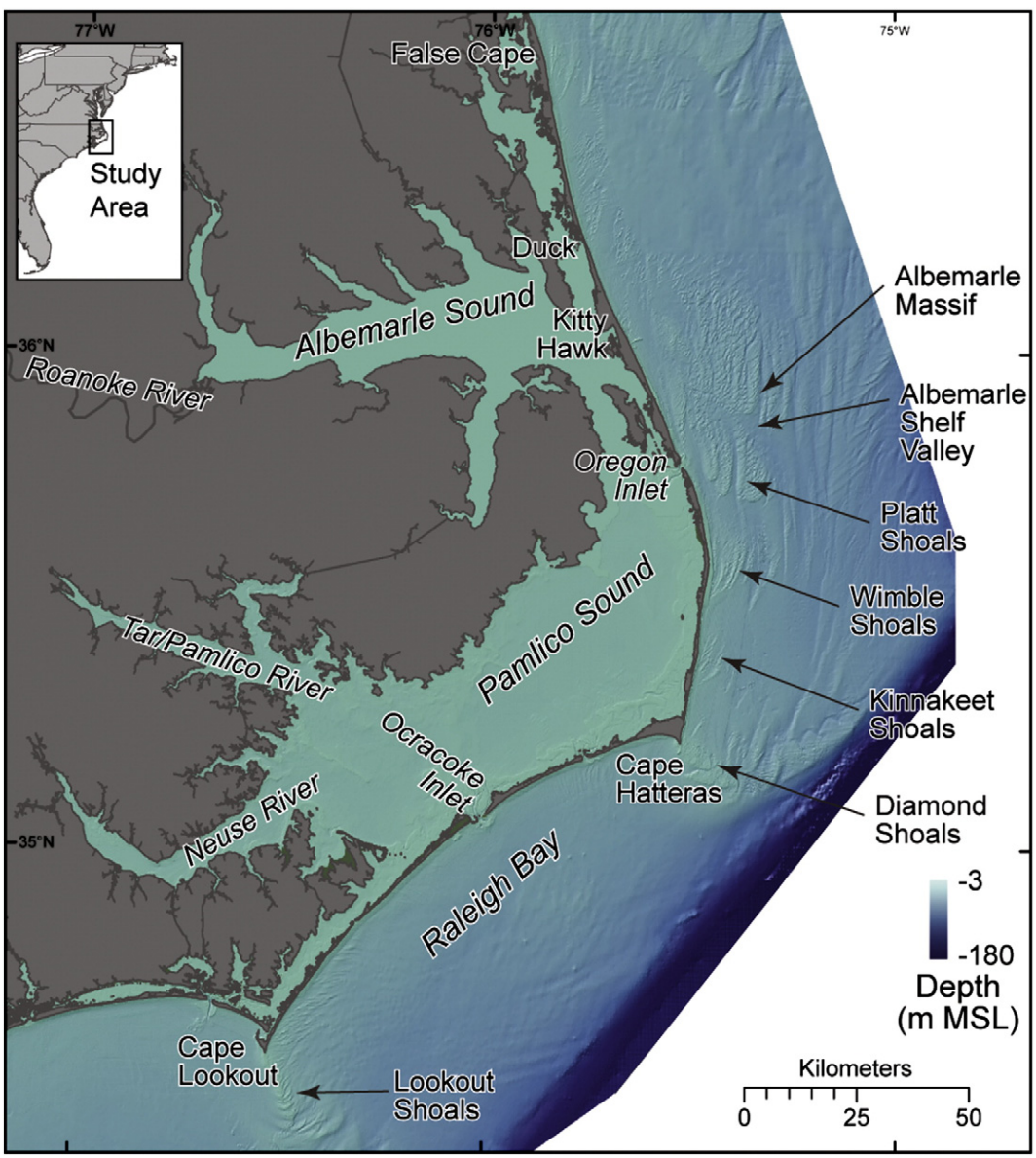

Fig. 1. Map of the study area in northeastern North Carolina. Bathymetry data is from the NOAA NGDC Coastal Relief Model (www.ngdc.noaa.gov/mgg/coastal/startcrm.htm) and this study.

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 km^2 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

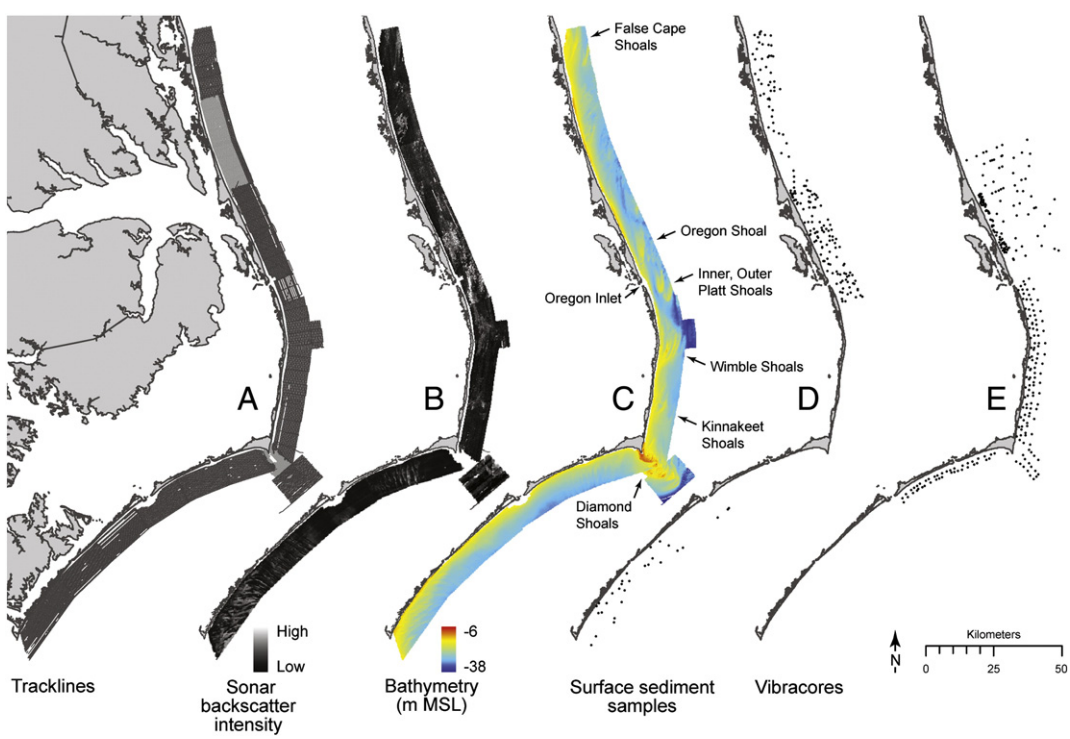

Fig. 2. Maps showing data used in this study. A) Tracklines for chirp and boomer seismic systems, sidescan sonar, and bathymetry systems. Dark gray indicates swath bathymetry, light gray indicates single-beam fathometer (off Duck and inner portion of Diamond Shoals). B) Sidescan sonar mosaic, depicting 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

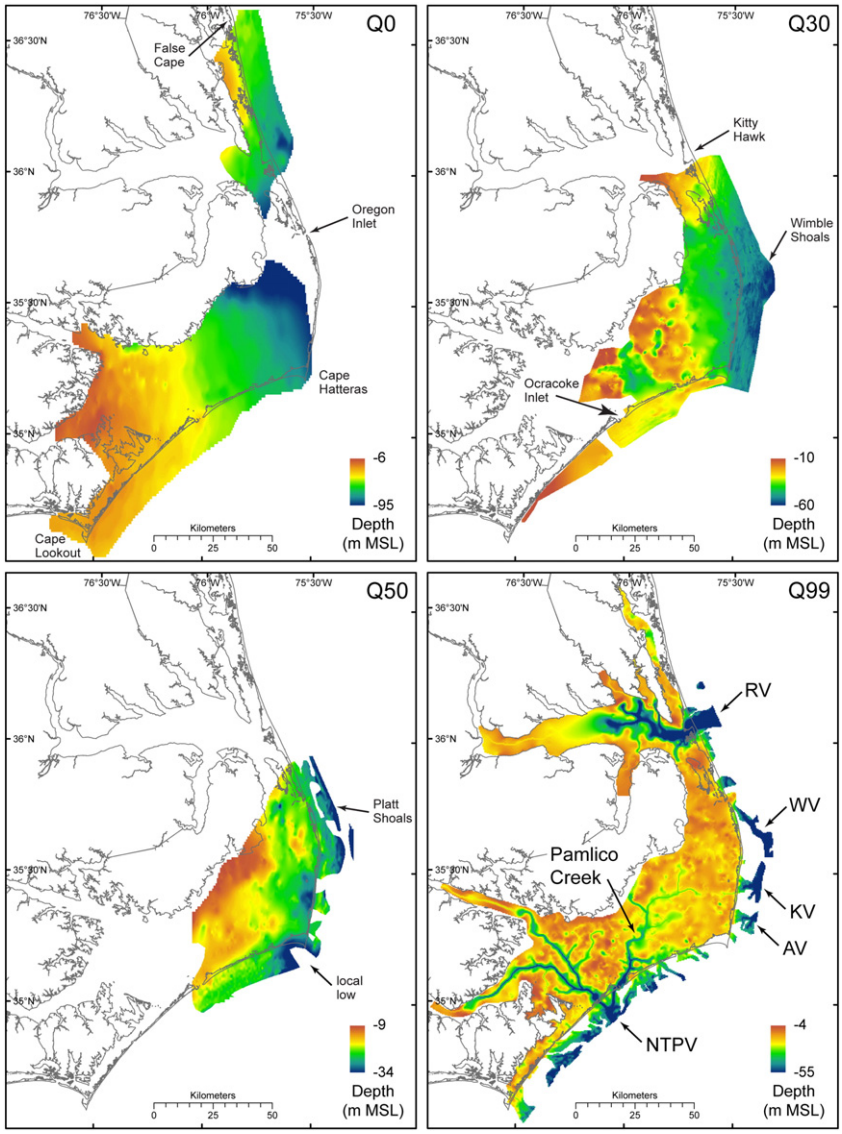

Fig. 3. Maps showing the depth of regional seismic reflections mapped in this study and by Mallinson et al. (2010). In Q99 panel, major paleofluvial valleys discussed in text are identified: RV = Roanoke Valley, WV = Wimble Valley, KV = Kinnakeet Valley, AV = Avon Valley, NTPV = Neuse-Tar-Pamlico Valley.

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

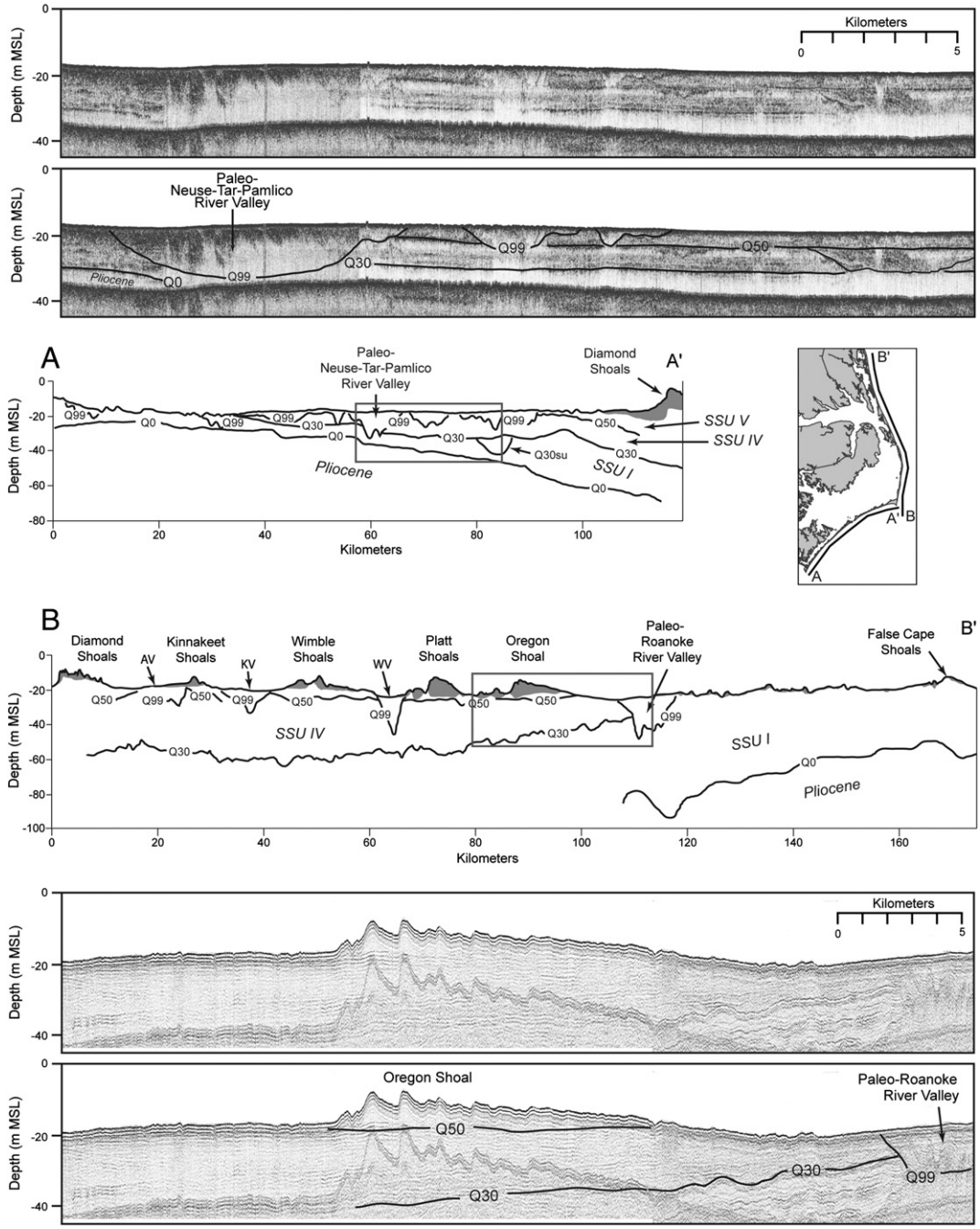

Fig. 4. Interpreted seismic sections (A-A', B-B') for the inner shelf study area, showing major seismic reflections and names of seismic stratigraphic units following Mallinson et al. (2010). Gray shaded areas in interpreted sections indicate Holocene sand bodies. On section B-B', AV = Avon paleo-fluvial 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

