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Jennifer L. Miselis  
*Virginia Institute of Marine Science*

Jesse E. McNinch  
*Virginia Institute of Marine Science*

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# Calculating shoreline erosion potential using nearshore stratigraphy and sediment volume: Outer Banks, North Carolina

Jennifer L. Miselis<sup>1</sup> and Jesse E. McNinch<sup>1</sup>

Received 6 August 2005; revised 4 January 2006; accepted 6 February 2006; published 17 June 2006.

[1] Despite the acknowledged influence of coastal geological framework on the behavior of beaches and barrier islands and a wealth of geological and bathymetric observations from the inner shelf, quantitatively connecting those observations to shoreline behavior has been difficult. Nearshore geologic and morphologic variability described by recent research is not well represented by conventional geologic parameters, such as mean grain size and shoreface slope, used in most shoreline change models. We propose that total nearshore sediment volume, as calculated to a continuous seismic reflection surface, provides a flexible and robust metric for use in the prediction of shoreline change. This method of determining the volume of sediment in the nearshore accounts for three-dimensional sandbar morphologies and heterogeneous seafloor sediments. The decadal-scale shoreline change rate for northeastern North Carolina is significantly correlated to the volume of sediment in the nearshore when a geologically defined base is used in volume determinations, suggesting that the shallow stratigraphic framework of transgressive coasts is an important influence on decadal shoreline behavior. Nearshore sediment volume was overestimated when an arbitrary depth-constant baseline was used and was not correlated to decadal shoreline change. This implies that a volume metric which accounts for both framework geology and variable seafloor morphology better represents the geologic character of the shoreface and may help to improve existing models of shoreline change. An empirical model of regional shoreline erosion potential demonstrates the importance of incorporating nearshore sediment volume, shallow framework geology, and surface morphology when predicting seasonal to decadal shoreline evolution.

**Citation:** Miselis, J. L., and J. E. McNinch (2006), Calculating shoreline erosion potential using nearshore stratigraphy and sediment volume: Outer Banks, North Carolina, *J. Geophys. Res.*, *111*, F02019, doi:10.1029/2005JF000389.

## 1. Introduction

[2] The quantity of transport-relevant sediment, sediment that can be actively transported in the modern littoral system, is considered in two ways in numerical sediment transport models. First, a thin sediment layer defined by small-scale bed forms on the seabed is thought to represent the active envelope of sediment over timescales of seconds to months in many short-term sediment transport exercises [Harris and Wiberg, 2001, 2002]. Second, the total volume encompassed between a constant depth base (some determination of depth of closure) and the seafloor is often considered to be homogenous and available for shoreface profile evolution over long timescales [Bernabeu *et al.*, 2003; Dean, 1997; Dean *et al.*, 1993; Hallermeier, 1978; Kana, 1995]. These methodologies create a substantial gap in temporal scale with respect to when sediment may be

available for transport within the active littoral system and do not accurately reflect the volume of sediment available during this time period of years to decades. This paper proposes a new methodology for determining the volume of transport-relevant sediment that spans years to decades by using a geology-defined base from which to determine volume. We present results from the Outer Banks of North Carolina that indicate a correlation between decadal-scale shoreline change and geologically defined nearshore sediment volume. This work not only has implications for sediment transport models but also may profoundly influence how sediment availability is considered in beach and nearshore settings. Furthermore, these results go beyond qualitatively connecting geology and shoreline change through the parameterization of geophysical observations and suggest a possible mechanism by which geology exerts control on shoreline evolution.

### 1.1. Framework Geology and Shoreline Change

[3] The influence of framework geology in coastal processes, though believed by many to play a significant role [Boss *et al.*, 2002; Browder, 2005; Harris *et al.*, 2005; Hine

<sup>1</sup>Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, USA.

and Snyder, 1985; McNinch, 2004; Rice *et al.*, 1998; Riggs *et al.*, 1995; Schupp, 2005; Thieler *et al.*, 1995, 2000, 2001; Tiedeman, 1995], is poorly understood and not well represented in conceptual or numerical models of shoreline change. This problem stems, in part, from the fact that geology has not been synthesized to create a variable capable of being easily incorporated into models of shoreface and shoreline change while at the same time representing the geologic variability of coastal systems [Honeycutt and Krantz, 2003]. The primary obstacle to the development of a geologic metric for shoreline change studies is the difficulty of transforming qualitative, geophysical observations into parameters that can be used in quantitative models. Mean grain size and shoreface slope have traditionally been used to represent shoreface sediment and morphology, but geophysical surveys of the nearshore and shelf have demonstrated the influence of framework geology not only on barrier island evolution and modern geomorphology [Belknap and Kraft, 1985; Demarest and Leatherman, 1985; Evans *et al.*, 1985] but also on sediment heterogeneity and morphologic variability of the shelf [Harris *et al.*, 2005; McNinch, 2004; Riggs *et al.*, 1995; Schwab *et al.*, 1997; Thieler *et al.*, 1995]. This has forced a reevaluation of the utility of the traditional parameters and of the interaction between waves, currents, and seafloor characteristics [Pilkey *et al.*, 1993; Thieler *et al.*, 1995, 2000].

[4] Despite gains made in characterizing the geology of nearshore and inner shelf systems, little progress has been made in quantifying and parameterizing geological observations and their influence on shoreline change. Thieler *et al.* [1995] demonstrated the spatial heterogeneity of inner shelf sediments due to the influence of framework geology and implied a connection between their observations and shoreline change. Nevertheless, this connection was indirect given that few data were collected in the nearshore where much of the sediment exchange between the beach and shelf occurs [Wright and Short, 1984]. Schwab *et al.* [2000] convincingly linked barrier island stability (a proxy for shoreline change) to increased sediment supply from the reworking of relict inner shelf sediments and McNinch [2004] visually correlated shore-oblique bars and concomitant exposures of the underlying strata to shoreline change. While both studies were integral in asserting the influence of framework geology on shoreline behavior, neither was able to quantify the spatial relationships presented.

[5] Honeycutt and Krantz [2003] suggested geostatistics as a means for quantifying spatial relationships on geologic scales and were successful in statistically relating large-scale geologic transitions to shoreline change in Delaware. Schupp [2005] took the work of McNinch [2004] a step further and used statistics to quantify the relationship between the presence of shore-oblique bars and gravel outcrops and shoreline change. Though quantitative analyses were pursued in these last investigations, neither produced a geological metric useful for predicting shoreline behavior.

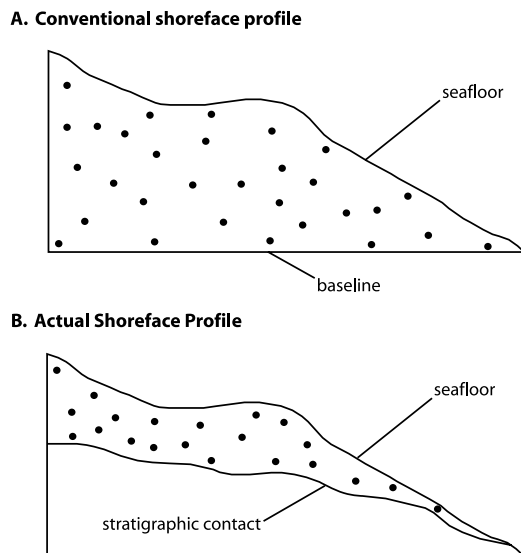
[6] These recent investigations provide strong evidence that the geologic framework of the inner continental shelf contributes to surface sediment heterogeneity, shoreface morphology and sediment availability. For that reason, we believe it is important to parameterize the influence of

antecedent geology so that it can be successfully integrated into shoreline change models.

## 1.2. Transgressive Surfaces as a Volumetric Baseline

[7] Investigations into the Quaternary history of shelf sediments in North Carolina have shown a series of fluctuations in sea level producing both transgressive sequences and regressive unconformities [Mallinson *et al.*, 2005; Riggs *et al.*, 1992]. Spatial variability in preservation potential, largely due to fluvial incision during the last lowstand of sea level, contributes to the complex stratigraphy of the shelf [Belknap and Kraft, 1985; Mallinson *et al.*, 2005; Riggs *et al.*, 1992]. This phenomenon is not specific to North Carolina, as investigations of the shelf off the east coast of the U.S. show numerous examples of fluvial incision and infilling during the Pleistocene when sea level was lower [Belknap and Kraft, 1985; Duncan *et al.*, 2000; Foyle and Oertel, 1997; Toscano, 1992; Toscano and York, 1992]. Presently, and for the last 10,000 years, sea level is rising and many shorelines are retreating landward in response. Transgressive ravinement surfaces, regional stratigraphic features that mark the landward progression of the shoreface during the last transgression, cap infilled paleochannels of the U.S. Atlantic shelf and have been repeatedly identified in many investigations [Browder, 2005; Demarest and Kraft, 1987; Duncan *et al.*, 2000; Fischer, 1961; Foyle and Oertel, 1997; Goff *et al.*, 2005; Stamp, 1921; Swift, 1968]. Because upper infilling sequences are thought to have started in the late Pleistocene and early Holocene [Mallinson *et al.*, 2005; Riggs *et al.*, 1992], the transgressive ravinement surfaces do not necessarily represent the basal Holocene surface in North Carolina. Transgressive ravinement surfaces generally separate shoreface and nearshore sands from estuarine/lagoonal sediments [Swift, 1968; Walker, 1992] and are often termed erosional or transgressive lags because ravinement processes winnow out smaller grain sizes [Cattaneo and Steel, 2003]. Also, the surfaces are generally physically continuous in open-coast marine systems [Cattaneo and Steel, 2003]. Transgressive ravinement surfaces are also characterized by lithological changes. Transgressive lags are coarse-grained deposits comprising shells, gravel, and pebbles produced during shoreface erosion [Cattaneo and Steel, 2003; Van Wagoner *et al.*, 1990].

