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SHORE-OBLIQUE BARS, NEARSHORE GRAVEL OUTCROPS, AND THEIR CORRELATION TO SHORELINE CHANGE

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In Partial Fulfillment
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Master of Science

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Courtney A. Schupp
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APPROVAL SHEET

This thesis is submitted in partial fulfillment of

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ABSTRACT

This study demonstrates the physical concurrence of shore-oblique bars and gravel outcrops in the surf zone along the northern Outer Banks of North Carolina. It details, both qualitatively and quantitatively, the relationships between these subaqueous features and shoreline change on a range of temporal and spatial scales. Previous studies have noted the existence of beach-surf zone interactions, but in general, relationships between nearshore geological features and coastal change are poorly understood. Understanding the connection between the surf zone and the subaerial beach is important for understanding coastal zone dynamics and developing predictive engineering models.

The surf zone and nearshore region of the Outer Banks is predominantly planar and sandy, but there are several discrete regions with shore-oblique bars and interspersed gravel outcrops. These bar fields have relief up to 3 m, are several kilometers wide, and were relatively stationary over a 1.5-year survey period, although closer to shore, at depths less than 7 m, they change position and orientation (48° to 87° from North). All gravel outcrops observed in the study region, a 40 km length, were located alongside a shore-oblique bar, in a trough that had width and length similar to that of the associated bar. Seismic surveys show that the outcrops are part of a gravel stratum underlying the active surface sand layer.

Cross-correlation analyses demonstrate high correlation between shoreline change on several temporal scales (100-year and monthly datasets) and the adjacent surf-zone bathymetry and sediment distribution. Regionally, areas with shore-oblique bars and gravel outcrops are correlated with on-shore areas of high short-term shoreline variability and high long-term shoreline change rates. The major peaks in long-term shoreline erosion are onshore of shore-oblique bars, but not all of the shore-oblique bars are associated with high rates of long-term shoreline change.

SHORE-OBLIQUE BARS, NEARSHORE GRAVEL OUTCROPS, AND THEIR CORRELATION TO SHORELINE CHANGE

INTRODUCTION

The influence of hydrodynamic conditions and sediment supply on nearshore bedforms and shoreline change along the mid-Atlantic coast has been documented by many studies (see Dolan et al., 1977; Kraft et al., 1979; Schwartz et al., 1981; Wright and Short, 1984; Belknap and Kraft, 1985; Niederoda et al., 1985; Carter and Woodroffe, 1994; Schwab et al., 2000; Plant et al., 2001; Thieler et al., 2001b), but these parameters do not account for all of the shoreline change occurring in those study areas (Fenster and Dolan, 1993; Lee et al., 1998). Many of these shoreline-shaping processes occur in the surf zone, which can behave as a source of or a barrier to energy and sediment moving between the beach and the nearshore, and which until recently has been difficult to survey with traditional geophysical mapping tools. Results presented here address the lack of data in the surf zone and indicate that surf zone morphology and seafloor sediment distribution may need to be considered when evaluating short-term and long-term shoreline change.

The goals of this research were to explore the relationship between two parameters—shore-oblique bars and sediment distribution in the surf zone and nearshore region-- and to relate these parameters both qualitatively and quantitatively to each other, as well as to shoreline change on several temporal and spatial scales. This thesis first explores the geologic framework of the Outer Banks, existing literature on nearshore bars and sorted bedforms, and methods for measuring shoreline change. The collection and content of the bathymetry, surface sediment distribution, and shoreline change datasets are then described. A description of the inter-survey changes in morphology and surficial sediment distribution in each study site follows. The spatial relationships of the shore-oblique bars to gravel outcrops, and of those two features to shoreline variability and long-term shoreline change, are described and quantified with chi-square calculations and cross-correlation analyses. The discussion explores the inter-survey stability of shore-oblique bars, the sediment heterogeneity seen in the surf zone and nearshore, the spatial relationships between bathymetry and shoreline change, and the unique morphology of shore-oblique bars.

Geologic Framework

Although many studies have addressed the influence of inherited framework geology on modern shoreline behavior (Belknap and Kraft, 1985; Riggs et al., 1992; Snyder, 1993; Riggs et al., 1995; Riggs et al., 1996; Schwab et al., 2000), particularly in terms of the regional bathymetry and the varying susceptibility of inherited and modern sediments to erosion, none has quantified the connection between alongshore shoreline variability and nearshore geologic variations that stem from complex unconsolidated stratigraphy such as that of the northern Outer Banks. This framework was created by multiple glacio-eustatic sea level fluctuations that cut fluvial channels through older, underlying strata during the Pleistocene (Riggs et al., 1992; Boss et al., 2002). Fluvial and estuarine sediments subsequently filled the channels, and the barrier system migrated landward. Pleistocene river channels appear to underlie some areas within the study region in the northern Outer Banks (Snyder, 1993; Riggs et al., 1995; Boss et al., 2002; Browder and McNinch, 2003).