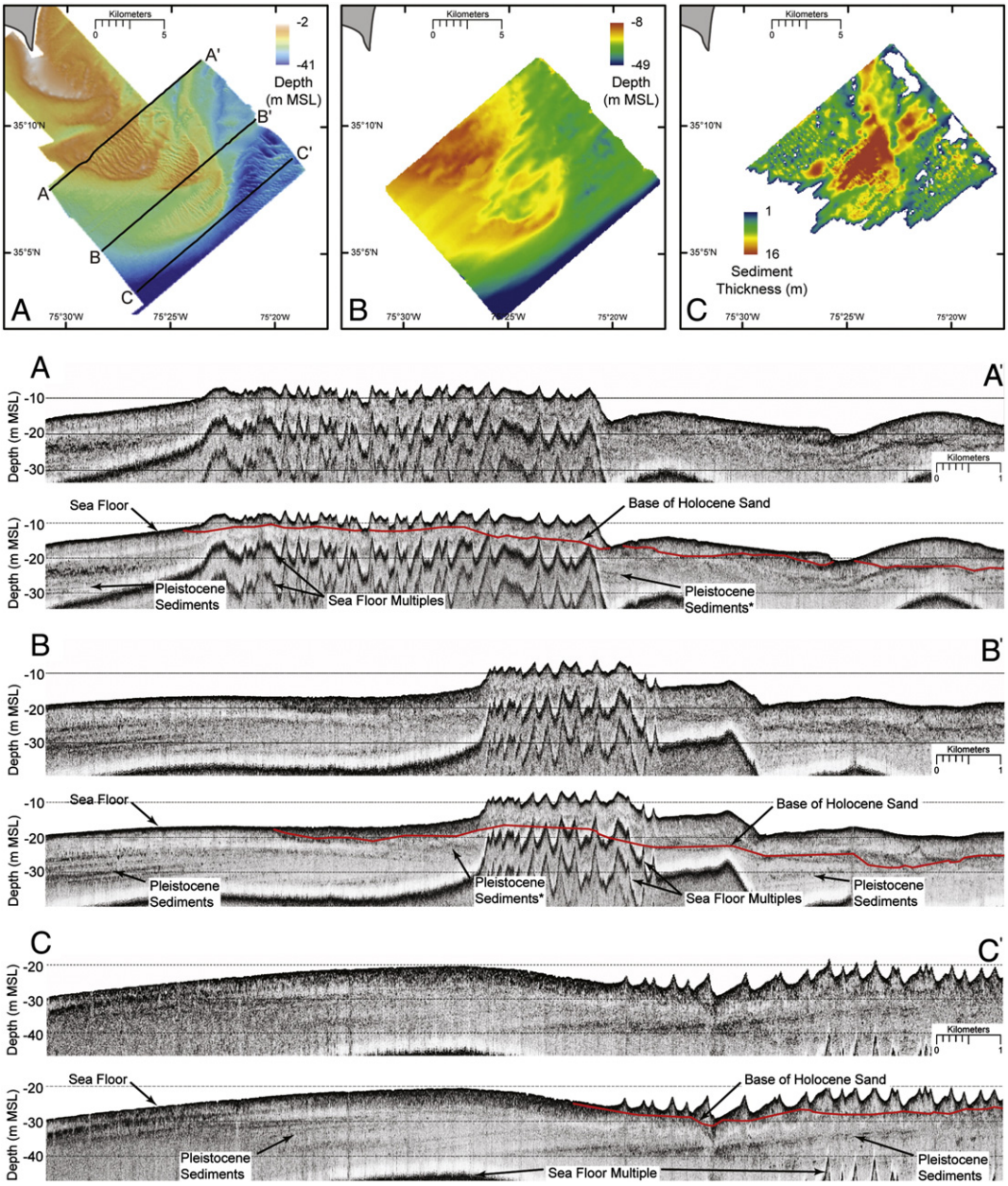

Fig. 5. Maps and seismic data for Diamond Shoals. A) Bathymetry of Diamond Shoals and locations of representative chirp seismic data shown below. B) Map showing depth to the top of the interpreted Pleistocene–Holocene unconformity at the base of the Holocene sand. The surface has variable relief. C) 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

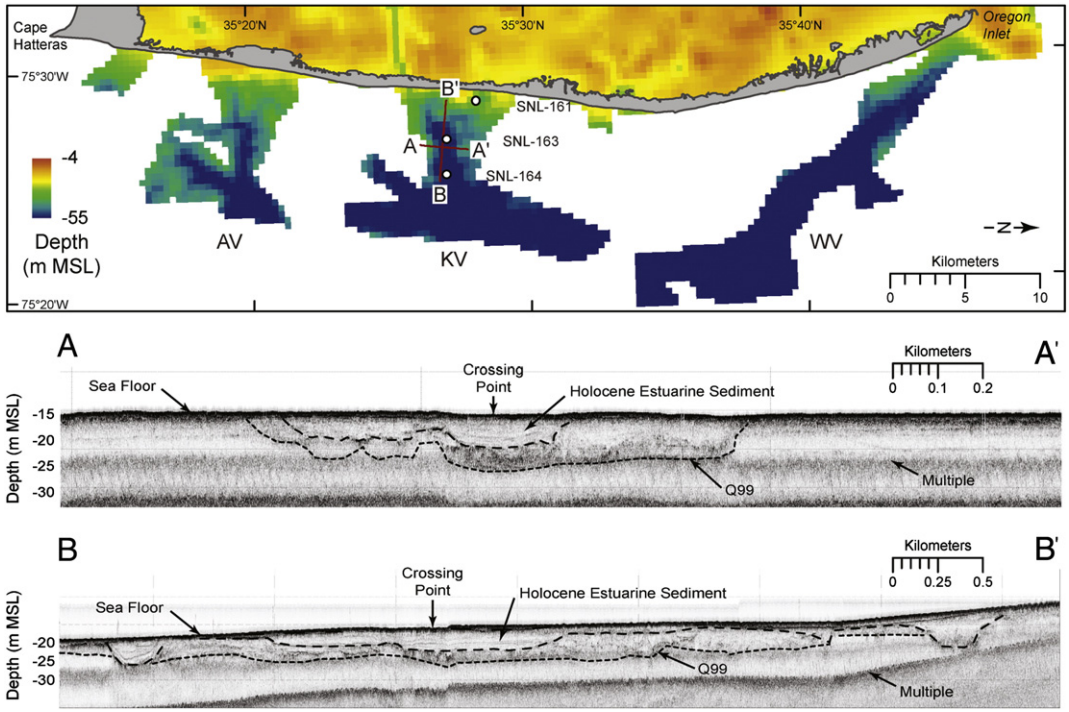

Fig. 6. Map and interpreted chirp seismic data showing the depth of fluvial incision and fill of the three major paleovalley systems off Hatteras Island. AV = Avon paleo-fluvial valley, KV = Kinnakeet paleo-fluvial valley, WV = Wimble paleo-fluvial valley. Location of seismic lines A-A' and B-B' are 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

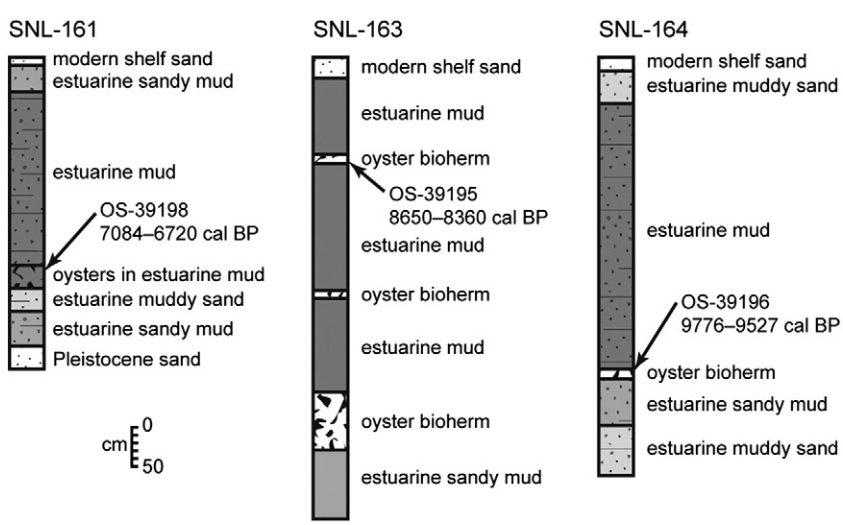

Fig. 7. Interpretive diagrams for three vibracores from the Kinnakeet paleo-fluvial valley off Hatteras Island. Core locations are shown on Fig. 6. The cores show typical estuarine sequences that comprise the valley fill.

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.

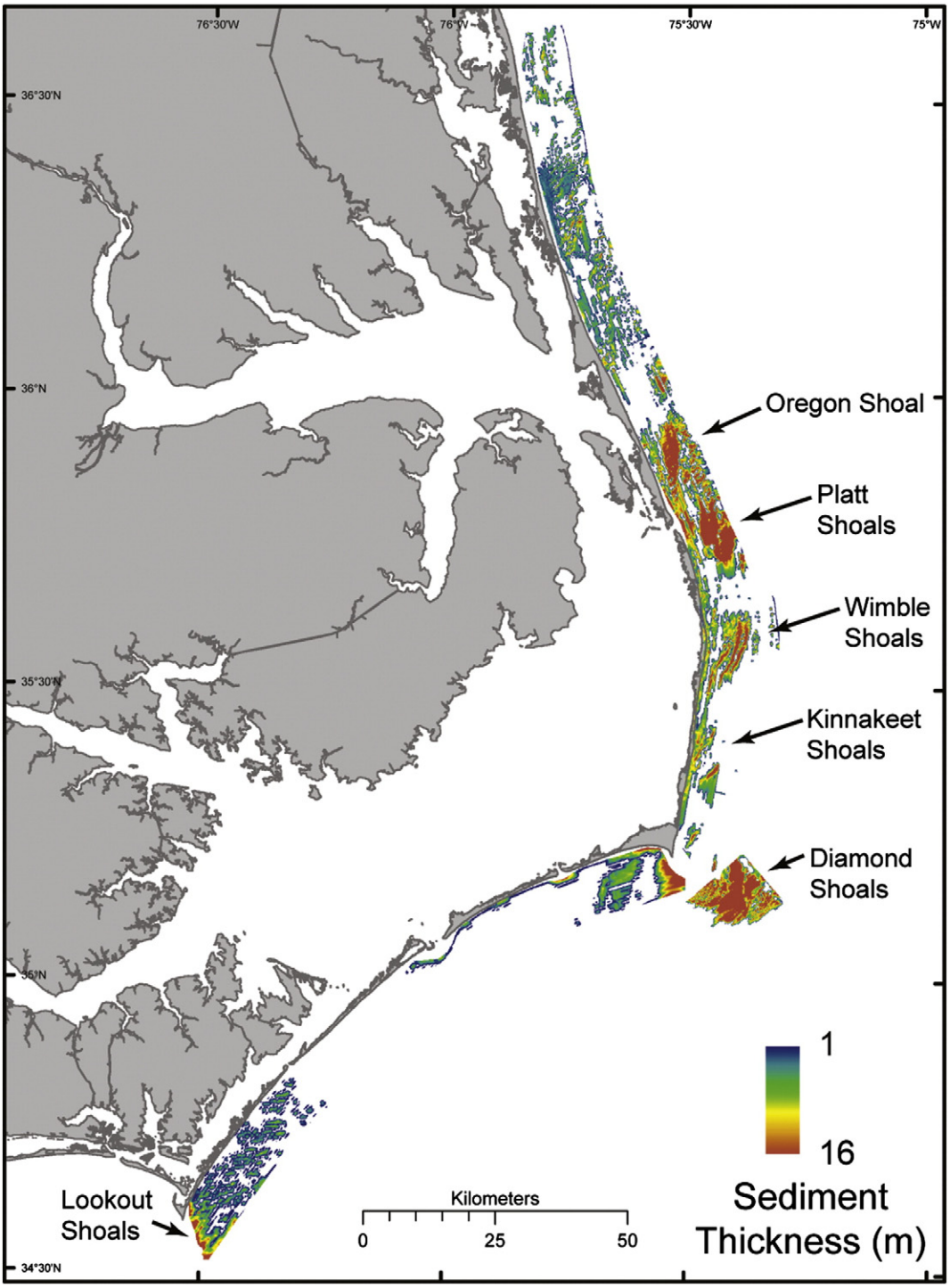

Fig. 8. Map showing the interpreted thickness of Holocene sand in the study area. Major shoal features discussed in text are identified.

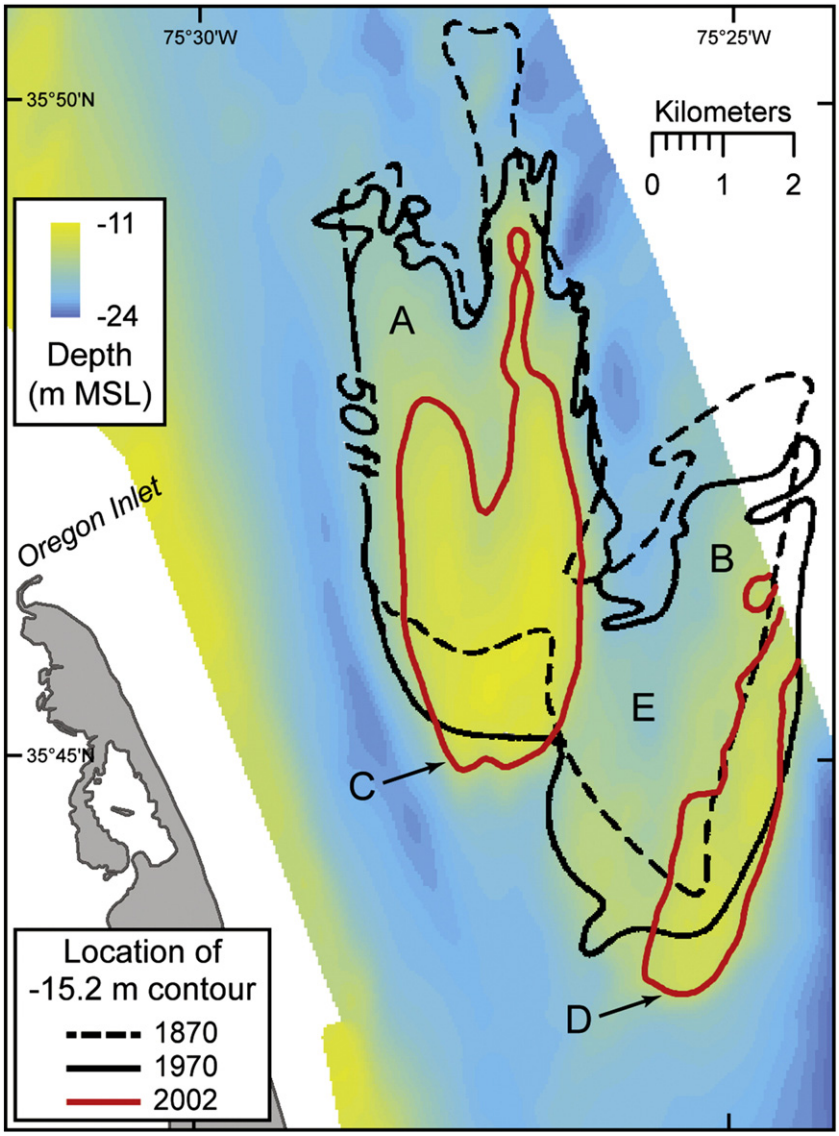

Fig. 9. Map showing bathymetry of inner and outer Platt Shoals and changes in the −15.2 m contour from 1870 to 2002. Distances of southward movement: A = 3 km; B = 2.5 km; C = 0.5 km; D = 0.75 km. E = 3 m of deepening (sea floor erosion). (1870 and 1970 contours from Swift et al., 1978.).