[8] Because of their continuous nature and distinct lithology, transgressive ravinement surfaces have been easy to identify in high-resolution seismic profiles [Duncan *et al.*, 2000; Foyle and Oertel, 1997; Goff *et al.*, 2005] making them ideal for use as a baseline for nearshore volume calculations. Transgression is a process that occurs over large spatial scales (i.e.,  $10^2$ – $10^3$  km). Small-scale, discontinuous reflection surfaces ( $10^{-1}$ – $10^1$  km) are most likely related to more local processes, such as those that create storm beds, and could not be confused with a transgressive surface in a regional investigation. Additionally, transgressive ravinement surfaces are usually physically continuous, suggesting that the material below them is segregated from the material above. We argue that sediment below the transgressive surface in the region of the surf zone and beach may be exhumed and mined by an active, modern ravinement surface but, in most cases, this will occur over timescales much longer than those discussed in this paper



**Figure 1.** (a) Idealized cross-shore profile showing the traditional shoreface representation using depth of closure as an arbitrary baseline. The speckled region represents the volume of sediment available for transport by waves and currents. Usually, this volume of sediment is assumed to be homogenous [Dean, 1997; Dean et al., 1993; Kana, 1995; Bernabeu et al., 2003]. (b) Idealized cross-shore profile based on the findings of this study, where the volume of the speckled region is dictated by the variability of the subsurface geology and seafloor morphology. Without reworking of the stratigraphic contact, the volume of sediment available for transport is limited. The sediment above the contact is considered to be transport relevant.

and thereby contribute only insignificant volumes of sediment. Furthermore, although the age and lithology of the most recent (uppermost) transgressive surface varies depending on region and cross-shelf location, the overlying Recent sandy sediment found in the nearshore and beach provides a more accurate quantification of transport-relevant sediment. Finally, transgressive ravinement surfaces have been identified not only on the east coast of the U.S [e.g., Duncan et al., 2000; Foyle and Oertel, 1997; Goff et al., 2005], but also in other transgressive systems worldwide [Héquette et al., 1995; Tortora, 1996], thereby increasing the applicability of the approach presented in this paper to other coastal systems.

### 1.3. Measures of Nearshore Sediment Volume

[9] Sediment volume traditionally has been calculated by means of repeated cross-shore profiles [Davis et al., 2000; Emery, 1961; Hicks et al., 2002; Hill et al., 2004; Kana, 1995; Lee et al., 1998]. The volume measured, however, is often a change in volume between the first profile surveyed and the most recent profile and does not represent the total amount of sediment that may be available over time. The latter measure is especially important on sediment-starved coasts, like that of North Carolina. If total volume is determined using cross-shore profiles, it is often calculated from an arbitrary baseline, drawn from the depth of closure landward [Hallermeier, 1978, 1981; Kana, 1995; Nicholls et al., 1998], and assumes an infinite layer of homogenous

sediment [Bernabeu et al., 2003; Dean, 1997; Dean et al., 1993] (Figure 1a). However, as some studies have shown, this is not a valid assumption [McNinch, 2004; Pilkey et al., 1993; Thieler et al., 1995, 2001] and may artificially inflate the amount of sediment available [Schwab et al., 2000]. In addition, cross-shore profiles may not be representative of the entire beach. Given the spatial and temporal variability of the shoreline [List and Farris, 1999; Stockdon et al., 2002]; the alongshore variability in the nearshore bar, not only in its position but also its morphology [Konicki and Holman, 2000; Lippmann and Holman, 1989; McNinch, 2004]; and the differing geological characteristics of the nearshore and the beach, the results of discreet profile surveys may not be applicable to the beach 100 m away, let alone in a completely different system. A more realistic cross-shore profile scenario is shown in Figure 1b, in which the wedge of shoreface sand is dissected by a stratigraphic contact and is not homogenous.

[10] Over shorter time periods (hours, days, weeks), hydrodynamicists have quantified the response of cross-shore profiles to energetic events [Elgar et al., 2001; Gallagher et al., 1998; Lee et al., 1998]. The methods used often rely only on cross-shore hydrodynamic measurements and assume little to no input from longshore transport or other sources, so it is difficult to include their short-term observations as part of a dynamic sediment budget considering decadal shoreline change. Kana [1995] determined a meso-scale ( $\sim 10^1$  to  $10^2$  km;  $10^1$  to  $10^2$  years) sediment budget for Long Island, New York. However, he relied on two-dimensional cross-shore profile data using a determined depth of closure as a baseline for volume calculations, which likely overestimated the total amount of sediment [Schwab et al., 2000]. Regional sediment budgets have also been determined from a geological perspective, such as the volume of sediment that spans the Holocene [Kelley et al., 2005; Locker et al., 2003; Schwab et al., 2000], but correlation of nearshore sediment volume to shoreline change was not tested.

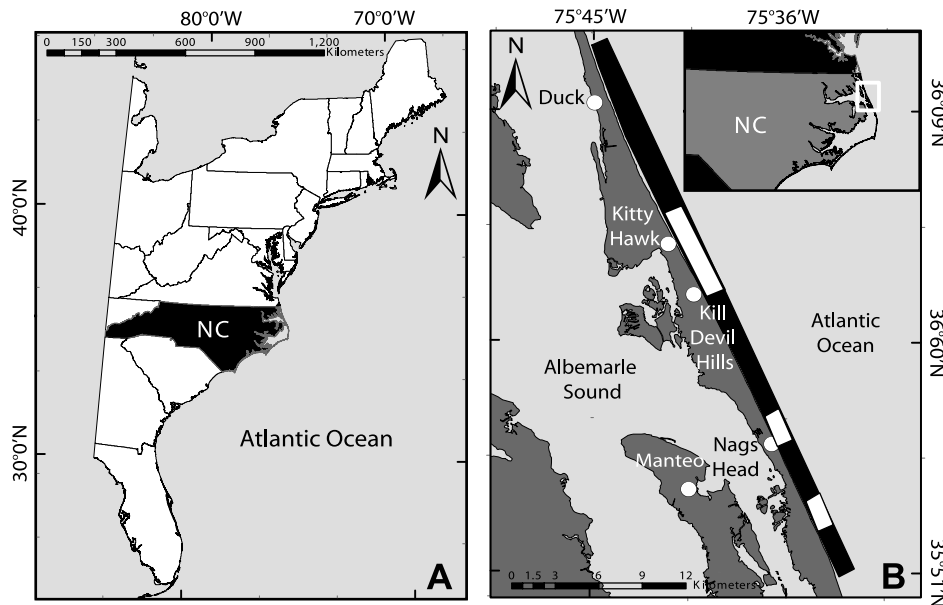
[11] We generate our nearshore sediment volume parameter on the basis of a transgressive surface identified in North Carolina in three dimensions (cross-shore, alongshore, vertical) using densely spaced geophysical observations. While hydrodynamic processes control the seafloor surface or upper limit of our calculation, the lower limit is determined by the depth to the interpreted stratigraphic contact. Using this observation-based method, we generate a volumetric parameter that accounts for the described geologic variability of the nearshore (surficial and subbottom), represents a timescale more appropriate for annual-decadal shoreline erosion modeling, and can be easily compared with shoreline change measurements. As such, this paper addresses the following objectives: (1) measure the spatial variability of sand thickness in the nearshore, (2) determine if nearshore sediment volume defined by a constant depth (depth of closure) correlates with shoreline change, and (3) assess the relationship between geologically defined nearshore sediment volume and decadal shoreline change.

## 2. Study Area

### 2.1. Geologic Setting

[12] The coastline of North Carolina is made up of a series of barrier islands which form arcuately shaped





**Figure 2.** (a) Eastern coast of the United States. (b) Bodie Island in the northeastern Outer Banks, North Carolina. Important geographical locations are indicated with open circles. The black box indicates the survey region where geophysical data were collected in the summer of 2002. The white boxes indicate discrete regions in which shore-oblique bars and exposures of the underlying geology were mapped. The northernmost bar field is referred to as the Kitty Hawk bar field in the text, while the two to the south are referred to as the northern and southern Nags Head bar fields, respectively. Inset: The white box indicates the region shown in the larger map.

cusate forelands that front the extensive estuarine complex of the Albemarle and Pamlico Sounds (Figure 2). The long, linear barrier islands (Outer Banks) are typical of those formed in microtidal, wave dominated systems and have few inlets [Hayes, 1979]. The study area is located in the northeastern portion of the Outer Banks on the Atlantic side of Bodie Island, from Duck, North Carolina, to southern Nags Head, North Carolina (Figure 2b). The geology of the coastal plain of North Carolina is controlled by the crystalline basement surface on which the coastal plain sediments were deposited. This surface is not a seaward dipping platform, but instead is composed of a series of arches and basins [Horton and Zullo, 1991]. The Albemarle Embayment underlies the study area, which is bounded by two topographic highs: the Norfolk Arch to the north, and the Cape Fear Arch to the south [Horton and Zullo, 1991]. The basin-like nature of the embayment served to preserve much of the Quaternary sequence (50–70 m thick) in the northern coastal province, deeply burying the Tertiary and Cretaceous strata [Riggs *et al.*, 1992, 2002]. Using seismic reflection data, Mallinson *et al.* [2002] determined that gently dipping Miocene beds were overlain by the southward prograding beds of the Pliocene unit, which is unconformably overlain by the Quaternary section.