On the northern Outer Banks, waves and wave-induced currents produce a very high net southerly sand transport, estimated to be 500,000 to 1 million m^3/yr, and are comprised primarily of relict sediments that were deposited on the shelf during low stands of sea level (Inman and Dolan, 1989). In comparison, net northerly sediment transport in southern Virginia, just north of the Outer Banks, is only 160,000 m^3/yr (Inman and Dolan, 1989). Despite the very high rate of alongshore sediment transport, some areas of the nearshore seafloor are devoid of modern deposits of sand. Outcrops of relict sediments are exposed in the surf zone and nearshore areas (Pearson, 1979; Snyder, 1993; Riggs et al., 1995) and are part of two major sediment units that Pearson (1979) documented between the shoreline to 5 km offshore. A thin layer of modern shoreface sediment unconformably overlies relict fluvial and estuarine sediments; both units outcrop on the inner shelf along Wilmington and Nags Head, the latter being within this study's regional survey area and approximately 11 km south of the smaller survey sites. The contact documented by Pearson (1979) constitutes a major reflection in high-resolution seismic data and is also evident in seismic data collected in conjunction with this study.

Nearshore and surf-zone morphologies

Many studies have described bar morphologies seen in the surf zone and nearshore areas of the Atlantic coast (see Komar, 1998 for an extensive review). These forms include both linear and crescentic shore-parallel bars, transverse bars, ridge and runnel, and shoreface-attached ridges. The features may range in length from meters to kilometers (Bruun, 1955, and Moody, 1964, as cited in Niederoda and Tanner 1970), may have rhythmic spacing (Bruun, 1955, and

Hom-Ma and Sonu, 1963, as cited in Niederoda and Tanner, 1970), and may be attached to the shore (Schwab et al. 2000) or to the alongshore bar (Konicki and Holman, 2000). Some studies surmised that these bars influence the shoreline by focusing advancing waves and channeling sediment offshore (Shepard 1952 as cited in Niedoroda and Tanner, 1970; Aubrey et al., 1982).

Four surf-zone bar morphologies are discussed in Wright and Short's categorization (1984) of six beach types, ranging from dissipative to reflective (Figure 1). The authors describe a shore-parallel bar and trough combination, in which the bar may be straight or crescentic, and the trough is 2-3 m deep. Crescentic shore-parallel bars have rhythmic undulations with 100-300 m spacing. Transverse bars are associated with rip currents and appear to form when the horns of crescentic bars weld to the beach. The final form, known as ridge and runnel, is comprised of small irregularly spaced rips. All of these forms are found within 250 m of the subaerial beach, in less than 2 m water (depth below MLW).

Lippman and Holman (1990) provide additional insight on the bar forms set forth by Wright and Short (1984) by discussing the spatial and temporal variability of the various morphologies and by expanding two of the bar categories (Figure 2). First, they describe two types of the longshore bar-trough combination, both with long dominant length scales (100 m – 1 km): a linear bar, and a longshore variable but non-rhythmic bar. Next, they categorized two types of the transverse bar and rip state described by Wright and Short (1984) by describing an attached bar with longshore rhythmicity, and a non-rhythmic attached bar.

Transverse bars are also described by Niederoda and Tanner (1970), who saw them on the Gulf Coast of Florida in water depths up to 1.5 m, which is 335 to 1000 m from the beach, with a spacing of 64 to 218 m and lengths of 107 to 640 m. Those transverse bars were seen along sandy beaches in low-to-moderate wave energy. They also reviewed other descriptions of transverse bars that can be 3.3 km long (Moody 1964), with relief of only a few meters (Bruun, 1955; Moody, 1964) and rhythmic spacing that can range from 300 m to 2 km (Bruun, 1955; Hom-Ma and Sonu, 1963) and which may or may not migrate.

Further descriptions of transverse bars were made by Konicki and Holman (2000), which details bars with lengths of 10-200 m and orientations at oblique or perpendicular angles to the shoreline. They named two types of bars: trough transverse bars, which extended seaward from the shoreline and had crests at 79 m spacing; and offshore transverse bars, which extended seaward from the shore-parallel sand bars and had crests spaced at 172 m. Both types of bars persisted for days to months and migrated alongshore.

Substantial investigations have been conducted along the mid-Atlantic coast on larger features called shoreface-attached sand ridges (Swift et al., 1972; Stubblefield and Swift, 1976;

Swift and Field, 1981). The ridges described by McBride and Moslow (1991) were seen along shorelines characterized by transgression, mixed-energy wave-dominated barrier islands, and laterally migrating tidal inlet systems. These features, which are linear and shore-oblique, were found in less than 20 m of water. They had side slopes up to 1°, heights up to 10 m, and widths and lengths over 1 km.

Sorted bedforms

Sorted bedforms are generally defined as bands of seafloor sediment that are much coarser than the surrounding seabed sediments. These features have been observed in many parts of the world (see Cacchione et al., 1984, and Murray and Thieler, 2004 for reference lists), and include rippled trough features on the Atlantic coast of Cape Cod, MA (Aubrey et al., 1982; Goff et al., 2004), coarse sediment bands off of southern California (Hunter et al., 1988), gravel-filled depressions on the shoreface of the Canadian Beaufort Sea (Hequette and Hill, 1995), and sorted sand beds along the east coast of New Zealand (Green et al., 2004; Trembanis et al., 2004). Sorted bedforms have also been mapped along the shoreface and inner continental shelf of the central California coast (Cacchione et al., 1984) and Wrightsville Beach, another North Carolina barrier island (Thieler et al., 2001b).