(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.

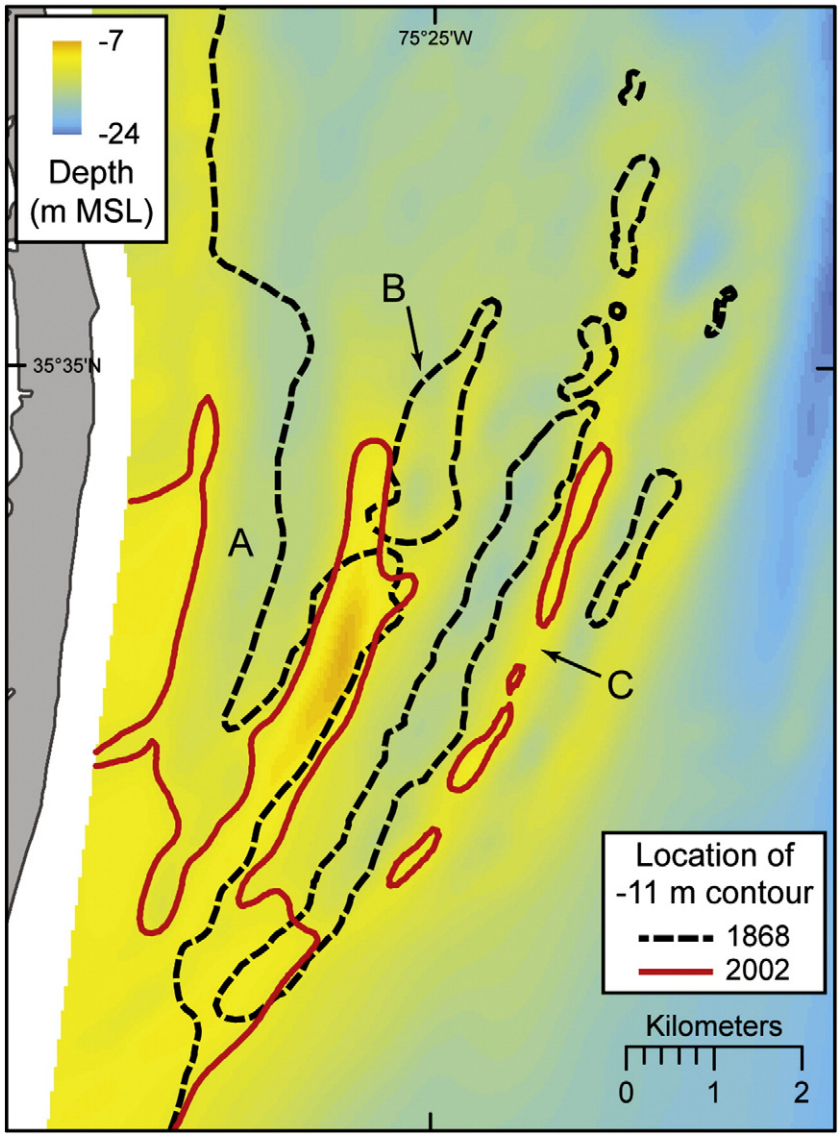

Fig. 10. Map showing bathymetry of Wimble Shoals and changes in the −11 m contour between 1868 and 2002. A = increase in shoreface steepness. B = 2 km reduction in shoreface-attached ridge length. C = 2.5 km reduction in shoreface-attached ridge length and seaward migration of 500 m. (1868 data from 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 km^2 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

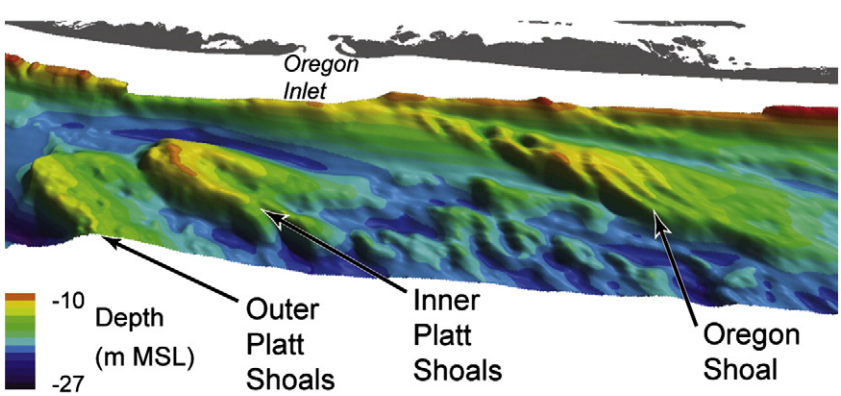

Fig. 11. Perspective view of shaded-relief bathymetric data for Oregon Shoal, and Inner and Outer Platt Shoals, looking west towards Oregon Inlet. The field of view is approximately 30 km wide, and the across-shore width of the data is 10 km. Vertical exaggeration is 100.

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

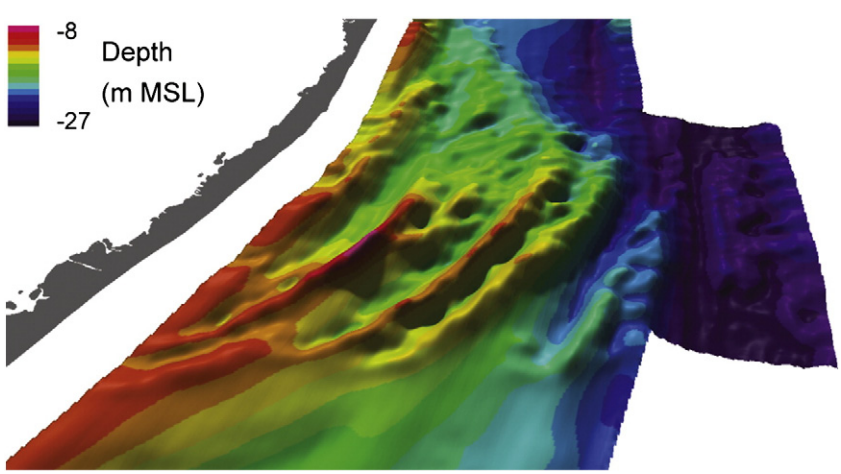

Fig. 12. Perspective view of shaded-relief bathymetric data for Wimble Shoals, looking north. Five distinct shore-oblique ridges are evident. The across-shore width of the data is 13.5 km. Vertical exaggeration is 100.

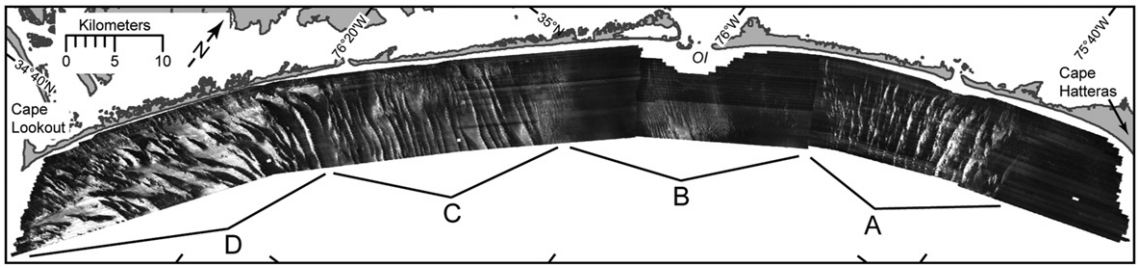

Fig. 13. Map showing sidescan sonar mosaic of Raleigh Bay, between Capes Hatteras and Lookout, and four distinct regions of sorted bedforms described in text. Low acoustic backscatter is depicted as dark tones and corresponds to fine-grained sediments; high acoustic backscatter is depicted as light tones 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

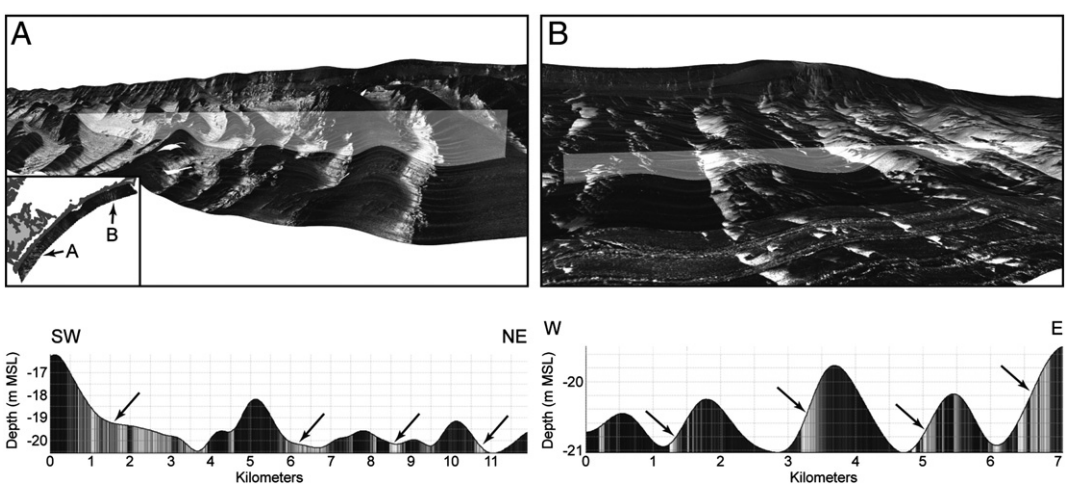

Fig. 14. Perspective views of bathymetry and sidescan sonar data, and bathymetric/backscatter profiles across sorted bedforms at the northern and southern ends of Raleigh Bay. Inset map shows location and look-direction of views in A and B. A) Portion of region D identified in Fig. 13, looking to the 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 ^{14}C-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.

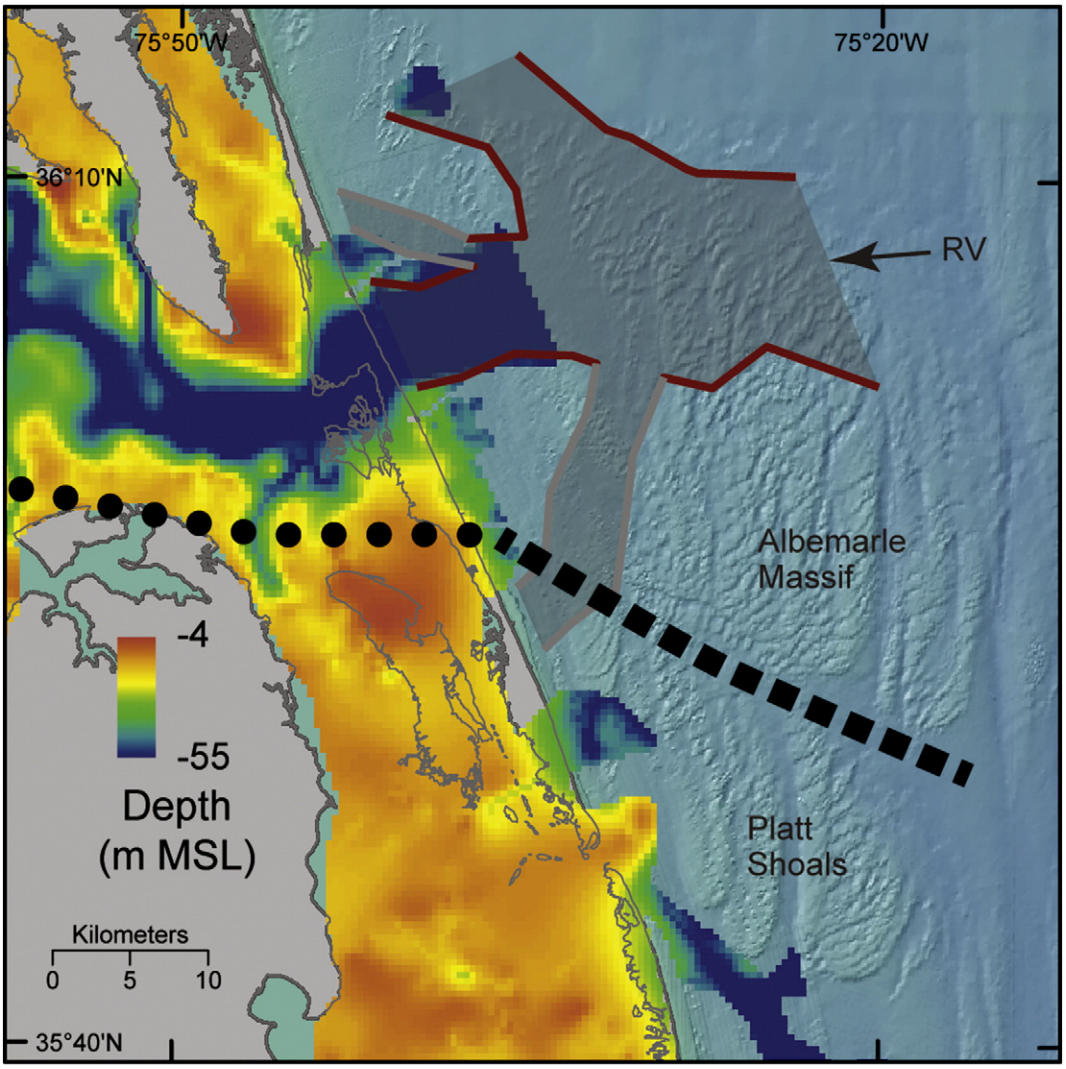

Fig. 15. Map showing the course of the paleo-Roanoke River valley (RV) through the study area, based on seismic data presented in this paper (color image of depth to the Q99 reflection) and by Boss et al. (2002) (red and gray lines with light gray shading), in relation to the course proposed by Swift 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 paleovalleys 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.