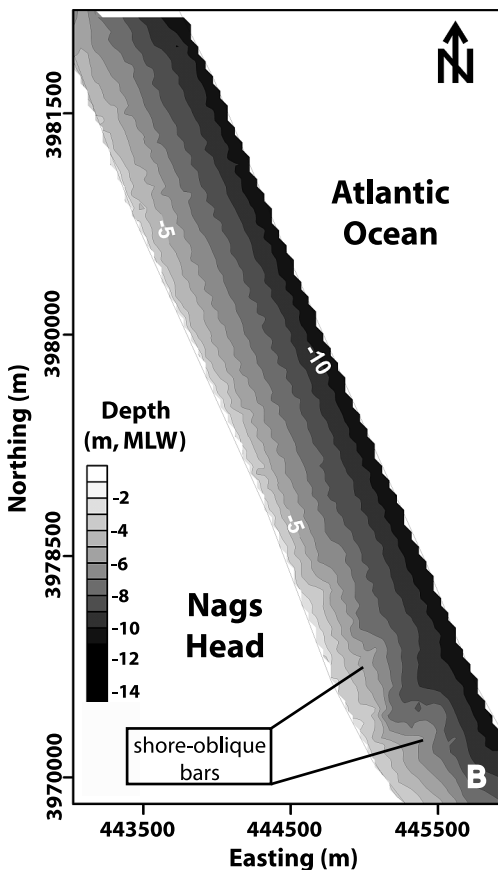
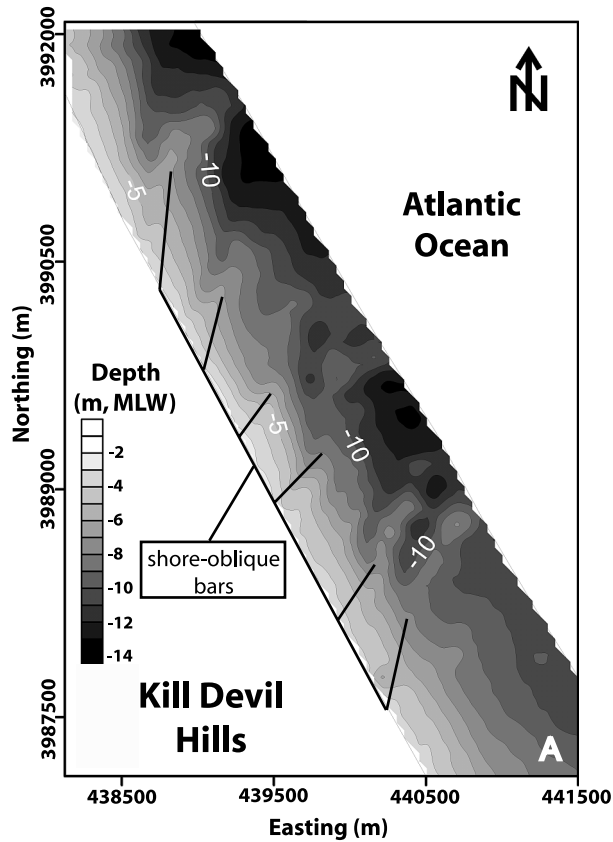
[13] Pleistocene sediments recorded many changes in sea level due to glaciation and were extensively incised by fluvial channels during periods of lower sea level [Mallinson *et al.*, 2005; Riggs *et al.*, 1992, 1995]. Perhaps the most dramatic example of this process is the paleo-Roanoke River valley, which has been dated as Pleistocene or Holocene in age [Mallinson *et al.*, 2005]. The paleochannel dominates the upper stratigraphic record in the eastern part of the Albemarle

Sound [Mallinson *et al.*, 2005] and has also been mapped on the Atlantic side of Bodie Island, underlying the town of Kitty Hawk [Boss *et al.*, 2002; Browder, 2005]. Sediments within the paleochannel are composed of muds, peats, sands, and gravels [Riggs *et al.*, 1992; Schwartz and Birkemeier, 2004].

[14] Cores described by Rice *et al.* [1998] and Schwartz and Birkemeier [2004], suggest that Holocene sediments thin to less than a meter in  $\sim 10$  m water depth near the US Army Corps of Engineers Field Research Facility in Duck, North Carolina (USACE-FRF). In southeastern North Carolina, the modern sediment layer, where observed, has been described as a “vaneer” [Riggs *et al.*, 1996; Thielert *et al.*, 2001]. Riggs *et al.* [1996] related the sediment starved nature of the South Atlantic Bight to lack of input from rivers and argued that the only source of sediment to the inner shelf and nearshore was through the reworking of relict sediments. Long-term and short-term erosional hotspots have been identified on the beach in our study area by Benton *et al.* [1997] and List and Farris [1999].

## 2.2. Physical Setting

[15] Given the presence of the USACE-FRF in Duck, North Carolina, detailed oceanographic characteristics of the study area are available online (<http://www.frf.usace.army.mil/frfdata.html>) and will only be summarized here. Tides are semidiurnal with a mean range of  $\sim 1$  m [Birkemeier *et al.*, 1985] and a spring tide range of  $\sim 1.2$  m [Fenster and Dolan, 1993]. The average significant wave height is  $1.1 \pm 0.6$  m (from 1980–1999, <http://www.frf.usace.army.mil/frfdata.html>). Wave energy is highest during the fall, winter, and early spring because of the frequency of extratropical



storms (nor'easters) [Lee et al., 1998]. Storm series were found to have greater impact on shoreface profile and beach change than individual storms [Lee et al., 1998]. The coastline is subject to hurricanes and tropical storms in the summer and fall months. The mean direction of longshore currents is to the south, though the current appears to flow to the north during periods of low wave energy (data available online at <http://www.frf.usace.army.mil/frfdata.html>).

### 3. Methods and Results

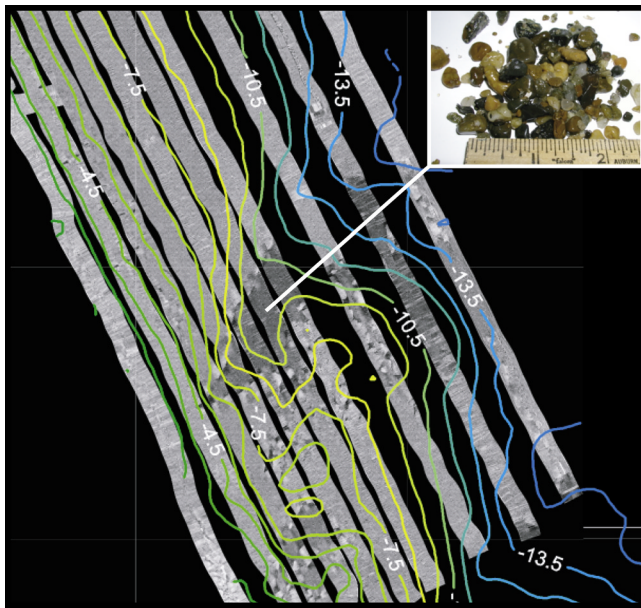
#### 3.1. Nearshore Geophysical Observations

##### 3.1.1. Methods

[16] Over 400 line kilometers of geophysical data were collected from May to June of 2002 along the coast of the Outer Banks of North Carolina, spanning the region from Duck, North Carolina, to just north of Oregon Inlet, aboard the U.S. Army Corps of Engineers' (USACE) amphibious LARC. The study area was separated into 5 km<sup>2</sup> blocks in which shore-parallel and shore-perpendicular lines were surveyed, at a line spacing of 100–150 m and 2.5 km respectively. All data were spatially referenced in real time using RTK-GPS. An interferometric swath system (Submetrix series 2000; 234 kHz) was used to map the bathymetry of the seafloor from ~1.5 m to ~15 m water depth or from as close to the beach as possible to approximately 1 km offshore. Acoustic backscatter from the same system was also collected to obtain information on changes in surficial seafloor lithology. High-resolution, chirp seismic reflection data (Edgetech 216, 2–10 kHz; speed of sound = 1750 m s<sup>-1</sup>) were collected in order to image shallow, nearshore stratigraphy. The integration of the swath bathymetry, acoustic backscatter and chirp seismic allowed for a multidimensional approach, capturing the alongshore, cross-shore, and vertical variability of not only the seafloor, but also the underlying strata.

[17] Seafloor depths (swath bathymetry) were heave- and tide-corrected to mean low water (MLW) using observed tides at the USACE-FRF in Duck, North Carolina. The data were then gridded, despiked, and smoothed. The grids were interpolated using kriging at a spacing of 50 m, which was determined to be the best method on the basis of the anisotropic nature of the data set. A simple linear semi-variogram was used with an anisotropy ratio of one and a variogram slope of one. Seismic reflection data were processed using SonarWeb Pro. Continuous and discontinuous subbottom reflectors were identified and digitized, as was the seafloor reflection. Heave is apparent in the seismic profiles because no swell filter was applied during acquisition. Digitization of the reflections was visually estimated through the heave for both seafloor and subbottom reflections

**Figure 3.** Bathymetry plots generated from the interferometric system in 5 km<sup>2</sup> blocks. Depths are in meters relative to mean low water (MLW). Northings and Eastings are in UTM Zone 18N, WGS 1984. (a) Region near Kill Devil Hills, North Carolina, where shore-oblique bars spanned the width of the nearshore. Bars in this region were consistently 200–400 m wide and 700–900 m in length. (b) One of the bar fields from Nags Head, in which the bars are much smaller.