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Exhibit B

Geologic control in the nearshore: shore-oblique sandbars and shoreline erosional hotspots, Mid-Atlantic Bight, USA

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Geologic control in the nearshore: shore-oblique sandbars and shoreline erosional hotspots, Mid-Atlantic Bight, USA

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Abstract

Beach and nearshore morphology, defined primarily by slope and sandbar development, is very dynamic and is largely controlled by waves, currents and regional sediment characteristics. Results presented here challenge this long-established concept and suggest that underlying, framework geology may also exert a first-order control on nearshore morphology by influencing the stability and/or persistent re-establishment of large-scale sandbar morphology and position as well as surface sediment characteristics. Repeated sub-bottom chirp and swath bathymetry surveys of the nearshore (2–10 m depths) covering over 56 km of the North Carolina Outer Banks and Southeastern Virginia indicate the following: (1) development of shore-oblique sandbars adjacent to large gravel outcrops that are surface exposures of the underlying geologic strata, (2) identical re-development or sustained maintenance of large-scale sandbar morphology and position before and after very energetic conditions, (3) vertical and horizontal heterogeneity of lithology and grain-size and a minimum volume of sand, ranging from 0 to 1.5 m thick, and (4) close spatial alignment between the location of outcrops/shore-oblique bars and shoreline erosional hotspots. A hypothesis is proposed from these findings that links framework geology to bar morphodynamics and sorted bedforms and, ultimately, erosional hotspots. Sediment transport and shoreline evolution models based solely on waves and currents and an assumption of unlimited and uniform sediment may be inadequate in similar heterogeneous, sand-limited regions.
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Keywords: shore-oblique sandbars; hotspots; beach erosion; nearshore morphodynamics; framework geology; North Carolina; Virginia; coastal processes

1. Introduction

The dynamic equilibrium between beach and sandbar morphology and nearshore energy has been well documented (Wright and Short, 1984; Wright, 1995; Komar, 1998; Plant et al., 2001). A feedback appears to exist wherein nearshore bathymetry influences waves and nearshore circulation that, in turn, affects sediment transport and leads to a dynamic response of the beach and sandbar morphology. Implicit in this concept of quasi-balance between

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nearshore morphology and energy is the assumption that an unlimited supply of homogenous sediment is readily available. Evidence is presented here that questions the widespread applicability of: (1) assuming unlimited and homogenous sand in nearshore sediment transport modeling, and (2) nearshore bathymetry predictions based solely on waves and currents and an average or median grain size at the seafloor surface. Results from seismic and swath bathymetry surveys that span 56 km of the Virginia–North Carolina nearshore suggest that the underlying geology influences the type of surface sediment distribution, the morphodynamics of nearshore bathymetry, and possibly shoreline behavior.

Inexplicable variability in shoreline change along relatively straight, sandy beaches has been observed for decades but remains, in many cases, poorly understood with respect to the controlling processes (Fenster and Dolan, 1993). Regions of anomalous erosion or accretion, recently referred to as shoreline hotspots, exist across a wide range of temporal and spatial scales. Hotspots were first recognized in long-term shoreline change maps calculated from aerial photographs, historical charts, and/or beach profiles. They typically exceed several kilometers in alongshore extent and often persist for several decades (e.g. Terwindt and Battjes, 1990; Morton et al., 1995; Benton et al., 1997; Gravens, 1999). Recent advances in shoreline and nearshore observational techniques that include LIDAR (Sallenger et al., 2000), dual-channel GPS (List and Farris, 1999), and video imaging (Lippman and Holman, 1989; Holland et al., 1997) have revealed even smaller spatial and temporal variations in shoreline morphology that occur over alongshore distances as small as hundreds of meters and over time periods as short as days to weeks.

Rapid rates of shoreline change in some regions may be explained by existing concepts such as inlet-associated shoreline fluctuations (Dean and Work, 1993; Fenster and Dolan, 1996) or changes related to shoreline engineering (Kraus and Galgano, 2001). Many shoreline hotspots, however, defy our basic understanding of alongshore-dominated sediment transport and the exchange of sediment across the nearshore and thus represent substantial modeling and coastal management dilemmas. Many coastal geologists have argued that large-scale and long-term shoreline behavior is influenced by framework geology (Demarest and Leatherman, 1985; Kraft et al., 1987; Pilkey et al., 1993; Riggs et al., 1995; Schwab et al., 2000; Gayes et al., 2002) but the mechanisms connecting framework geology with shoreline erosion remain speculative. Many have shown that wave refraction/diffraction around bathymetric highs or lows (e.g. O'Reilly and Guza, 1993; Bender and Dean, 2002), which may be formed by relict geologic substrates exposed on the inner and mid-shelf, could generate alongshore gradients in wave energy and eventually lead to spatial variations in shoreline change (Kraus and Galgano, 2001). This may in fact explain a common forcing behind many shoreline hotspots but how wave energy influenced by relict shelf topography may be expressed in the nearshore with respect to bar morphodynamics and sediment characteristics and how this translates to higher beach erosion have not been fully addressed. Results presented in this paper are noteworthy because they focus on the geology and bathymetry of the nearshore, where few surveys of this nature have been conducted and where much of the sandbar and beach-related sedimentary processes occur. This also differs from earlier work because it shows stable or recurring three-dimensional morphology that is difficult to explain given the existing paradigm of a dynamic nearshore shoreface composed of unconsolidated sand and forced principally by energetic waves.

Objectives of this study were to measure: (1) the thickness of sand, (2) the surface sediment distribution, and (3) the shoreface morphology (e.g. large-scale sandbars) across the nearshore through multiple energetic conditions as well as to determine if these variables were spatially correlated with regions of long-term, heightened beach erosion. This paper begins with background information regarding shoreline erosional hotspots and proposes a broad definition that encompasses many published observations. Data derived from repeated nearshore surveys of bathymetry, surface sediment distribution (defined by backscatter), and underlying geologic strata from southeastern Virginia and the North Carolina Outer Banks are presented next. The discussion addresses large-scale stability of shore-oblique sandbars and topographic lows across the nearshore and its association with regions in which large areas of underlying geology were exposed on the seafloor. Lastly,

analyses will show the spatial correlation that appears to exist between the location of these outcrops and shore-oblique bars and the location of long-term (Benton et al., 1997; Hobbs et al., 1999) erosional hotspots.

1.1. Definition of shoreline hotspots

High-resolution shoreline observations provided by new monitoring techniques, such as dual-channel GPS and LIDAR, have revealed a wide array of shoreline behavior and have resulted in a host of different names and categories for eroding and accreting regions (Dean et al., 1999; Kraus and Galgano, 2001; McNinch and Drake, 2001; List et al., 2002). The term 'hotspot' appears most frequently but the definition has not been clearly established. Dean et al. (1999) defined an erosional hotspot as a region that erodes more than model expectations relative to adjacent shorelines. From this definition, 12 categories of hotspots were developed based on possible causes. Kraus and Galgano (2001) later expanded this hotspot categorization to include 18 different types.

A recent workshop on hotspots, hosted by the USACE-Field Research Facility (see www.frf.usace.army.mil/hotspots for a list of participants and abstracts), established a broader definition that encompasses most of the published observations and does not attach a possible cause or model performance to the description. Three types were identified by consensus at the workshop. Fig. 1 illustrates shoreline change through time at one location for each type of hotspot behavior. An *erosional hotspot* is defined as an area of shoreline that undergoes high net erosion and may also exhibit high variance relative to adjacent regions (Fig. 1A). Examples of erosional hotspots are often seen on long-term shoreline change maps (e.g. Benton et al., 1997; Hobbs et al., 1999) where one region expresses increased and sustained erosion relative to surrounding areas. An *accretional hotspot* is an area of high net accretion that may also display

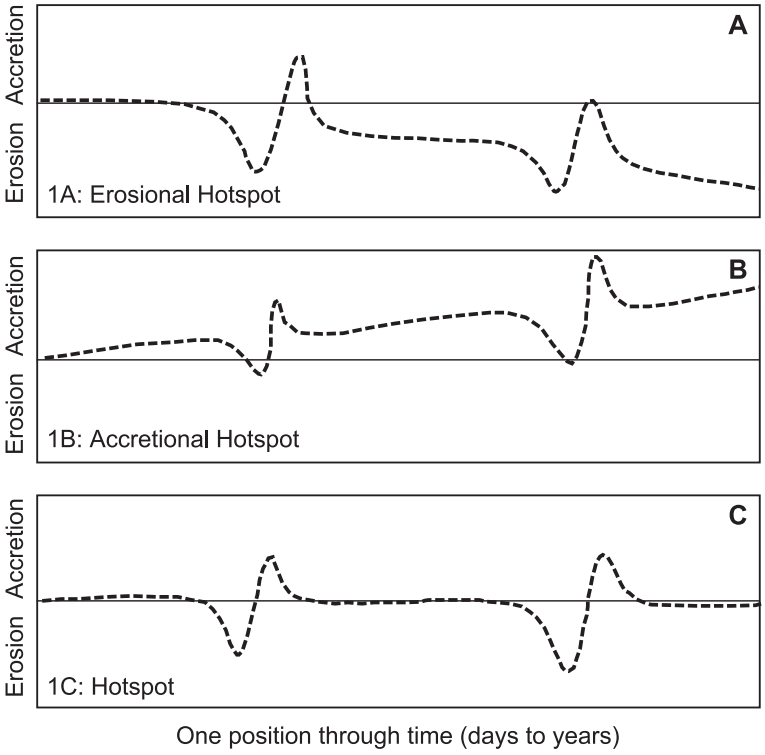

Fig. 1. Diagrammatic illustration of temporal shoreline change at one location, showing variance with net erosion (A: *erosional hotspot*); variance with net accretion (B: *accretional hotspot*); and variance with minimal net change (C: *hotspot*).

high variance relative to adjacent regions (Fig. 1B). A *hotspot* describes a region of shoreline that exhibits high variance with minimal net change relative to the surrounding area (Fig. 1C). In the case of hotspots, high variance in shoreline position is often seen around storms where regions that erode greatly during a large wave event subsequently recover a comparable amount in a matter of days following the storm with negligible net change (e.g. List and Farris, 1999). List et al. (2004) also has shown that the location of hotspots may shift from storm to storm and in some cases occur ephemerally. The temporal and spatial scales in which all of these definitions apply span days to decades and hundreds of meters to kilometers, respectively. All three hotspot categories have been documented along the North Carolina Outer Banks and Southeastern Virginia (Benton et al., 1997; Hobbs et al., 1999; List and Farris, 1999).

2. Site selection and field setting

An initial field site was selected in July 1999 based on the results of an exploratory bathymetric survey using an interferometric swath bathymetry system mounted on the USACE Field Research Facility's (FRF) Light Amphibious Re-supply Cargo (LARC) vessel. This survey revealed the presence of an isolated cluster of shore-oblique bars grouped around an exposed mud and gravel substrate that was located well seaward of the shore-parallel bar and surrounded by an otherwise featureless, low-sloping convex shoreface. The apparent anomalous presence of these sandbars and outcropping muddy substrate was sufficiently intriguing that a survey region surrounding these features was developed to repeatedly survey and track their evolution from 1999 to 2001. This field site is located approximately 1.5 km north of the FRF pier in Duck, NC and spanned 2 km alongshore from the 2 to 10 m isobaths (Fig. 2; panel A). The field site was later expanded to include the shallow sub-bottom, seafloor and bar morphology, and surface sediment distribution across the nearshore of southeastern Virginia and a portion of the North Carolina Outer Banks. This additional area was surveyed in May–June 2002 using the LARC and extended 40 km from Duck to South Nags Head, NC and 16 km from Dam Neck to Back Bay Wildlife Refuge, Virginia (Fig. 2; panels B and C, respectively). A subset of region B, approximately 4 km in Kitty Hawk, NC, was subsequently resurveyed in March and November 2003.

The nearshore of the northern Outer Banks is relatively narrow for the US east coast with an average distance of 1 km between the shoreline and the 10 m isobath. Tides are semidiurnal with a range of 0.97 m, and the mean annual significant wave height is 0.9 m (see www.frf.usace.army.mil for extensive online oceanographic information and annual published reports such as Leffler et al., 1998). Beach and nearshore sediment around the FRF pier has been characterized on several occasions since the early 1980s via grab samples, box cores, vibracores, and side-scan sonar (Byrnes, 1989; Hanes et al., 1995; Drake, 1997). Surficial sediment in the area is largely a bimodal mixture of medium quartz sand and small pebbles. Sediment size becomes progressively fine in the offshore direction, grading to very fine and fine sands, and contains less than 10% silt.

Schwartz et al. (1997) collected shallow vibracores across two transects through the surf zone near the FRF pier and found a thin prism of modern sands overlying a 'pre-modern' unit. The pre-modern substrate was interpreted as a tidal-influenced facies complex composed of layers of organic-rich mud and fine sand alternating with shelly gravel and very coarse sand (Schwartz et al., 1997). The authors believed these deposits would not be generated in present conditions of the nearshore and interpreted them as layers of coarse storm or inlet-related sediment being carried into a low-energy setting such as a barrier lagoon. Although the cores were limited in their spatial extent and can reflect only the geologic nature of the area immediately surrounding each core location, they suggest that the underlying geology in this region is largely unconsolidated but lithologically different from the surface sands (e.g. mud and gravel) and that less than 1.5 m of sand covers the surf zone.