**Figure 4.** Acoustic backscatter (side-scan sonar) mosaic with overlain bathymetric contours. Darker colors indicate higher-amplitude returns. A grab sample from the trough to the north of the shore-oblique bar retrieved poorly sorted gravel. Seismic reflection data reveal that this material generates the continuous reflection surface mapped throughout the survey region (modified from *McNinch* [2004] with permission from Elsevier).

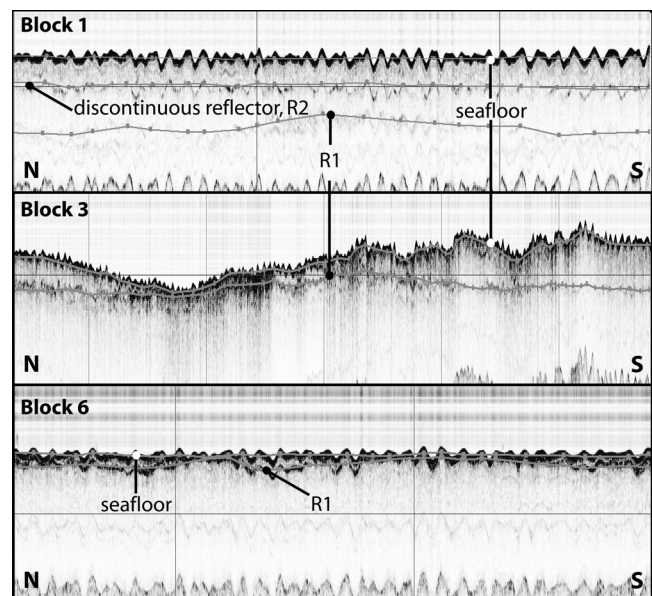
and was completed by one person thus limiting subjective differences that may occur when multiple persons participate in data processing. Sediment thicknesses for the survey area were calculated by subtracting the subbottom reflector depths from the seafloor depths at each digitized point. The thickness (i.e., surface of uppermost continuous reflector) was then subtracted from the seafloor bathymetry grid so as to relate the uppermost, continuous reflection surface to a vertical datum, in this case, MLW. Isopach maps and maps of the continuous subbottom reflection were created for each 5 km<sup>2</sup> region using interpolated grids with a 50 m spacing.

### 3.1.2. Results

[18] Because the results from the work of *McNinch* [2004] are the basis for this study, they are summarized here for the purpose of describing nearshore morphology. The bathymetric data revealed many examples of a typical, concave-up shoreface with shore-parallel contours as well as regions with groups of shore-oblique sandbars. These sandbars were present in three clusters (Figure 2b), although they varied in the extent of their expression (Figure 3). Usually, they spanned the width of the nearshore (~1 km), had 1–1.5 m of relief, and ranged from 100–500 m wide. The acoustic backscatter data showed that the surf zone and nearshore did not have a homogenous surficial sediment composition. In fact, most of the variability in seafloor lithology was associated with the shore-oblique features, in that rippled, coarser sediment (Figure 4) almost always appeared in a bathymetric low, or trough, to the north of each shore-oblique sandbar. The position of the sandbars and gravel outcrops persisted throughout a variety of forcing conditions [*McNinch*, 2004].

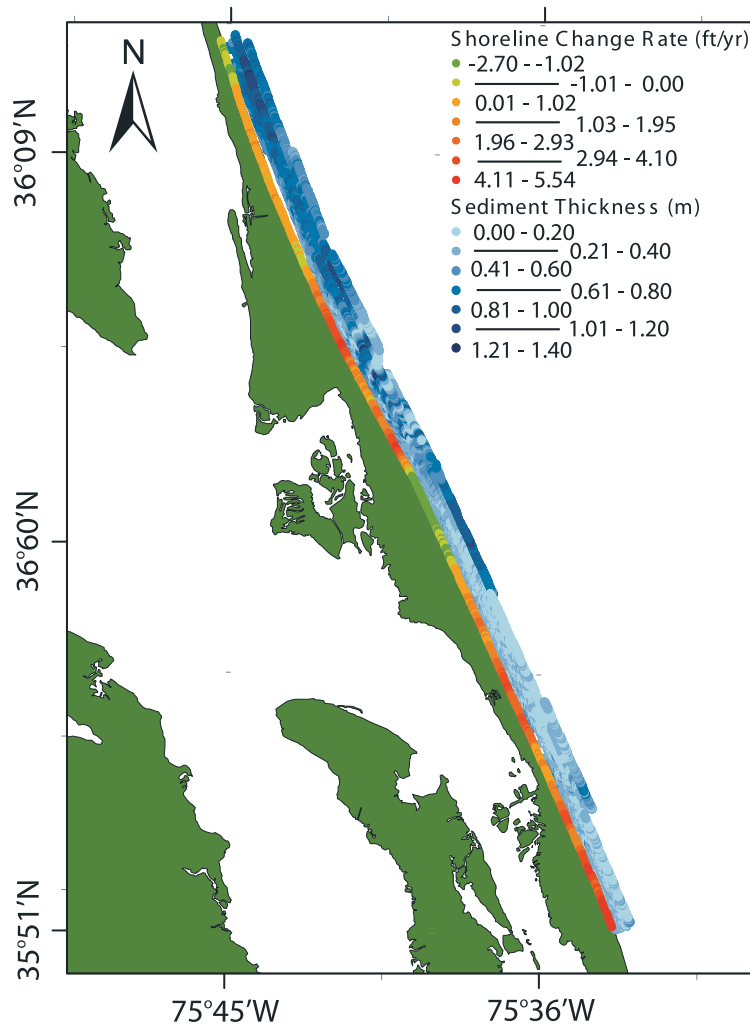
[19] Seismic reflection data reveal that the rippled, gravel portions of the seafloor are exposures of an underlying substrate (Figure 5). The seismic and acoustic backscatter data were ground truthed via grab samples of the surface sediment and vibracores [*McNinch*, 2005], which demonstrated that the shore-oblique bars were fine to medium sand and the underlying continuous substrate (at least where it was exposed at the surface of the seafloor and cored) was gravel, coarse sand and/or cohesive mud. Interpretation of the seismic data indicated that the exposures were part of one continuous reflection surface, designated R1, underlying the entire survey area. In the northernmost 10 km<sup>2</sup> section, a second reflection surface was identified above R1 (Figure 5, block 1). However, to the south, the second reflection was either missing or discontinuous (Figure 5, block 3 and block 6).

[20] Sediment thicknesses were measured from the seafloor to the continuous reflector (R1). Sediment thicknesses above R1 for eight 5 km<sup>2</sup> survey blocks are detailed in Table 1. The results clearly show how the upper, sandy layer thins toward the south of the survey area. The average thickness of sediment above R1 in the surveyed area is less than 0.5 m. Standard deviations in sediment thickness, used as a proxy for variability of sediment distribution, were calculated for each 5 km<sup>2</sup> block. Variable sediment distribution (high standard deviation) is associated with the blocks in which shore-oblique bars and rippled gravel



**Figure 5.** Seismic reflection data collected at 1750 m s<sup>-1</sup> in 5 km segments. Block 1: a typical seismic profile from the northern region of the survey area. Note the presence of two reflection surfaces here, R1 being the lower of the two. Block 3: a seismic profile collected near Kitty Hawk, North Carolina, showing a shore-oblique bar in cross section in the southern part of the profile. Note that R1 is exposed at the surface of the seafloor just to the north of the shore-oblique bar. Block 6: a seismic profile typical of those collected near Nags Head, North Carolina, and in the southern region of the survey area. Note that the discontinuous reflector, R2, is missing from the profile.





**Figure 6.** Isopach map generated from seismic data (R1), shown in shades of blue, with darker shades representing thicker sediment. Along the shoreline, decadal shoreline change data from the North Carolina Division of Coastal Management are plotted, with green representing accretion and shades of red and orange signifying erosion. Note the thinning of sediment to the south.

patches were present. In Figure 6, individual thickness measurements are spatially plotted in map view for comparison with shoreline change. Though the sediment clearly thins toward the south, there is no visually apparent trend between thickness and variability in decadal shoreline change.