3. Methods and results

3.1. Shore-oblique sandbars and mud/gravel outcrops

An interferometric system (Submetrix, Series 2000) mounted on the LARC and integrated with a

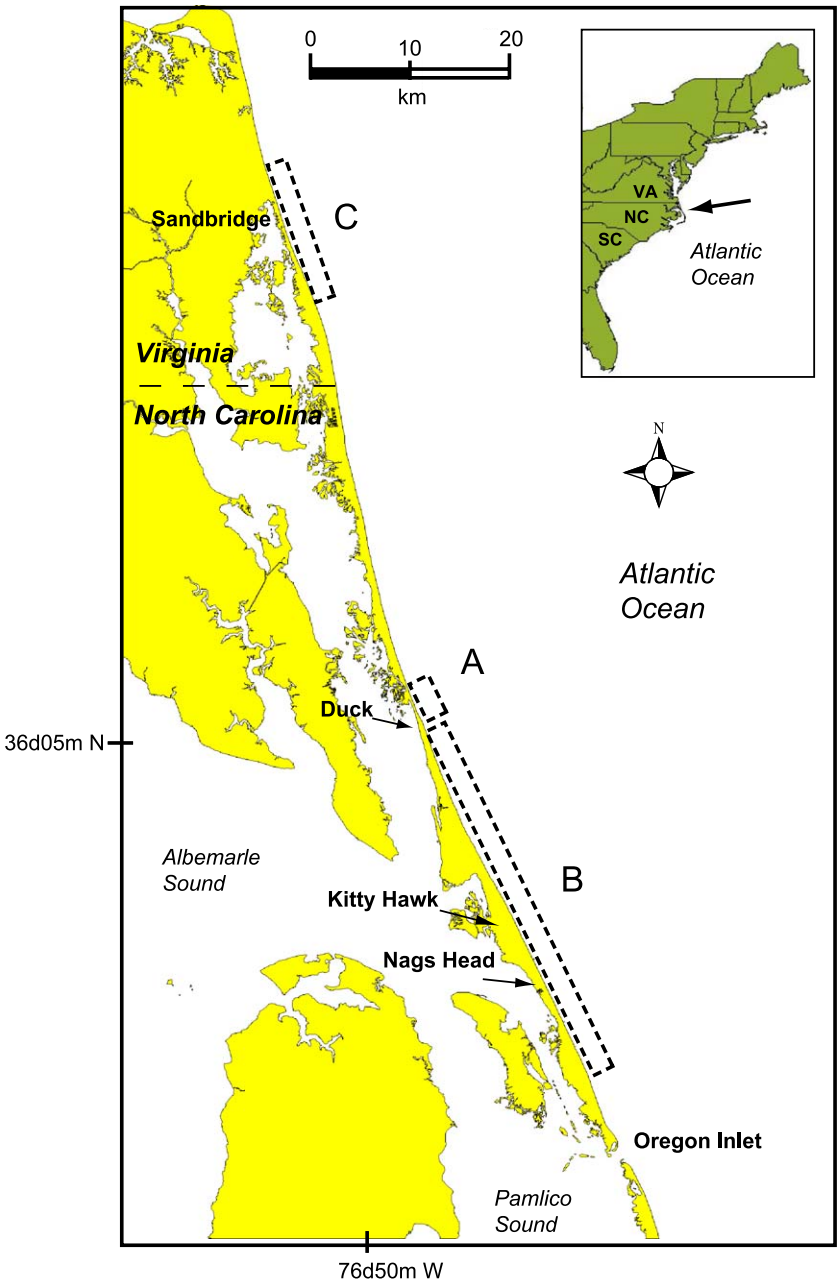

Fig. 2. Location map of nearshore surveys at Duck, North Carolina (A); northern Outer Banks from Duck to Nags Head, North Carolina (B); and southeastern Virginia from Dam Neck to Back Bay Wildlife Refuge, Virginia (C).

motion sensor and real-time kinematic GPS (RTK-GPS) was used to map the bathymetry and acoustic backscatter of the seafloor across the surf zone of the field sites (Fig. 2). The interferometric system provided swath bathymetry and side-scan sonar images (backscatter) across a swath width of approximately eight times the water depth. The amphibious vessel provided virtually unlimited access to the surf

zone, from the 10–12 m isobath to the trough, reaching depths of less than 2 m during favorable weather conditions. Soundings were measured relative to mean low water (MLW) using the vertical control provided by RTK-GPS (±5 cm) and checked with the NOAA tide station located on the FRF pier. RTK-GPS also provided horizontal control on the order of 5 cm but the cumulative errors associated with vessel motion, speed of sound variations, and acoustic attenuation/noise placed our depth sounding precision conservatively at 15–20 cm in the horizontal and vertical. A comparison of soundings collected by the CRAB (Birkemeier and Mason, 1984) and the LARC-mounted interferometric system in a small area near the FRF pier resulted in an average vertical difference of less than 1 cm with a standard deviation of less than 7 cm.

3.1.1. Ephemeral features—Duck, NC field site

Interferometric swath surveys across the smaller Duck field site (Fig. 2A) in July and August 1999 first revealed shore-oblique bars clustered around a small exposure of mud and gravel substrate in water depths of 5–6 m (Fig. 3A). These sandbars were relatively small, measuring roughly 100 m in length, 25 m wide with amplitudes in the 1–2 m range. Konicki and Holman (2000) identified bars oriented perpendicular to the shoreline from this same region using video cameras and called them *offshore transverse bars* because the bars extended seaward from the shore-

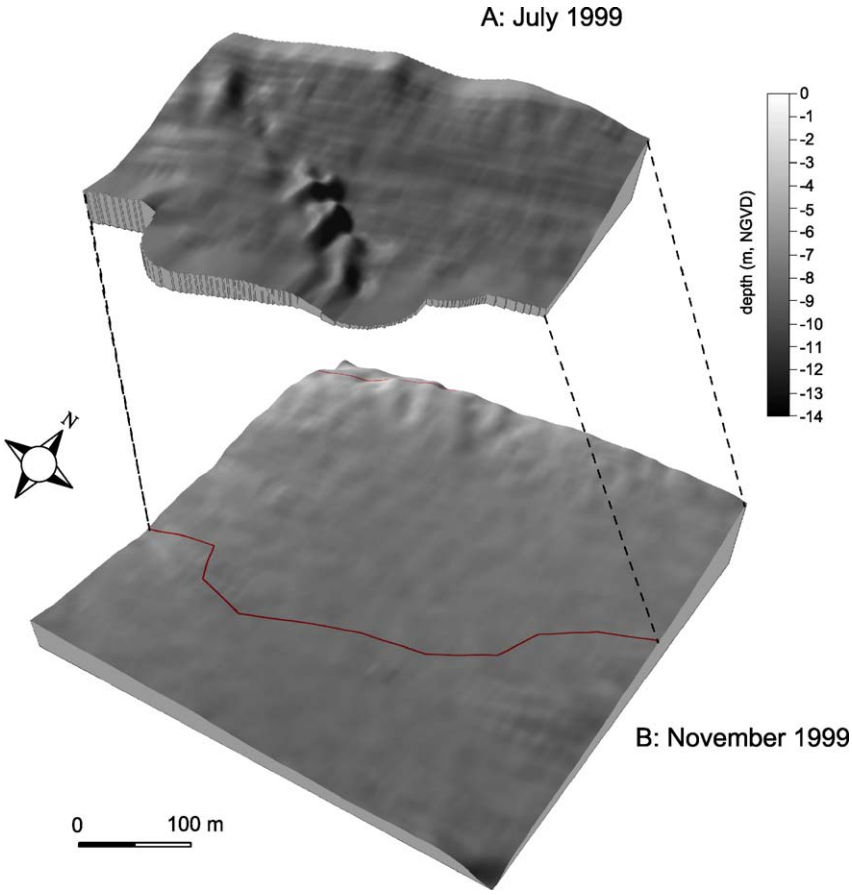

Fig. 3. Duck, NC nearshore bathymetry in July 1999 (top) showing small shore-oblique sandbars and depressions with mud-gravel outcrops. Seafloor bathymetry from the same region following Hurricane Dennis in November 1999 is shown in the lower image. All evidence of shore-oblique sandbars and gravel outcrops was removed from the seafloor surface, presumably by the hurricane.

parallel bar. Most of the shore-oblique bars seen in this study were isolated to the nearshore and did not extend seaward of the 12 m isobath nor did they appear to be associated with a larger, more seaward, shoreface-attached ridge complex (described in Off, 1963; Swift, 1975; McBride and Moslow, 1991; Snedden and Dalrymple, 1998).

The acoustic signature of the outcropping mud and gravel was significantly different from the surrounding fine sand of the shoreface and thus easily identifiable in the backscatter amplitudes from the interferometric system. Acoustic interpretations of the lithology were groundtruthed with grab samples and two vibracores collected from the CRAB and positioned via RTK-GPS. One vibracore, located on the mud outcrop, showed a complex facies of organic-rich, cohesive mud layers between beds of fine sand and shelly gravel similar to the description of the 'pre-modern' unit provided by Schwartz et al. (1997). The other vibracore, located on the crest of one of the shore-oblique bars, showed a moderately well-sorted fine to medium sand unconformably overlying the pre-modern unit. A subsequent survey in August 1999 showed minimal change in the position of the shore-oblique bars or the outcropping pre-modern unit. No significant wind or wave energy events occurred between the July and August 1999 surveys, and no other surface exposure of the pre-modern unit was seen across the field site.

Hurricane Dennis approached the region in late August 1999 and generated substantial wave energy. Significant wave height of >4 m was measured at the FRF 13-m wave array (see www.frf.usace.army.mil/frfdata.html). Post-storm interferometric surveys in September and November 1999, along with surface sediment grab samples, showed that the small shore-oblique bars were no longer present (presumably eroded and redistributed across the shoreface) and that the muddy-gravel substrate was buried by fine sand. The shoreface appeared to return to a more 'textbook' post-storm condition with a featureless convex shoreface devoid of shore-oblique bars in the outer surf zone and a uniform distribution of fine sand across the seafloor (Fig. 3B). Interestingly, later surveys in September 2000 and February 2001 revealed re-exposure of the mud and gravel substrate along with small shore-oblique bars but the location of the outcrops had shifted landward and now appeared in the inner surf zone.

3.1.2. Stable features—Kitty Hawk, North Carolina

Results from the larger field sites, Duck to Nags Head, NC and Sandbridge to Back Bay National Wildlife Refuge, VA, (Fig. 2B and C) revealed a similar pattern of isolated clusters of shore-oblique bars flanking large outcrops of underlying mud and gravel substrates. The size of the shore-oblique sandbars and adjacent outcrops, however, were much larger at two regions, Kitty Hawk NC and Sandbridge VA, and spanned much of the nearshore from the 2 to 10 m isobaths (Figs. 4 and 5, respectively). The nearshore morphology of the outcrop regions contrast greatly with the more commonly found smooth, convex shoreface seen across most of the field site. Also, unlike the ephemeral behavior of the Duck outcrops and bars, repetitive surveys of the Kitty Hawk site showed stability of these large-scale features before and after several very energetic events. Smaller clusters, having one or two outcrops and flanking shore-oblique bars, were found at four other locations from Sandbridge, VA to Nags Head, NC.

A smaller region within the Kitty Hawk site, approximately 4 km alongshore that encompassed both the shore-oblique features and the adjacent planar shoreface (see inset box in Fig. 4), was surveyed again following a Northeaster in March 2003 and in November 2003 following Hurricane Isabel. These surveys revealed very similar morphology and position of the shore-oblique features when compared to May 2002. Fig. 6 (top panel) shows a color-filled bathymetric chart compiled from the November 2003 depths. Two large shore-oblique bars with flanking troughs are visible extending from the 5 to 10 m isobaths as well as a smaller shore-oblique feature located south of the larger bars and in depths ranging from 3 to 5 m. The middle panel in Fig. 6 shows the same color-filled bathymetry from November 2003 with the March 2003 bathymetry draped on top as white contour lines. The bottom panel shows November 2003 bathymetry with May 2002 bathymetry draped on top as white contour lines. The similarities of the large-scale, shore-oblique features are remarkable, particularly in the shallow areas of the nearshore where the morphology of these unconsolidated sediments can easily be influenced by wave

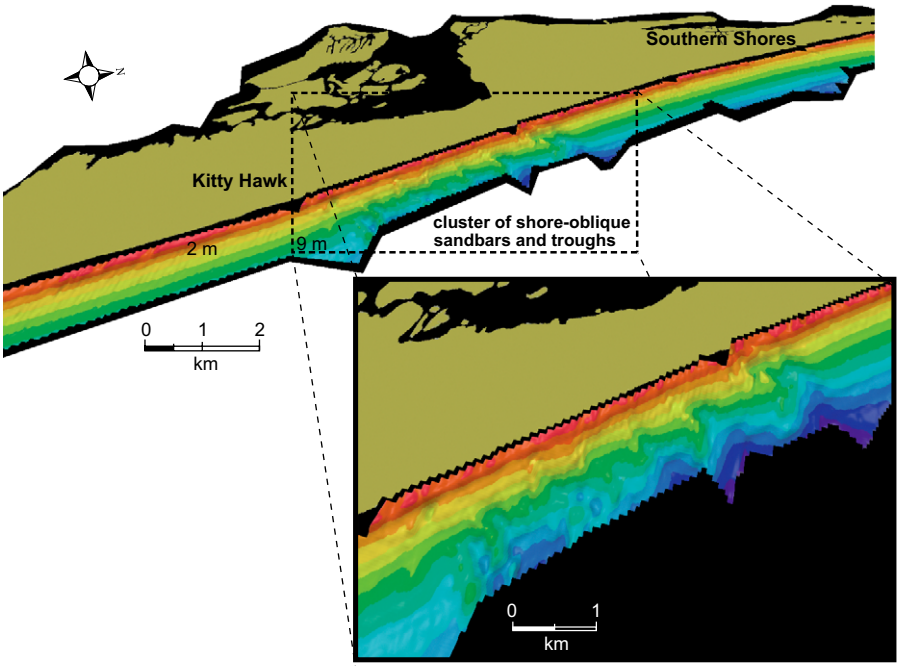

Fig. 4. Shoreline and nearshore bathymetry from Nags Head to Duck, North Carolina showing a large cluster of shore-oblique sandbars and troughs near Kitty Hawk in contrast to the smooth, slightly convex shoreface of the surrounding regions.

energy. The May 2002 survey was conducted during a long fair-weather time period, following several weeks wherein the wave energy measured at the nearby Field Research Facility in Duck was less than 1.5 m. The March 2003 survey, in contrast, was conducted 2 days after a Northeaster storm that generated sustained 2–3 m high waves (>30 h). The November 2003 survey followed Hurricane Isabel,

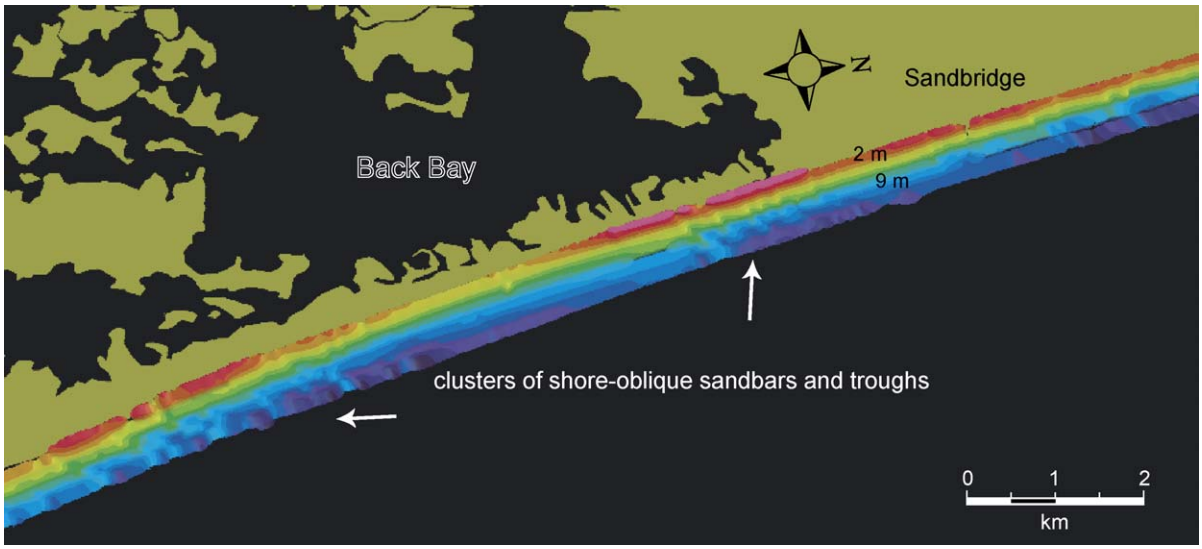

Fig. 5. Shoreline and nearshore bathymetry from Back Bay Wildlife Refuge to Dam Neck, Virginia showing several clusters of shore-oblique sandbars and troughs in contrast to the smooth, slightly convex shoreface of the surrounding regions.

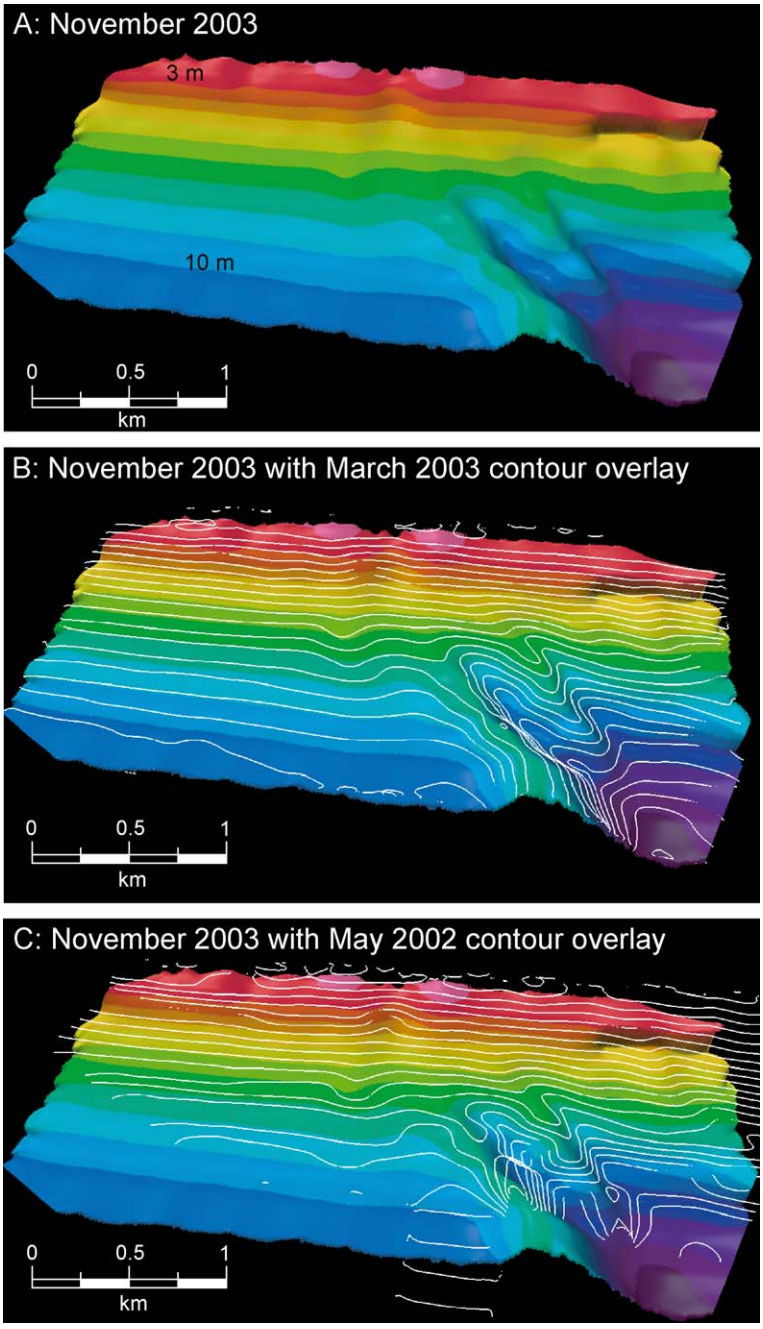

Fig. 6. A sequence of nearshore bathymetry collected at the Kitty Hawk, North Carolina site that encompasses a region characterized by a smooth, convex shoreface adjacent to large, shore-oblique sandbars and troughs. (A) Three-dimensional block diagram of depths measured after Hurricane Isabel in November 2003. (B) November color bathymetry with March 2003 bathymetry (post-northeaster storm) overlaid as white contours. (C) May 2002 bathymetry (fair weather), shown as white contours, with the November 2003 colored bathymetry. The large-scale morphology and position of these shore-oblique features remained similar after each fair-weather and post-storm survey.

which created significant wave heights in excess of 8 m (the highest ever measured at the FRF). Although the November 2003 survey does not reflect immediate post-storm conditions—6 weeks had elapsed since the hurricane—the position and morphology of the shore-oblique features were essentially identical after each of the fair-weather and post-storm surveys.

Backscatter intensity from the Kitty Hawk surveys is shown in Fig. 7. Areas of high backscatter, shown here as bright patches, were groundtruthed via surface sediment grab samples and found to be gravel while the darker areas are fine to medium sands. The top panel (A) shows a backscatter mosaic, collected during the May 2002 survey, draped over the May 2002 bathymetry. Linear patches of gravel are visible on the seafloor surface, exposed in the shore-oblique troughs (see larger scale insets). The middle (B) and bottom (C) panels show backscatter draped on bathymetry from the March and November 2003 surveys, respectively. Like the May 2002 mosaic, exposures of gravel are found along the shore-oblique troughs on both post-storm mosaics. The colored lines

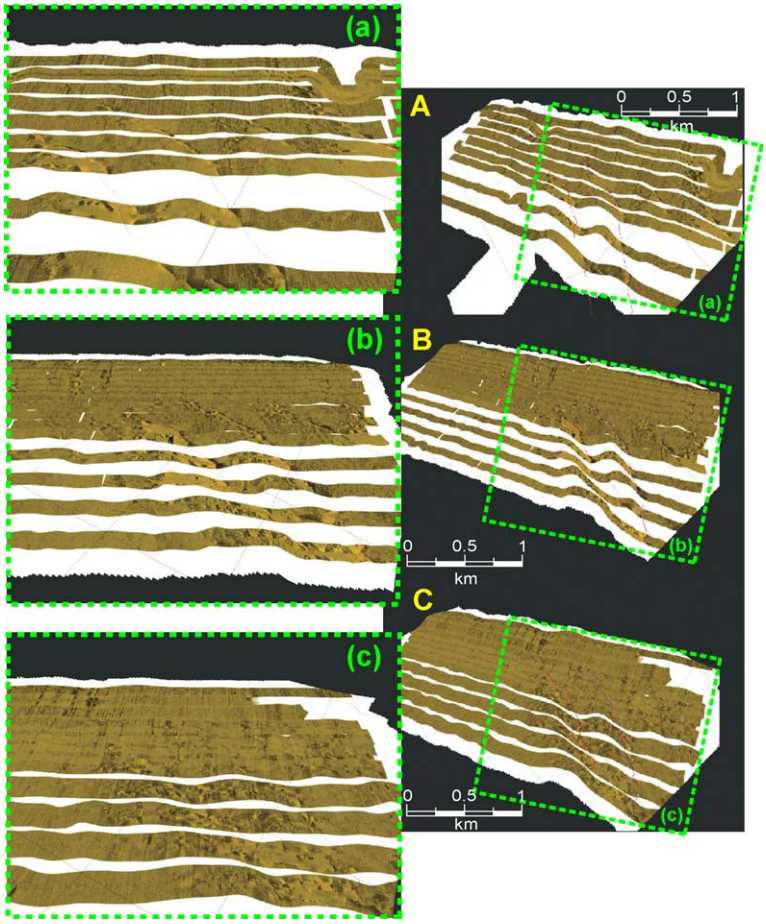

Fig. 7. Side-scan sonar mosaics draped over the bathymetry of the nearshore from the Kitty Hawk, North Carolina site that encompasses a region characterized by a smooth, convex shoreface adjacent to large, shore-oblique sandbars and troughs. The high backscatter, shown as bright patches, correlates to gravel on the seafloor surface, and the dull areas are fine to medium sand. The mosaic images from top to bottom were surveyed in May 2002 (a), March 2003 (b), and November 2003 (c), respectively. The colored lines mark the sand-gravel contacts measured in March 2003 and are overlaid in the same position on the May 2002 and November 2003 mosaics. Small-scale changes in surface sediment distribution are visible but the large-scale morphology of the gravel outcrops appears consistent between the post-storm and fair-weather points of observation.

mark the sand-gravel contacts measured in March 2003 and are overlaid in the same position on the May 2002 and November 2003 mosaics. These comparisons indicate changes in surface sediment distribution at a small scale, seen in these examples as thin sand layers migrating around the gravel outcrops. The dispersal of gravel, however, beyond the trough and northern flanks of the adjacent sandbars is quite limited, and the large-scale morphology of the gravel outcrops remains similar between surveys.

3.2. Minimal sand draped over a continuous seismic reflection

An Edgetech 216S, 2–15 kHz, chirp sub-bottom profiler was towed simultaneously during the interferometric swath sonar surveys at all field sites using dual-channel GPS for navigation control. Collectively, the two systems provided a synoptic, three-dimensional map of the seafloor morphology and surface sediment as well as the depth and morphology of the underlying substrates and the acoustic nature of these substrates. The combination of these data is particularly useful in determining accurately the elevation, relative to a vertical tidal datum, of underlying substrates. Sub-bottom reflections are typically mapped relative to the distance from the seafloor surface by converting acoustic travel time to distance using an estimate of the speed of sound through the type of sediment/rock encountered. Depth below the seafloor was estimated using 1750 m/s (Hamilton, 1971) for sandy sediment and the reflection depth relative to MLW was determined by adding the sediment thickness above a given reflection with the seafloor bathymetry from the interferometric data.

A strong reflection is visible beneath the shore-oblique bars and remains virtually continuous across the entire field site. When the reflector is exposed on the seafloor, often in the shore-oblique troughs, high backscatter from the interferometric system along with surface sediment grab samples indicate that the outcrops are largely gravel. The sub-bottom profiles reveal an underlying surface that is relatively smooth, mirroring the overlying convex-shaped shoreface. An exception to this smooth, convex-shaped underlying substrate is found in areas where shore-oblique bars and large gravel outcrops occur. In these areas, the topography of the underlying surface is more irregular

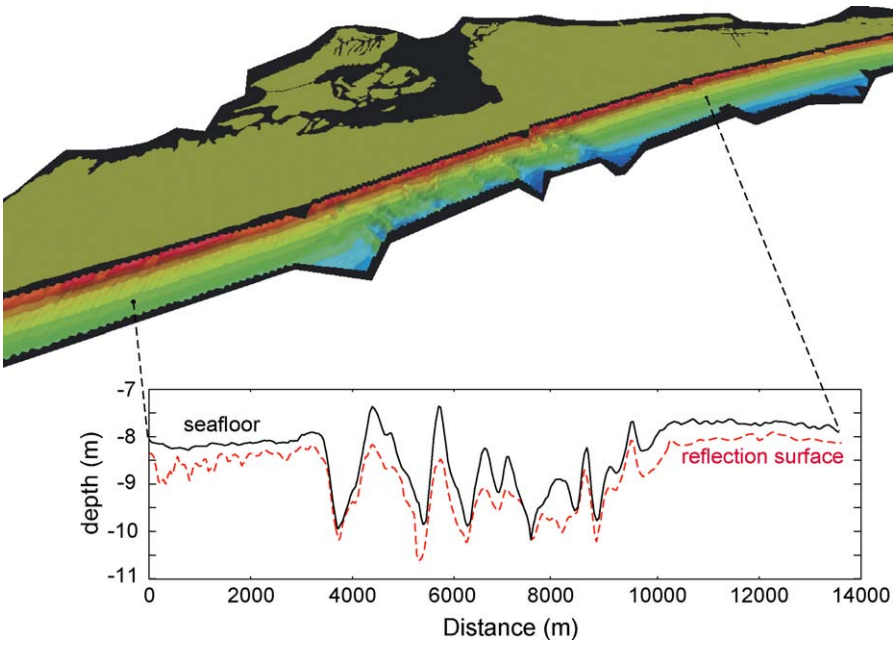

Fig. 8. Cross section of the seafloor and surface of the underlying substrate along a 14-km line that is oriented shore-parallel and includes the Kitty Hawk shore-oblique bar cluster. Note the high relief of both the underlying substrate (dashed line) and seafloor (solid line) in the outcrop-bar region in contrast to the smooth surfaces seen to the north and south.

with greater vertical relief in the alongshore direction. An example from the Kitty Hawk region depicted in Fig. 8 shows a cross section of the surface of the seafloor (solid line) and the surface of the underlying substrate (dashed line) along a track oriented shore-parallel roughly 500 m from the beach. The amplitude of relief in the outcrop regions is on the order of 3 m while the surrounding areas exhibit alongshore relief typically less than 50 cm. The underlying reflection only becomes exposed in the shore-normal depressions and typically on the north flank of the shore-oblique bars.