### 3.2. Volume Calculations and Results

#### 3.2.1. Methods: Geologically Defined Volumes

[21] To calculate nearshore sediment volumes, each 5 km<sup>2</sup> survey block was subdivided into five ~1 km<sup>2</sup> blocks for a total of forty ~1 km<sup>2</sup> blocks for the entire survey area. The isopach for the smaller blocks was interpolated with a 10 m grid spacing using kriging. Again, a simple linear semivariogram was used with an anisotropy ratio of one and a variogram slope of one. Volumes (m<sup>3</sup>) were calculated using the Trapezoidal Rule in Surfer<sup>®</sup>. The area of the subblocks was not exactly 1 km<sup>2</sup> after gridding. When the 1 km<sup>2</sup> blocks were subdivided from the larger blocks, the number of grid nodes at the 50 m spacing may not have been consistent

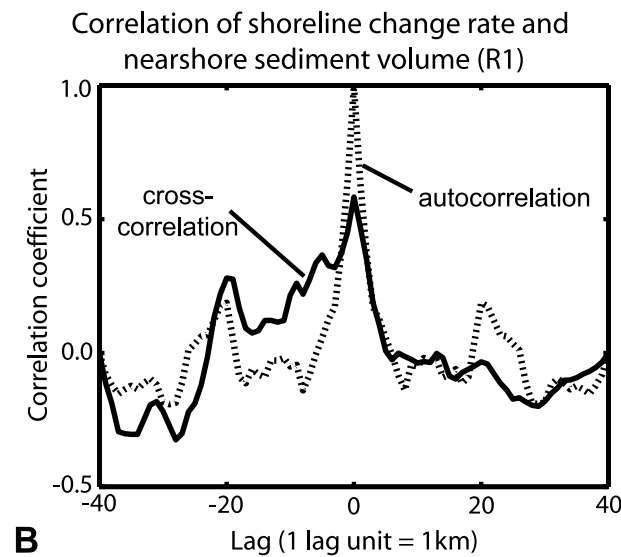
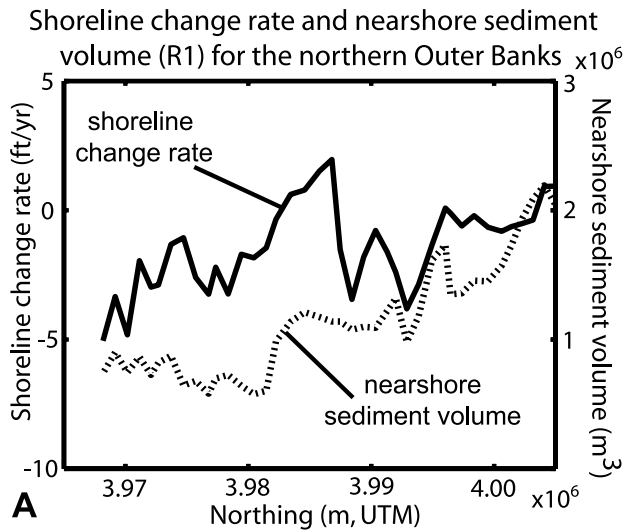
within each division. Therefore the volumes were normalized so that areal effects would not bias the calculations. The following equation was used to normalize the data where  $A_i$  is the area of individual 1 km<sup>2</sup> block  $i$ ,  $A_{max}$  is

**Table 1.** Average Sediment Thicknesses Calculated From R1 for Eight 5 km<sup>2</sup> Survey Blocks<sup>a</sup>

Block	Area	Average Thickness (m)	Standard Deviation (m)	Thickness Range (m)
Block 1	Duck	0.77	0.16	0.39–1.21
Block 2	Southern Shores	0.60	0.15	0.24–1.00
Block 3	Kitty Hawk	0.48	0.27	<b>0.0–1.26</b>
Block 4	Kill Devil Hills	0.43	0.23	<b>0.0–1.29</b>
Block 5	S. Kill Devil Hills	0.35	0.20	0.07–1.12
Block 6	Nags Head	0.23	0.12	<b>0.0–0.65</b>
Block 7	S. Nags Head	0.26	0.13	0.0–0.83
Block 8	Whalebone	0.27	0.15	<b>0.0–1.00</b>

<sup>a</sup>Note that the average thickness decreases southward. Thickness ranges in bold represent regions in which the acoustic backscatter data indicated that the underlying surface was exposed at the seafloor. Average thickness for the entire survey area was less than 50 cm.





**Figure 7.** (a) Plot of nearshore sediment volume (dashed line) as calculated to R1 and decadal shoreline change rate (solid line) with negative numbers indicating erosion for the 40 km<sup>2</sup> survey area (left to right is south to north). Overall, when nearshore sediment volume decreases, shoreline change rate decreases (more erosive). (b) Plot of the cross correlation between nearshore sediment volume and shoreline change (solid line). The dotted line is an autocorrelation. The correlation coefficient for this analysis is 0.58 at zero lag and is significant at the 95% confidence level ( $df = 10$ ).

the maximum area of all 1 km<sup>2</sup> blocks, and  $V_i$  is the volume of sediment calculated for 1 km<sup>2</sup> block,  $i$ :

$$V_i / (A_i / A_{\max}) = V_{normi} \quad (1)$$

Note that  $(A_i / A_{\max})$  is a dimensionless ratio and therefore the final units for normalized volume are in cubic meters.

[22] The volume of shore-oblique bars was calculated to determine their volumetric contribution. The limits of each shore-oblique bar were visually estimated from maps of the bathymetry and digitized in Surfer<sup>®</sup>. The isopach data were culled to the area of the bar limits and the volume of just

that area was calculated using the Trapezoidal Rule in Surfer<sup>®</sup>. The total amount of sediment contained within the bars regionally and locally was also calculated. For the regional calculation, the sum of the volume of all of the bars ( $V_{bi}$ ) was divided by the sum of the normalized volume of each individual subblock ( $V_{normi}$ ):

$$\text{Regional Percentage} = \left[ \frac{\sum(V_{bi})}{\sum(V_{normi})} \right] * 100 \quad (2)$$

For the local calculation, the sum of the volume of the bars in one particular bar field ( $V_{bxi}$ ) was divided by the sum of the normalized volume of each individual subblock in that bar field ( $V_{normxi}$ ):

$$\text{Local Percentage} = \left[ \frac{\sum(V_{bxi})}{\sum(V_{normxi})} \right] * 100 \quad (3)$$

### 3.2.2. Methods: Volumes Defined

#### Using Depth of Closure

[23] The volume between seafloor bathymetry and a horizontal plane at a depth of closure elevation relevant to the study area was calculated for each 1 km<sup>2</sup> subblock. Depths tested were -6, -8, and -9 m (relative to MLW) and correspond to averages from 12 years of profile measurements, empirically derived depths using wave heights, and an estimate of depth of closure over time periods greater than one year, respectively [Nicholls *et al.*, 1998]. Because information for the empirical depth of closure equation is more widely available than data from a 12-year beach profile survey, the -8 m depth is used for the correlation analysis [Hallermeier, 1978].

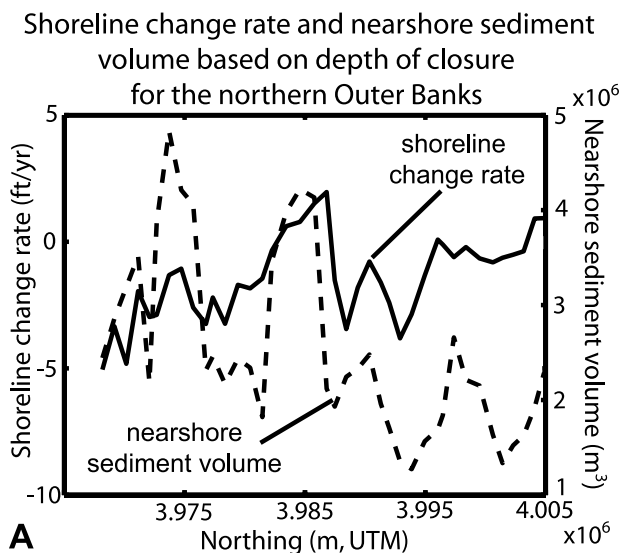
#### 3.2.3. Shoreline Change Data and Cross Correlation

[24] North Carolina Division of Coastal Management (NC DCM) calculated decadal shoreline change rates for the region with the end point method in which the change in shoreline position is divided by the change in time (data available online at <http://dcm2.enr.state.nc.us/Maps/chdownload.htm>). The calculations were based on measurements from aerial photos from the early 1930s through 1998, thus the rates presented span almost 70 years. Spatial correlation between (1) nearshore sediment volume based on R1 and decadal shoreline change rate and (2) nearshore sediment volume based on depth of closure and decadal shoreline change were assessed using cross-correlation analysis. All correlation analyses were performed using MATLAB, which uses demeaned Pearson's product moments.

#### 3.2.4. Results

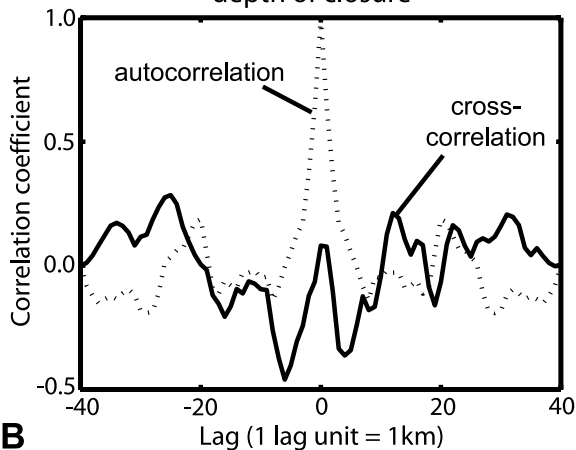
[25] When nearshore sediment volume defined by R1 is compared to decadal shoreline change a positive trend is observed. Generally, when sediment volume is low, the shoreline tends toward erosion (Figure 7a). Overall, the volume decreases toward the south as shoreline erosion increases toward the south. Over small spatial scales, increases in volume correspond to less erosion of the shoreline. Nearshore sediment volume and shoreline change rate are statistically correlated ( $p = 0.05$ ) with a correlation coefficient of 0.58 at a lag of zero (Figure 7b) using ten degrees of freedom, which is defined here by the length of the data set divided by the width of the autocorrelation above zero [Zar, 1999].