The thickness of surface sand across the entire field site is minimal, rarely exceeding 1.5 m. Fig. 9 shows an isopach map of the surface sand thickness covering a 20 km reach of nearshore that includes the Kitty Hawk region. Average sand thickness for three, 4-km-long stretches of nearshore is also shown in Fig. 9. Mean thickness for all areas is less than 50 cm. Although the average thickness of sand is roughly

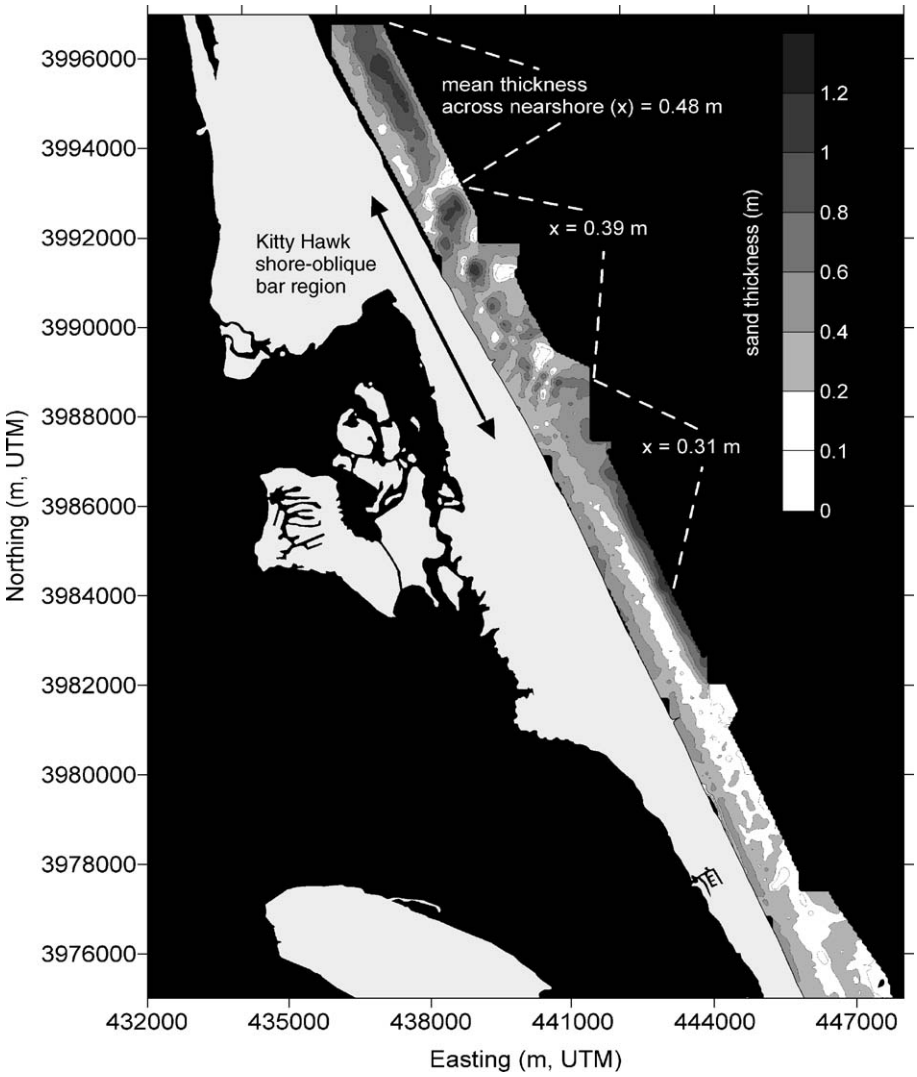

Fig. 9. Isopach map showing sand thickness across the nearshore of Kitty Hawk, North Carolina and surrounding areas. Average sand thickness from three, 4-km-long sections is presented in the text. Note the shore-normal orientation of sand encompassed within shore-oblique sandbars from the outcrop region versus the shore-parallel distribution in the surrounding areas.

equal across the field sites, the spatial distribution is noticeably different in the area where shore-oblique bars and outcrops occur. In the outcrop regions, surface sediment is encompassed within the large sandbars and oriented obliquely to the shoreline, whereas the adjacent more planar shorefaces have the majority of sand widely distributed and oriented shore parallel.

4. Discussion

4.1. Correlation of erosional hotspots with shore-oblique sandbars and gravel outcrops

A total of seven groups of large gravel outcrops, each with associated shore-oblique sandbars, have been identified in the nearshore of the 56 km field site. A wide expanse with multiple outcrops and adjacent sandbars was expressed at two sites while the remaining five exhibited only two or three gravel exposures with flanking shore-oblique bars. It is unknown whether the position and large-scale morphology of all of these outcrops and bars are ephemeral as seen at the Duck site or stable as observed at the Kitty Hawk site. The locations of the outcrops and bars are shown in Figs. 10 and 11 for the North Carolina and Virginia field sites, respectively. The top panel in both figures displays the depth gradient measured along a line of strike oriented shore-parallel down the length of the field sites, approximately 500 m seaward of the beach. Depth gradients allow depths to be normalized between field sites and delineate clearly the areas with alongshore relief in the form of outcrop lows and shore-oblique bars. Long-term shoreline change rates (spanning 40 years; end-point methodology) for the length of the North Carolina field site are shown on the bottom panel in Fig. 10 (from Benton et al., 1997). Four significant erosional hotspots, all exceeding an erosion rate of 1 m/year, are apparent, and in each case an occurrence of outcrops and shore-oblique bars is

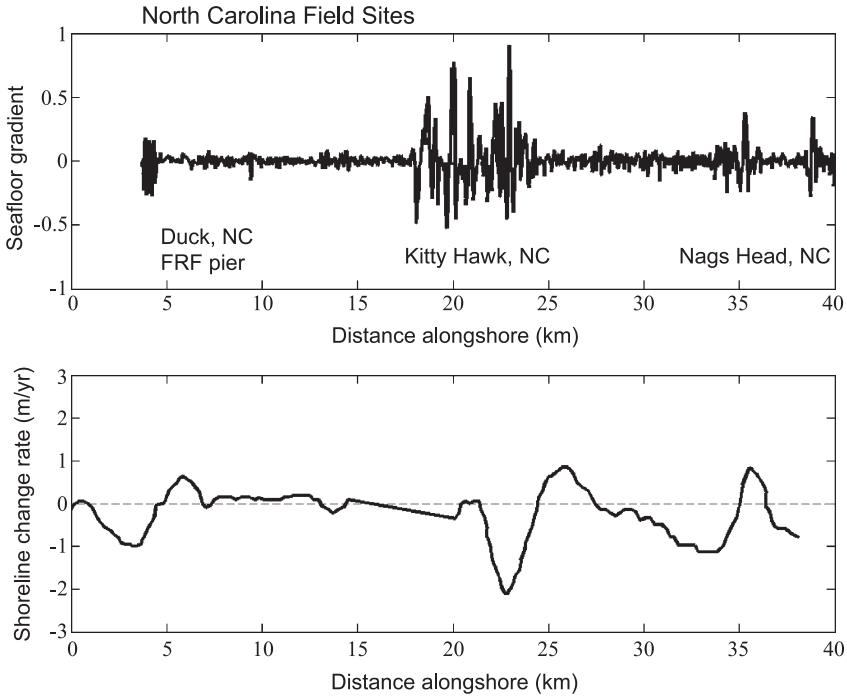

Fig. 10. Graphical spatial correlation of shore-oblique sandbars and gravel outcrops with shoreline change rate. (A) Seafloor surface gradient calculated from depths along a shore-parallel transect which highlights areas with high bathymetric relief (sandbars and depressions oriented shore-normal) from Duck to Nags Head, North Carolina. (B) Long-term shoreline change (m/year) across the same region. Data from Benton et al. (1997).

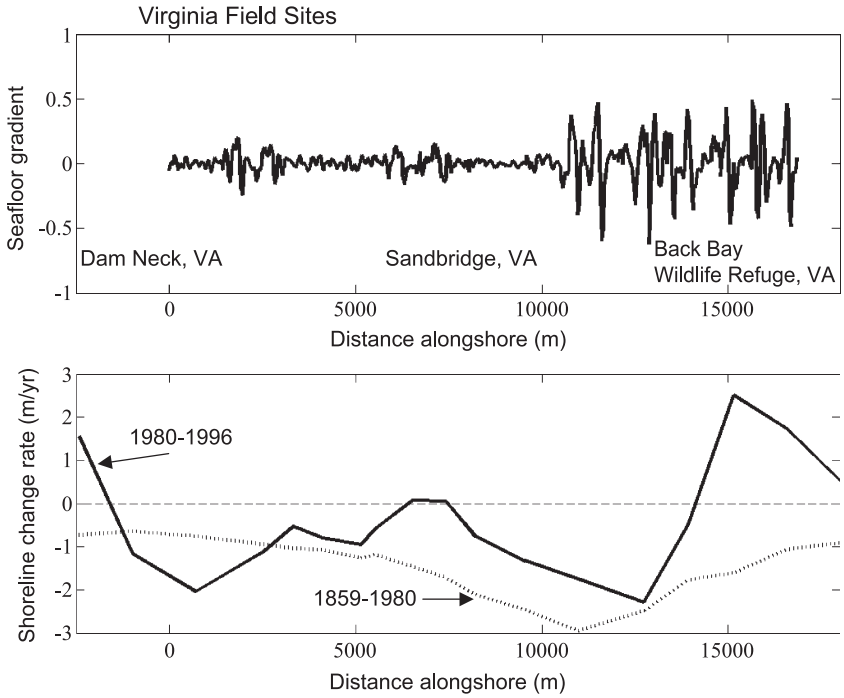

Fig. 11. Graphical spatial correlation of shore-oblique sandbars and gravel outcrops with shoreline change rate. (A) Seafloor surface gradient calculated from depths along a shore-parallel transect which highlights areas with high bathymetric relief (sandbars and depressions oriented shore-normal) from Dam Neck to Back Bay Wildlife Refuge, Virginia. (B) Long-term shoreline change (m/year) across the same region. Data from Hobbs et al. (1999).

closely aligned. The erosional hotspot shown at the far south end of the plot (near km 38 in Fig. 10), however, reaches a peak farther south and is likely influenced by the proximity to Oregon Inlet and the resulting shoreline changes associated with a migrating inlet and ebb tidal delta.

The US Geological Survey has been monitoring the North Carolina shoreline from Corolla to Oregon Inlet since 1997 using a dual-channel GPS system mounted on an ATV called SWASH (List and Farris, 1999). The standard deviation of shoreline change (defined as the intersection of MHW and the beach) from an initial baseline has been calculated from shoreline surveys, conducted primarily before and after storms. These surveys have shown recurring hotspot behavior in the Kitty Hawk region where large clusters of bars and outcrops have been found and an ephemeral occurrence of a hotspot near the Duck outcrop site. Many of the short-term hotspots that List has observed (List et al., 2004), however, are ephemeral and/or spatially shifting and do not appear to correlate with the location of outcrops and shore-oblique features in the nearshore. Also, the regions of long-term erosion are not all reflected in the short-term behavior measured by SWASH (List et al., 2004). List and Farris (1999) show, for example, high standard deviation (hotspot) for a large region north of Duck, NC but a matching erosional hotspot is not seen in the long-term change map (Benton et al., 1997). Intuitively, long-term shoreline change simply reflects an integration of short-term shoreline behavior so either the long-term map is flawed or more than 5 years of shore-term observation is needed to more closely mirror long-term trends.

Fig. 11 shows a similar alongshore-oriented profile of depth gradient from Sandbridge to Back Bay National Wildlife Refuge, Virginia in the top panel. Long-term annual erosion rates (end-point rate for 1859–1980) for the same area are shown on the lower panel (from Hobbs et al., 1999). The 1859–1980 calculation shows shoreline change prior to renourishment and other extensive shoreline engineering efforts

in this study area. The annual change rates determined from 1859 to 1980 show widespread beach erosion, exceeding the 1 m/year level over roughly 12 km (from 4000 to 18,000 on the x axis of Fig. 11) of the 16 km field site. The area of maximum erosion, near 12000 m on the x-axis, aligns with the largest cluster of outcrops and shore-oblique bars. The two smaller occurrences of shore-oblique features are encompassed within the overall shoreline loss region but do not show a distinct and separate shoreline change at each location. The 1980–1996 shoreline change estimate used numerous beach profiles through the years that included seasonal variations but also may have been influenced by seawalls across much of Sandbridge and a large renourishment project (~1 million m^3) in Dam Neck, VA. Despite these possible external influences, the area of highest erosion still aligns with the largest set of shore-oblique bars and outcrops. The two smaller, isolated groups of bars and outcrops located in the middle of the field site do not have a clear shoreline hotspot signal.

Although the number of shore-oblique bars/outcrops and documented erosional hotspots is too limited along the length of the combined field sites to support a worthwhile statistical analysis, the close spatial correlation warrants further investigation. If a link is later confirmed, the expression of large shore-oblique sandbars and outcropping geology in the surf zone of sand-limited settings may provide a clue as to the presence of erosional hotspots. What often requires years of beach surveying to determine alongshore variations in erosion may be identified by a nearshore survey of the bar morphology and underlying geology. Also, unraveling the process-relationship between underlying geology and erosional hotspots could greatly improve erosion mitigation strategies. Questions, such as whether the underlying strata will re-exert itself over time if buried by a renourishment fill, may be addressed if we understand how/if underlying geology influences the development and stability of large-scale nearshore features.

4.2. Geologic control—stability of large-scale shore-oblique sandbars and outcrops

The large-scale, shore-oblique sandbars observed in the nearshore of the North Carolina and Virginia sites contrast both in size and stability from previously documented transverse bars and possibly represent an end-member or separate category altogether of nearshore bar. These differ from the small, low-energy transverse bars documented by Bruner and Smosna (1989) and Niedoroda and Tanner (1970) and from the wave-controlled transverse bars described by Wright and Short (1984). Konicki and Holman (2000) examined 10 years (1987–1996) of Argus time exposure video images from the nearshore region north of the FRF pier (near the Duck field site: Fig. 2A) and repeatedly observed transverse bars emanating from shore-parallel bars in both the trough and outer surf zone. Although these showed no relationship to rip currents like the observations of Wright and Short (1984) and appeared to be decoupled from longshore currents (Barcilon and Lau, 1973), they were spatially and temporally dynamic, migrating alongshore and getting reworked during storm conditions. It is unclear whether the offshore transverse bars observed by Konicki and Holman (2000) are related or in fact are the same small, ephemeral shore-oblique bars surveyed in 1999 (Section 3.1.1). What is apparent, nevertheless, is that a wide range in size, orientation, and behavior exists for shore-oblique/transverse nearshore sandbars, and our current understanding of waves and currents forcing bar morphodynamics over a patchy substrate is inadequate to fully describe these observations.

The fundamental question that this work brings to light is whether framework geology, defined in this region as layers of largely unconsolidated fluvial and estuarine (non-sandy) sediment (Riggs et al., 1995; Schwartz et al., 1997; Boss et al., 2002) that underlie the surface sand, can influence nearshore morphodynamics. Waves are clearly important and are the principal forcing component in bar morphodynamics and shoreline change. Results from the Kitty Hawk outcrop region, however, show sustained or nearly identical re-development of shore-oblique sandbars and gravel outcrops in the nearshore (active surf zone during Hurricane Isabel) through a year and a half of fair weather and multiple storm events. The stability of these unconsolidated bedforms in a setting with such a dynamic wave climate suggests that waves and currents are not the only first-order variables shaping nearshore morphology.

Ripple scour depressions and/or persistent linear patches of sorted sediment are ubiquitous across much of the world's inner shelves (Murray and Thieler, 2004). The author is not aware of similar observations extending into the surf zone but suspects that this may be a result of limited side-scan sonar surveys in the nearshore and as described here are not necessarily an anomalous occurrence. Although ripple scour depressions were first associated with downwelling mean currents (Cacchione et al., 1984), recent studies indicate that similar sorted bedforms may be maintained in shallow, wave-dominated settings without strong, seaward-directed mean flows (Green et al., 2004; Trembanis et al., in press). The May–June 2002 nearshore surveys, which covered 56 km, revealed numerous (>20) linear patches of gravel outcrops that reached depths as shallow as 3 m and appeared very similar to previously described sorted bedforms (Fig. 12). In all instances in which a large outcrop of gravel occurred, defined as greater than 100 m width, large shore-oblique bars were present and located on the south side of the outcrop (Schupp et al., 2002).