[26] The relationship between shoreline change and nearshore sediment volume based on depth of closure was also



A

Correlation of shoreline change rate and nearshore sediment volume based on depth of closure



B

**Figure 8.** (a) Plot of nearshore sediment volume (dashed line) based on depth of closure and decadal shoreline change rate (solid line) with negative numbers indicating erosion for the 40 km<sup>2</sup> survey area (left to right is south to north). Overall, when nearshore sediment volume decreases, shoreline change rate increases (more accretion). (b) Plot of the cross correlation between nearshore sediment volume and shoreline change (solid line). The dashed line is an autocorrelation. The correlation coefficient for this analysis is  $-0.46$  at a lag of 5 km and is not significant at the 95% confidence level ( $df = 10$ ).

tested (Figure 8). In Figure 8a, the curve for volume based on depth of closure trends subtly opposite to the shoreline change record. The magnitude of the depth of closure volumes to the south is much higher than that of the volumes based on R1 (Figure 8a), despite the fact that there is more shoreline erosion to the south. This implies that high volumes (based on depth of closure) correspond to more erosive shoreline behavior. Unlike in the correlation of shoreline change and R1 volumes, there is not a visually well-defined peak in the correlation of shoreline change and volumes based on depth of closure (Figure 8b). Depth of

closure defined volume was not correlated to shoreline change at a level of significance greater than  $p = 0.10$  (peak correlation coefficient =  $-0.46$  at a lag of 5 km) using ten degrees of freedom (Figure 8b).

[27] In order to address the three-dimensional character of nearshore morphology and the variability in sediment availability, the volume of sediment in the surf zone and nearshore was calculated for the entire survey area and for the individual shore-oblique bars. Because the migration of sandbars is an important process by which sediment is exchanged between the beach and the nearshore, it is important (1) to know how much sand the shore-oblique features contain and (2) to determine their volumetric contributions regionally and locally. Here, “regional” refers to the entire survey area while “local” refers only to areas in which shore-oblique bars are present. The shore-oblique bars contributed only 7.9% of the total sediment volume for the region. However, their local contribution to the total sediment volume was significantly higher. In this study, there were 3 areas (or bar fields) in which the shore-oblique bars were present. The extent of the bar fields varied. In Kitty Hawk, the largest bar field spanned  $\sim 5.5$  km of the nearshore. There, the volume of sediment in the bars represented 44% of the total nearshore sediment volume for that area. South of that site, smaller bar fields were identified in Nags Head (spanning  $\sim 1$  km each). At the first site, the volume of sediment contained in the bars represented 14% of the total volume of the bar field, while at the second site, the percentage was slightly lower, at 11%.

### 3.3. Shoreline Erosion Potential Model

#### 3.3.1. Model Parameterization

[28] An empirical model was created in order to demonstrate the utility of the geology-defined nearshore sediment volume metric. First, an average thickness ( $AvgT$ ) for each 1 km<sup>2</sup> region was calculated by dividing the normalized volumes by the standard area ( $1 \times 10^6$  m<sup>2</sup>). In order to account for the presence or absence of shore-oblique bars, a dimensionless bar metric ( $BM$ ) was developed for each 1 km<sup>2</sup> block using the following equation:

$$BM_i = 1 - (V_{bi}/V_{normi}) \tag{4}$$

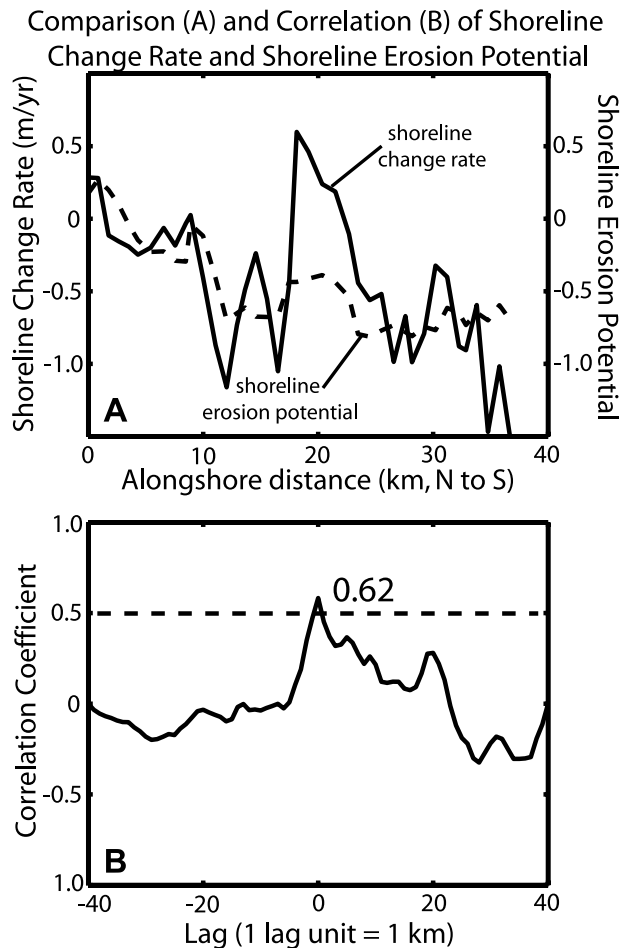
$V_{bi}$  is the volume of the shore-oblique bars within each 1 km<sup>2</sup> block  $i$  (value of zero if there are none) and  $V_{normi}$  is the normalized volume for the same block. If there were no bars present,  $BM_i = 1$ . Finally an adjusted thickness ( $AT$ ) parameter was generated by multiplying the average thickness value by the bar metric for each block:

$$AT_i = AvgT_i * BM_i \tag{5}$$

The  $AT$  values for each block were then plotted versus 1 km averages of the shoreline change rate as calculated by NC DCM. A regression line was fit to the data, providing the equation for shoreline erosion potential:

$$\text{Shoreline erosion potential} \approx \sqrt[2]{3}(AT) - 1.2 \tag{6}$$

Since there are no units of time in the value of  $AT$ , the equation generated provides only shoreline erosion potential rather than a rate. The equation was forced with adjusted



**Figure 9.** (a) Plot of observed decadal shoreline change rate (solid line) and our shoreline change proxy based on only geologic parameters (dashed line). Overall, when the shoreline is erosive, our proxy indicates erosion. In some places, accretion and erosion are underestimated. (b) Plot of the cross correlation between the observed shoreline change rate and our shoreline change proxy (solid line). Correlation coefficient is 0.62 at zero lag and is significant at the 95% confidence level ( $df = 10$ ).

thickness values from the survey and a curve representing the erosion potential for the region is plotted versus the actual record of shoreline change rate (Figure 9a). Cross-correlation analysis was performed on the model-generated shoreline erosion potential and the observed shoreline change rate to determine the success of the model proxy.

### 3.3.2. Model Results

[29] Two geologic metrics are used to generate the empirical formula presented in Equation (6). The first variable is sediment thickness, or the average distance between the surface of the seafloor and the seismic reflector, R1 for a  $1 \text{ km}^2$  region. The vertical variability of the underlying geology is accounted for by this metric, such that larger thicknesses indicate either an increase in the depth of R1, an increase in seafloor height in the presence of positively expressed seafloor morphology, or some combination of the two. The second variable used was a bar metric which incorporated the volumetric contribution of shore-

oblique bars. Correlation of the model results with the observed shoreline change rate produced a correlation coefficient of 0.62, which is significant at the 95% confidence level using ten degrees of freedom (Figure 9b).

## 4. Discussion

### 4.1. Volumetric Baselines From Shallow Nearshore Stratigraphy

[30] The seismic reflector, R1, is the baseline to which nearshore sediment thicknesses and volumes were calculated. Using R1 as the baseline for our calculations produces a quantity (thickness or volume) of sediment above the reflection surface that bridges the gap between event-scale sediment transport and long stratigraphic timescales and thus makes it well suited for comparison with decadal shoreline change. This geology-defined nearshore volume neither represents the active sediment transport layer as defined in many transport models (mm to cm), which would represent a timescale of hours to days [Harris and Wiberg, 2001, 2002], nor overestimates the volume by assuming uniform sandy sediment above an arbitrary depth-constant baseline [Bernabeu *et al.*, 2003; Dean, 1997; Hallermeier, 1978; Kana, 1995].

[31] The continuity of R1 throughout the study area ( $\sim 40 \text{ km}$ ) suggests that the sediment above it is isolated from the sediment below. Without reworking the contact that R1 represents, the underlying sediment is unavailable for transport, limiting the amount of sediment available for exchange with the shoreline and shelf. It could be argued that the sediment below the transgressive surface in the region of the surf zone and beach could be exhumed and mined by the active ravinement surface. In most cases, however, this will occur over timescales much longer than those discussed in this paper and is not likely to contribute a significant amount of sediment [Goff *et al.*, 2005]. The discontinuous reflection surface, R2, seen above R1 in some areas (Figure 5, Block 1) is not used because its discontinuous nature suggests sediment was exposed and reworked in many surrounding areas (where it was not present, Figure 5, Block 6) and may be associated with reworking and movement of sorted bed forms [Murray and Thielert, 2004]. Also, the discontinuous nature of R2 may reflect much more recent and spatially ephemeral deposition or winnowing from storm events and therefore is not appropriate for a regional volume assessment.

[32] The lithology of R1 appears to be distinct from the sediment above it and below it. Near Kitty Hawk, North Carolina, where R1 is exposed at the surface of the seafloor, it is composed of gravel and shell hash (Figure 4). The areas around the exposures (shore-oblique bars) are composed of fine- to medium-grained sands. Vibracores collected from the region around the USACE-FRF in Duck show a persistent coarse layer at approximately the same depth below the seafloor as the depth to R1 in the seismic reflection record [Schwartz and Birkemeier, 2004] suggesting that the surface we interpreted may be composed of gravel throughout the survey area. Preliminary vibracores collected from the Kitty Hawk study area in May 2005 support the observations from Duck, North Carolina, and suggest that the lithology of R1 is spatially variable, but that it is coarser than the units above and below it [McNinch,



2005]. A more thorough analysis of the vibracore data will be presented in a subsequent paper, therefore only relevant field descriptions are discussed here. The vibracores consistently showed shoreface sands of varying thicknesses (~0–200 cm) at the top of the core. At the base of the shoreface sands was a poorly sorted unit, which was composed of a combination of gravel and coarse sand 10–30 cm in thickness. We believe this unit generated the acoustic contrast we interpreted as R1, which overlies finer-grained sands and muds containing back-barrier shell fragments.

[33] On the basis of lithologic studies conducted in the survey area [Rice *et al.*, 1998; Schwartz and Birkemeier, 2004], recently acquired nearshore vibracores [McNinch, 2005], and the regional continuity of the reflection surface, we believe that R1 is a transgressive ravinement surface. Swift [1968] states that ravinements “separate basal marsh, lagoon, estuarine, and beach deposits from overlying marine sand” in transgressive sequences. It follows then that the poorly sorted unit observed in the vibracores and at the seafloor (Figure 4) is a ravinement surface, since it separates the overlying marine sands from the underlying back-barrier/lagoonal sediments. Similar facies sequences have been presented in other investigations [Brooks *et al.*, 2003; Cattaneo and Steel, 2003; Chen *et al.*, 1995; Goff *et al.*, 2005; Swift, 1975]. This interpretation is also supported by a recent study near Martha’s Vineyard Coastal Observatory. Goff *et al.* [2005] mapped a “shallow, horizontal seismic reflector, a few tens of centimeters below the seafloor in shallower waters and >1 m in deeper water.” Not only was the reflector continuous throughout their study area (~3 × 5 km), it also intersected the seafloor in the topographic depressions of sorted bed forms, much like R1 is exposed at the surface of the seafloor in the northern troughs of the shore-oblique bars [Goff *et al.*, 2005]. They related their reflection surface to a gravel/coarse sand layer of variable thickness and concluded that it was an erosive lag associated with a transgressive ravinement. Both our interpretation and that of Goff *et al.* [2005] is consistent with a reflection surface, “T,” mapped from the middle New Jersey shelf [Duncan *et al.*, 2000].

[34] Using a mass balance of common grain sizes above and below the ravinement surface, Goff *et al.* [2005] concluded that the sediment below the gravel/coarse sand layer was not acting as a source of sediment for the shoreface. This is consistent with our volume-defining assumption that little to no reworking of R1 and sediment below R1 is occurring. First, the very definition of the reflection coefficient that generates the R1 reflection surface indicates that sediment below R1 has not been exhumed and reworked prior to the time of the survey. This is most certainly true when R1 is overlain by shoreface sands, but where it is exposed at the seafloor, it could be argued that the coarse material (i.e., R1) could be temporarily mobilized, the sediment below it mined, and redeposition of the coarse material could occur. Because the grain size of the R1 unit is larger than that of the fine- to medium-grained sands usually found at the seafloor, it is more erosion resistant. The estimated critical shear stress ( $\tau_{cr}$ ) for gravel is 40–640 dyne  $\text{cm}^{-2}$  while the critical shear stress for fine- to medium-grained sands is 1.25–5 dyne  $\text{cm}^{-2}$ , an order of

magnitude less [Wiberg and Smith, 1987]. This suggests that gravels are probably only transported during peak wave events. R1 may also act to armor the bed during fair weather conditions prohibiting the mining of underlying sediments [Kleinhans *et al.*, 2002]. Because of the thickness (10–30 cm) and distinct lithology of R1, we believe that (1) it will persist over decadal timescales and (2) it is unlikely to provide a substantial quantity of transport-relevant sand even over longer time periods when sediment below R1 may be exhumed and reworked. At the time of the survey, R1 was the lowest point of reworking and thus represents a conservative estimate of the depth of mixing for Recent sands in the nearshore and beach.

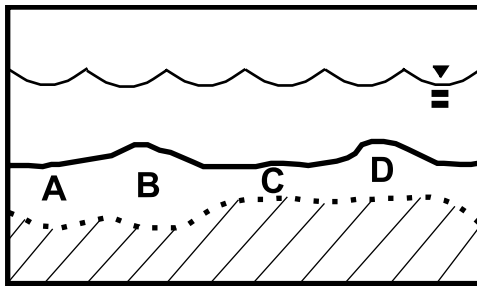
[35] R1, as mapped by Browder [2005], was shown to cap Pleistocene paleofluvial channels near Kitty Hawk, North Carolina. The transgressive surface mapped on the shelves of Massachusetts and New Jersey also capped relict channels [Duncan *et al.*, 2000; Goff *et al.*, 2005]. On the Virginia shelf, a reflection interpreted as a transgressive oceanic ravinement was also found to cap incised-valley fills initially carved by older iterations of the Chesapeake Bay [Foyle and Oertel, 1997]. Foyle and Oertel [1997] suggested that the shelves of New Jersey, Delaware, Maryland, and North Carolina had similar stratigraphic geometries to that of Virginia and thus those locations may offer a good opportunity to test the skill of our volume metric. Transgressive ravinement surfaces can be identified around the world, and therefore the calculations presented here could be used in a variety of nearshore systems, not just those of the east coast of the United States. It may also be applicable in systems as different as the southeastern coast of the Canadian Beaufort Sea [Héquette *et al.*, 1995] and the central Tyrhenian Sea [Tortora, 1996] where transgressive ravinement surfaces have been identified and acoustically mapped.

#### 4.2. Regional Relationship of Nearshore Sediment Volume and Shoreline Change

[36] The correlation between nearshore sediment volume and decadal shoreline change rate was statistically significant (Figure 7b). The trends of the two lines were similar such that when volume decreased, the shoreline became more erosive (Figure 7a). Using only one geologic parameter, transport-relevant sediment volume, much of the variability in the shoreline behavior could be explained. Because nearshore sediment volume was based on the depth to R1, our data suggest that the shallow geologic framework underlying sediment-starved shelves may be a primary factor in controlling the variability of the shoreline over decadal timescales (Figure 10). By taking into account the total amount of available nearshore sediment and the depth to a continuous, underlying stratum, regions of the shoreline that may be susceptible to long-term erosion can be identified.

[37] When depth of closure [Hallermeier, 1978, 1981; Nicholls *et al.*, 1998] was used to define the lower limit of nearshore sediment volume, the volumes were usually much higher than when a stratigraphic baseline was used (Figure 8a compared with Figure 7a). This is consistent with the conclusions of Schwab *et al.* [2000] who suggested that the work of Kana [1995] overestimated the amount of sediment for Long Island, New York, when depth of closure





**Figure 10.** Idealized alongshore cross section of the nearshore showing two variable surfaces, the seafloor (solid line) and a continuous sediment horizon (dotted line). The sediment below the dotted line is unavailable for transport (diagonal lines). In region A, the volume of sediment is increased by a low in the underlying stratum. In region B, there is a larger volume of sediment than at A due to the combined effect of positive seafloor morphology and a low in the underlying surface. At location C, the volume of sediment is limited by the underlying surface and lack of seafloor morphology. The volume in region D would be higher than that at C because of the variability of the seafloor morphology but not the underlying surface.