Recent observational work on sorted bedforms by Gutierrez et al. (in review) near Wrightsville Beach, NC and rippled scour depressions near Tairua, New Zealand (Green et al., 2004) has identified wave-driven, self-maintaining sorting mechanisms created by differences in seafloor roughness (Trembanis et al., in press). Murray and Thieler (2004) also showed through model simulations that differences in roughness, be it grain size or bedforms, created self-sustaining environments that were not conducive for settling of fine sand in the coarse-grained depressions. Green et al. (2004) showed that storm conditions were important for the growth and maintenance of coarse gravel patches while fair-weather conditions tended to promote the burial of these features. Consistent with these observational and modeling studies, high-resolution images from the nearshore side-scan sonar surveys revealed very sharp lines of contact between the sand and gravel (Fig. 12B), and repetitive surveys suggested that, though the contact lines may migrate, segregation of fine and coarse sediment domains was maintained (Fig. 7). Although none of these cited studies extended into the nearshore or outer surf zone, it seems reasonable that some form of a roughness-generated sediment transport gradient may be responsible for the stability of the shore-oblique bars and the exposed gravel patches. The observed stability of shore-oblique sandbars may result from minimal bar migration in areas where the sand layer is thin and overlies a much coarser substrate that becomes exposed. The shore-oblique sandbars may thus represent an efficient morphology balancing hydrodynamics with limited sand on a much rougher migration surface. If true, this could explain the ephemeral recurrence and smaller-sized, shore-oblique bars in the Duck region where the spatial distribution of the underlying coarse substrate was quite limited and easily buried (e.g. small relict tidal inlet that was filled with gravel or a patch of peat/cohesive mud). In contrast, the large and stable outcrops/sandbars of the Kitty Hawk and Sandbridge regions may overlie much larger expanses of coarse substrate that are less easily buried.

Many geophysical surveys across the inner and mid-continental shelf of North Carolina show a relatively smooth ravinement surface that has formed during the Holocene sea level rise, leaving only relict channel-fills and erosion-resistant highs covered by a very thin lens of modern sand (Hine and Snyder, 1985; Riggs et al., 1995; Boss et al., 2002). Traditional assumptions hold, however, that closer to the beach in the nearshore where the underlying geology is not consolidated, a thick homogenous wedge of sand covers the underlying substrate. This is not the case throughout the North Carolina and Virginia field sites where the thickness of the surface sand across the nearshore is limited and spatially variable (Fig. 9) and the topography of the underlying substrate is irregular in locations where the large shore-oblique features occur (Fig. 8). The spatial distribution of sediment thickness, though relatively thin throughout the field sites, does differ in that essentially all of the sand in the outcrop-hotspot regions is encompassed within the large shore-oblique bars while the surrounding areas have a more continuous drape of sand oriented shore-parallel.

Recent work investigating the attenuation or broadening of wave energy near the shoreline of the North Carolina Outer Banks in response to either topographic irregularities on the inner-mid shelf (Palmsten et al., 2002) or wave-bottom Bragg scattering and small scale roughness (Ardhuin et al., 2003) indicates that alongshore gradients in sediment transport may be generated. Numerous investigations using a variety

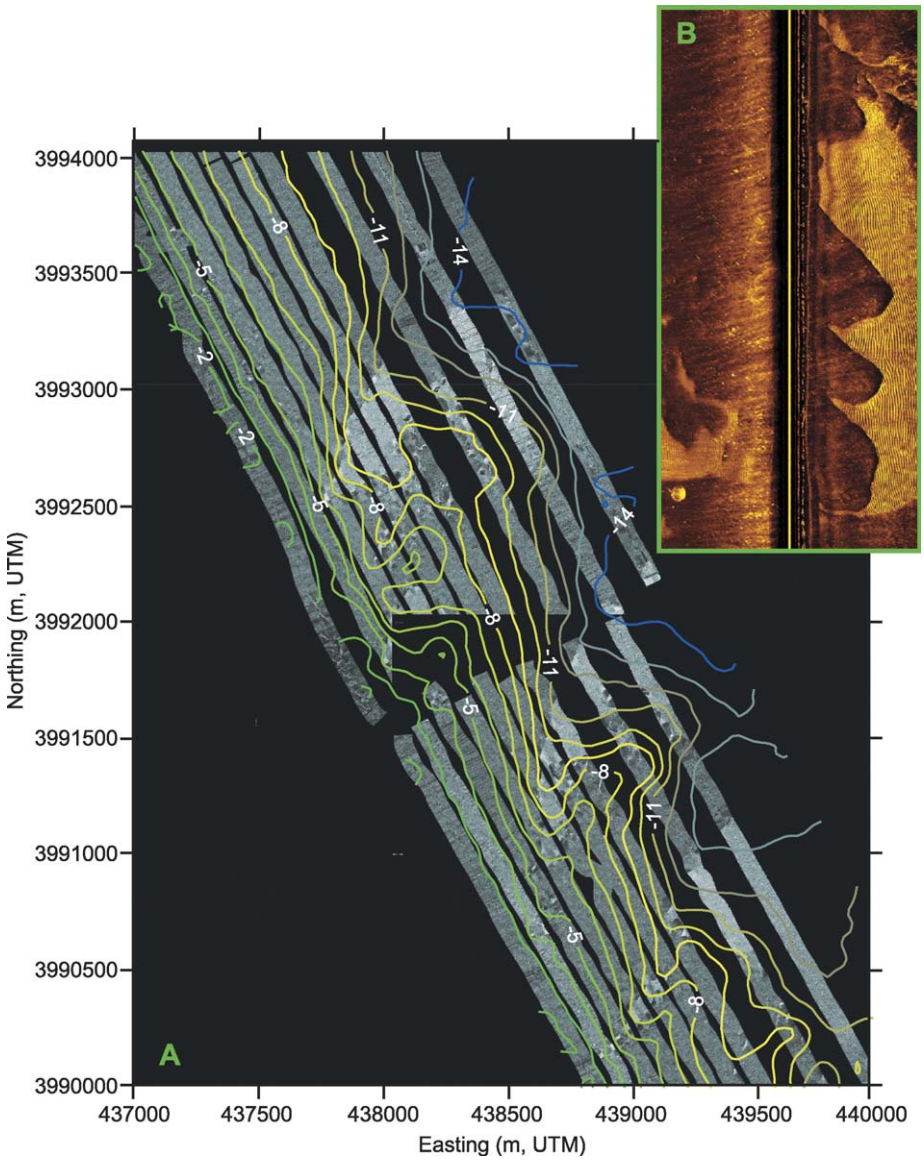

Fig. 12. (A) A side-scan sonar mosaic from the May–June 2002 nearshore surveys showing linear patches of gravel outcrops oriented shore-obliquely and extending into depths as shallow as 3 m. (B) High-resolution side-scan sonar images reveal very sharp lines of contact between the sand and gravel with the gravel being sorted into wave ripples.

of wave models show similar convergence or divergence of wave energy at the shoreline in response to topographic irregularities on the shelf (e.g. O'Reilly and Guza, 1993; Maa and Hobbs, 1998; Bender and Dean, 2002). Ashton et al. (2002, 2003) also argue that nearshore wave gradients may occur simply from self-organization of wave-driven hydrodynamics when waves approach a shoreline at an oblique angle and thus do not require irregularities in seafloor bathymetry to generate differences in alongshore sediment transport. Calculations of the total volume of sand encompassed within the NC–VA nearshore suggest that these potential large-scale gradients in wave energy and sediment transport have not created significant alongshore variations in nearshore sediment volume (Miselis and McNinch,

2002; 2003). Presumably if erosional hotspots could be explained by gradients in wave energy and net sediment transport alone, regions of less sand would align with documented erosional hotspots. Instead, measurements reveal little difference in volume between regions exhibiting shore-oblique features and erosional hotspots and those with more stable shorelines and no outcrops (Miselis and McNinch, 2002; 2003).

Sub-bottom chirp profiles collected in the nearshore also reveal a relict channel beneath many of the outcrop/shore-oblique bar regions identified in the NC–VA 2002 bathymetric survey (Browder and McNinch, 2004). This is exemplified in Fig. 13, which shows a cross section of a large channel directly beneath the Kitty Hawk outcrop/shore-oblique bar region where channel edges aligned with the outer edges of the shore-oblique bar cluster. The existence and location of this ancient channel had been identified in earlier seismic profiles run farther offshore which showed the presence of a former Pleistocene fluvial channel that was likely the ancient Roanoke River (Riggs et al., 1995; Boss et al., 2002). It is hypothesized that the in-filled lithology of these relict channels is coarser and has more steeply dipping bedding planes than the surrounding areas. These characteristics may lead to differential erosion of the underlying substrate when exposed (high relief exemplified in Fig. 8) and create a coarse migration surface that enhances self-maintaining sediment-sorting processes, making these outcrop regions conducive to the development and stability of large, shore-oblique sandbars. The location of initial exposure and differential excavation of the underlying gravel substrate may be a function of one of the bathymetry-influenced wave-focusing mechanisms discussed above. Simply put, not all regions with underlying layers of gravel will necessarily become exposed and generate these shore-oblique features—it may require a combination of steeply dipping beds of coarse substrate along with repeated gradients of wave energy to initiate the self-sustaining bedforms. The

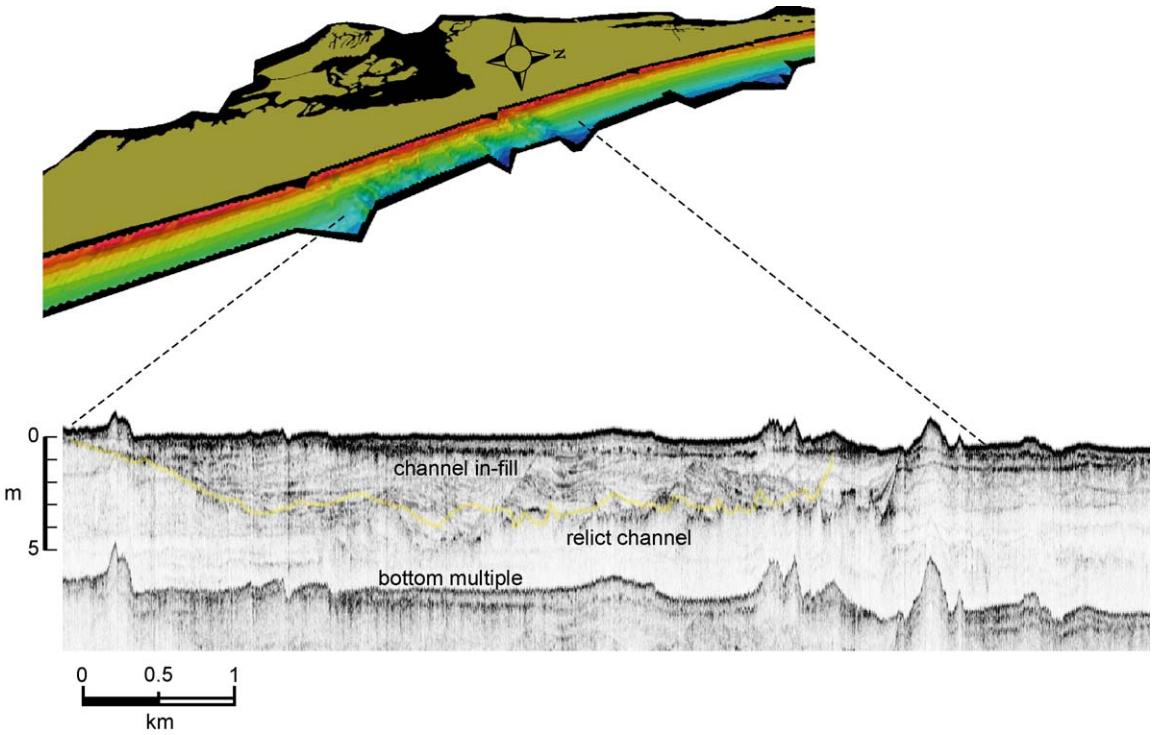

Fig. 13. A chirp sub-bottom profile that shows the incised channel and subsequent infilling of a large, Pleistocene river. The channel edges closely align with the boundary of shore-oblique features in Kitty Hawk, North Carolina.

increased long-term shoreline erosion may therefore be explained by the orientation of sandbars in the outcrop region allowing higher wave energy to be delivered directly to the beach and creating higher set-up during storms. This may, in turn, create greater sediment loss from the upper beach, albeit small and incremental, such that these regions do not fully recover over annual or decadal time periods and in the end behave as erosional hotspots.

5. Conclusions

Results from sub-bottom profiles and swath bathymetry collected across the nearshore of the North Carolina Outer Banks and Southeastern Virginia show the following:

(1) sediment grain-size heterogeneity across the seafloor surface and a thin drape of sand ranging up to 1.5 m thick across 56 km of nearshore;
(2) recurrence of large, shore-oblique sandbars and gravel outcrops at the same location and with similar morphology through multiple storm-fair-weather periods;
(3) ephemeral development of smaller shore-oblique bars and adjacent outcrops;
(4) relict channels underlying the large regions of outcrop/shore-oblique sandbars;
(5) high topographic relief on the surface of the underlying substrate where outcrops and shore-oblique sandbars occur;
(6) comparable volumes of sand across the nearshore between regions with outcrops/shore-oblique bars and the surrounding areas; and
(7) suggestive spatial alignment between the location of erosional hotspots and outcrops/shore-oblique bar regions.

Documenting the finite amount of surface sand, the heterogeneity of sediment grain-size on the seafloor, and the irregular topography of the underlying substrate in association with outcrops and shore-oblique sandbars in the nearshore highlights the need for models predicting dynamic bathymetry to consider framework geology in similar sediment-limited settings. Numerical simulations of sediment transport and bar morphodynamics under such settings will likely require a high-resolution spatial grid with dynamic boundary conditions for seabed and stratigraphic characteristics (e.g. sediment size, geotechnical properties, and bottom roughness changing in the vertical) in addition to considering a finite and variable amount of sand. These findings, in particular, may be useful in steering future work investigating sediment transport and bar migration when the base of the active prism of sediment is irregular and shallow and defined by unconsolidated, coarse sediment.

More frequent nearshore surveys over a longer time period across the VA–NC field sites would help determine the longevity of these shore-oblique features and better discern the differences in size and the variables which may influence their ephemeral or stable behavior. Also, additional sediment cores need to be obtained to groundtruth the seismic reflections and to more rigorously test the hypothesis of whether more coarse and steeply dipping beds of sediment underlie the outcrop/shore-oblique bar regions. Lastly, morphodynamics of sandbars in the inner surf zone need to be examined during storm and fair-weather conditions to determine if the shore-oblique features found in the nearshore extend to the beach and to gain insight into the mechanism(s) of sediment exchange between the beach and surf zone. Despite these limitations, the findings of this study indicate the need to incorporate vertical and spatial sediment-size heterogeneity into sediment transport models and form the basis of a hypothesis connecting framework geology to nearshore morphodynamics and long-term shoreline behavior.

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