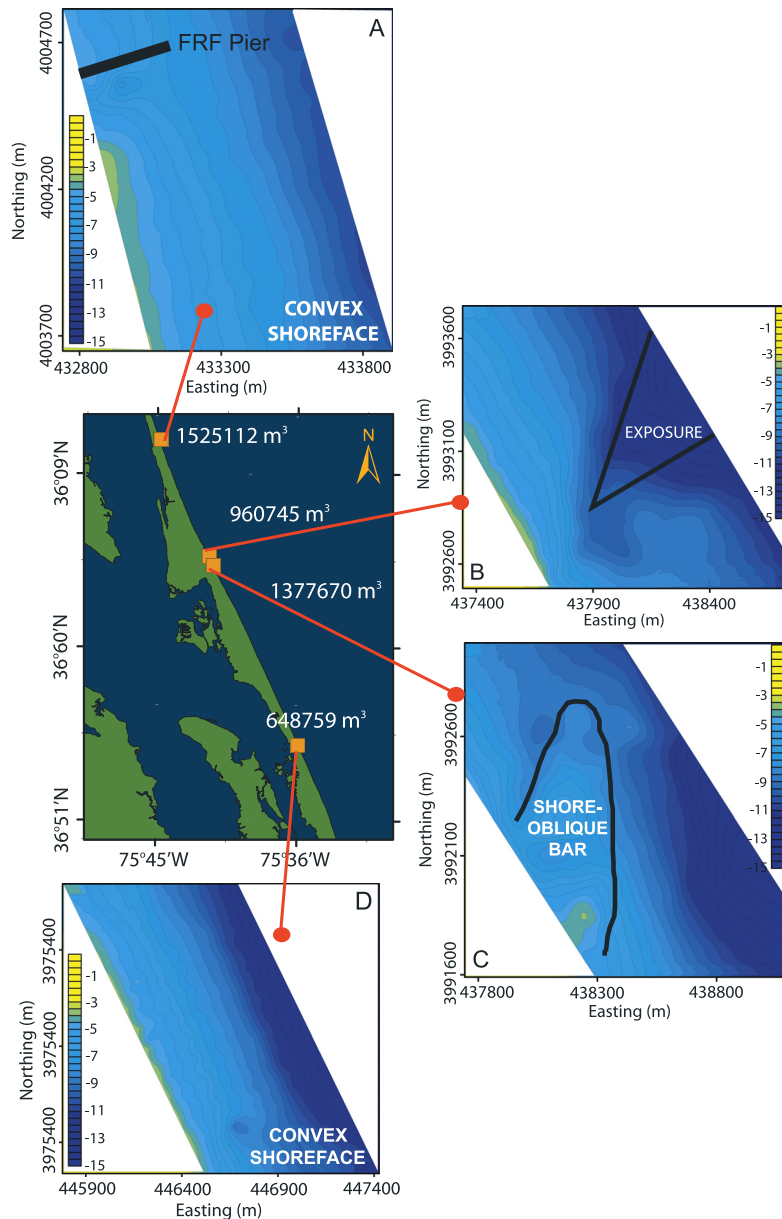
was used as a baseline. The correlation between volume using a baseline defined by depth of closure and decadal shoreline change was not statistically significant. This is most likely due to the lack of a typical equilibrium profile in the study area and the overestimate of available sand [Dean, 1997]. We chose a depth of closure value on the basis of field experiment data collected in Duck, North Carolina [Nicholls *et al.*, 1998], in the northern part of the study area, where there is a typical convex shoreface. While we believe that this may be a reasonable estimate of depth of closure for the defined time period, we argue that the assumptions of an equilibrium profile are violated in some parts of our study area. The shore-oblique bars in Kitty Hawk and Nags Head are three-dimensional and cannot be accounted for in two-dimensional shoreface profiles [Dean, 1997]. Furthermore, the shoreface in North Carolina is underlain by a nonsandy stratigraphic contact and therefore is not a homogenous wedge of sand [Bernabeu *et al.*, 2003; Dean, 1997; Hallermeier, 1978; Kana, 1995; Nicholls *et al.*, 1998]. Last, exposures of R1 at the surface of the seafloor contributes to the heterogeneity of surficial seafloor sediments, yet another violation of the assumptions of the equilibrium profile [Pilkey *et al.*, 1993]. Thus it seems that the method of estimating nearshore sediment volume using underlying geology more effectively captures the geologic character of the shoreface than the method using a depth-constant baseline such as depth of closure.

[38] Nearshore sediment volume, as calculated to a transgressive ravinement surface, is not completely controlled by the presence of positive seafloor morphology, but rather the combined influences of underlying geology and seafloor morphology. If divergences in longshore sediment transport were solely responsible for the volumes found in the nearshore, we would have expected a significant correlation between volume based on depth of closure and shoreline change (Figure 8b). By considering both geologic and hydrodynamic influences on nearshore sediment volume, a

significant correlation between shoreline change and volume was found (Figure 7b). While the shore-oblique bars (positive seafloor morphology) examined in this study comprised a large percentage of the total volumes of the individual bar fields, their presence/absence did not completely dictate the magnitude of sediment volume, further emphasizing the importance of the shallow geologic framework (Figure 11). On a local scale (within each bar field), 1 km<sup>2</sup> areas in which shore-oblique bars were present had more sediment than adjacent 1 km<sup>2</sup> areas in which R1 was exposed (Figures 11b and 11c). However, there were many 1 km<sup>2</sup> blocks without bars that had higher volumes than did blocks with shore-oblique bars (Figures 11a and 11c). There were also areas in which the underlying stratum was exposed that had more sediment than areas in which there were no exposures at all (Figures 11b and 11d). Additionally, our volume metric is capable of accounting for three-dimensional seafloor morphology. In contrast to shoreface profile models and models based on a “profile of equilibrium,” a model based on geologically defined volume could be applicable whether there are multiple shore-parallel bars, crescentic bars, or shore-oblique bars.

[39] An empirical model derived from the relationship between shoreline change and R1-based nearshore sediment volume was constructed to assess shoreline erosion potential. The modeled shoreline change potential compared closely to the observed shoreline change rate (Figure 9a; correlation significant at the 95% confidence interval). This strongly suggests that nearshore sediment volume may be a useful parameter for improving the prediction of decadal shoreline erosion in northeastern North Carolina. The intent of the model is not to predict shoreline change, however, but rather to demonstrate the first-order importance of nearshore sediment volume inshoreline behavior. The number calculated is not a shoreline erosion rate because there is no time component inherent in the calculation of nearshore sediment volume. Therefore the model yields a shoreline erosion potential value that can be used to determine how vulnerable the shoreline is to erosion (Figure 9a). The more negative the number generated with the model, the more prone that region of shoreline may be to erosion.

[40] The correlation of geology-based sediment volume to decadal shoreline change combined with the observations of persistent outcrops of underlying strata in the surf zone [McNinch, 2004] (Figure 4), appear to contradict traditional concepts of the role of longshore sediment transport in shoreline and shoreface change. The estimated magnitude of longshore transport in this wave-dominated region is  $\sim 1 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$  [Inman and Dolan, 1992]. It is unclear how such a large volume of sediment can be transported through the littoral zone while maintaining the overall location and morphology of shore-oblique bars and underlying strata exposures in the nearshore [McNinch, 2004]. We speculate that sorting and self-maintenance processes described at other sorted bed form locations [Green *et al.*, 2004; Gutierrez *et al.*, 2005; Murray and Thieler, 2004] may explain the persistent shore-oblique bar and trough features despite the huge flux of sand. Furthermore, the high correlation of nearshore volume to long-term shoreline change presented here suggests that although high volumes of sediment may be fluxing through the littoral system, the storage capacity of a given location is largely controlled by



**Figure 11.** Plots of seafloor bathymetry from 1 km<sup>2</sup> regions in the study area: (a) convex shoreface, (b) exposure, (c), shore-oblique bar, and (d) convex shoreface. White numbers indicate the volume of sediment within that region, demonstrating the independence of nearshore sediment volume from seafloor morphology. Though both Figures 11a and 11d represent regions without shore-oblique bars and exposures of the underlying surface, the volume of Figure 11a is much higher than that at Figure 11d. Although there is no shore-oblique bar in Figure 11a as there is in Figure 11c (delineated in black), the volume at Figure 11a is higher, demonstrating that morphology is not the sole factor in determining volume. In addition, regions in which the underlying surface is exposed (Figure 11b, within the “V”) do not always have less volume than regions without outcrops (Figure 11d). However, in those regions with bars and exposures (small spatial scale), adjacent regions can show sizable differences in volume (Figures 11b and 11c).

the underlying geology and may not simply be the result of wave-driven gradients in sediment transport.

**5. Conclusions**

[41] A suite of geophysical instruments was used to image the surface of the seafloor and underlying strata in three dimensions for a 40 km<sup>2</sup> region of the nearshore on

the northeastern coast of the Outer Banks of North Carolina. Total nearshore sediment volumes for 1 km<sup>2</sup> regions were calculated to a continuous seismic reflection surface and compared and correlated to a record of decadal shoreline change from the North Carolina Division of Coastal Management. The influence of shore-oblique bars and exposures of the underlying stratum on the volumetric signal were also investigated and an empirical model accounting for the total

volume of sediment and the presence or absence of nearshore shore-oblique bars was created. Analysis of the results led to the following conclusions:

[42] 1. Geologically defined nearshore sediment volume is a useful predictor of decadal shoreline behavior for the northeastern Outer Banks. It represents the results of hydrodynamic processes and the influence of framework geology, is independent of grain size, and can account for a variety of nearshore morphologies.

[43] 2. Nearshore volume determined using a depth of closure-defined baseline overestimated volume and was not correlated to decadal shoreline change. This emphasizes the importance of framework geology in the relationship between volume and shoreline change.

[44] 3. Regionally, the magnitude of nearshore sediment volume is not dictated by seafloor morphology, but locally, it is highly influenced by the presence or absence of shore-oblique bars and exposures of the underlying stratum.

[45] 4. A model forced with only geologic parameters (geologically determined nearshore and shore-oblique bar volumes) demonstrated skill in recreating the observed decadal shoreline change behavior at the field site. Inclusion of similar geologic parameters into more advanced shoreline change models may improve the success of the predictions. The applicability of the nearshore sediment volume metric and the model presented should be evaluated in other systems.

[46] **Acknowledgments.** The authors wish to recognize the U.S. Army Research Office (grant DAAD19-02-1-0307), the U.S. Geological Survey (Cooperative Agreement 02ERAG0034), and the U.S. Army Corps of Engineers, ERDC (USACE, ERDC) for their field and logistic support. First author support was provided by the U.S. Department of Defense (National Defense Science and Engineering Graduate Fellowship) and the National Oceanographic and Atmospheric Administration (NOAA Dr. Nancy Foster Scholarship, Award NA05NOS4291205). Conceptual support in which the ideas presented in this paper were tested in contrasting geologic settings was provided by the National Science Foundation (OCE0504690 and OCE0326831). Thanks also to the staff at the USACE Field Research Facility for their technical support. Special thanks to the external reviewers as well as W. Baldwin and G. Browder for insightful comments on the text. Last, we wish to acknowledge R. Townsend, G. Browder, C. Schupp, and H. Wadman for their assistance on the water and at the beach.

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J. E. McNinch and J. L. Miselis, Virginia Institute of Marine Science, College of William and Mary, 1208 Greate Rd., Gloucester Point, VA 23062, USA. (mcninch@vims.edu; jmiselis@vims.edu)