Sorted bedforms described by Thieler and others (2001b) were shore-oblique and asymmetric with a steeper downdrift side and a bathymetric low on the updrift side. They were usually 40 m to 100 m wide and as high as 1 m. The centers tended to be of coarser sediment, with finer sediment towards the edge and draped on the downdrift sides of the features; this sorting is probably controlled by grain size, alongshore transport, and bottom resuspension. The depressions were floored by shell hash, gravel, and underlying coastal lithosomes. Megaripples within the depressions had crests parallel to shore (Thieler et al., 2001b). Bedforms described by Murray and Thieler (2004) were shore-normal, asymmetric, floored by ripples of coarse shell hash and gravel, and sometimes separated by sand ridges. They develop just outside the fair-weather surf zone, are several kilometers long, and are quite narrow (less than 100 m). The shore-parallel ripples seen in the gravel exposures are probably due to smaller bottom boundary layer conditions (Murray and Thieler 2004) or by winter surface waves (Cacchione et al., 1984).

Several manuscripts, discussed below, describe the possible origin and effects of sorted bedforms. The bedforms are thought to be self-reinforcing and repeating, responding to both alongshore and cross-shore flows, and associated with sediment transport alongshore. Perhaps a small perturbation forms a feedback loop in which fine material is winnowed from coarser material, leading to increasingly organized larger bedforms (Murray and Thieler 2004). Other papers have attributed the depressions to high-energy shelves with storm-setup-induced downwelling (Cacchione et al., 1984), turbulence (Murray and Thieler, 2004; Green et al., 2004; Gutierrez et al., 2004), alongshore flow (Goff et. al, 2004), alongshore sediment transport (Murray and Thieler, 2004), scouring by rip currents, wave agitation, storm surge ebb return flow, and linear depressions that channel the sediment offshore (Thieler et al., 1995). According to the Wrightsville Beach study, sorted bedforms are believed to control the distribution, texture, and composition of surficial sediments and inner-shelf bathymetry (Thieler et al., 2001b), while underlying geology may control the shoreface profile shape (Thieler et al., 1995).

Shoreline change

Shoreline change is considered on several temporal scales for this study in order to distinguish between short-term variability and long-term trends and to balance the strengths and weaknesses inherent in each method of shoreline change measurement. Long-term shoreline change is usually considered for the period extending back to the first geographically referenced maps of an area, often an 1800s-era T-sheet from the forerunners of the National Ocean Service (NOS). Older shoreline data typically are sparse and were often collected to document storm damage; such maps may reflect a snapshot of a storm rather than a typical shoreline position for that period. The long-term change rates used in this research are end point rates (EPR), which are calculated by dividing the linear distance between earliest and latest available shorelines by the time period elapsed. More representative calculations may also include interim shoreline positions to determine a linear regression rate (LRR), which incorporates several sets of time periods and distances. When fewer sets of shorelines are used to determine a change rate, the influence of each shoreline increases, so shoreline datasets must be evaluated carefully to ensure that they are representative of long-term trends rather than storm responses (see Dolan et al., 1991, and Thieler et al., 2001a for reviews of methods for measuring shoreline change rates).

Short-term shoreline change may be measured over days or years, may be extracted from maps or measured in the field and, like long-term change, may be calculated using EPR or LRR as described above. Short-term data generally capture changes due to tidal inlet migrations (Honeycutt and Krantz, 2003), seasonal wave climate (Pajak and Leatherman, 2002), storm events (List and Farris, 1999), or engineering activities such as beach nourishment. The shoreline variability measurements used in this study capture monthly variability over several years.

List and Farris (1999) used several years of monthly shoreline position surveys on the Outer Banks of North Carolina to quantify shoreline hotspots, defined as regions of anomalously high net erosion or accretion in a given section of coastline (Dean et al., 1999; List and Farris, 1999; Kraus and Galgano, 2001; McNinch, 2004) that may also exhibit high variance in shoreline position (List and Farris, 1999; McNinch, 2004). The hotspots in this region are not attributable to engineering projects (Kraus and Galgano, 2001) or nearby inlets (Fenster and Dolan, 1996). Hotspot locations may be different during each storm, and may exhibit high erosion followed by a comparable amount of accretion during the ensuing calm weather (List and Farris, 1999) to result in little net change in shoreline position.

The shoreline in this area quickly and significantly responds to changes in the energy regime, and has migrated as much as 45 m over 3 years (Plant and Holman, 1996), but the major control on shoreline position is a subject of debate. Proposed controls include alongshore and cross-shore sediment transport resulting from wave action (Fenster and Dolan, 1993), wave direction (Plant and Holman, 1996), and wave height (List and Farris, 1999). The effects of these factors are often particularly noticeable when comparing pre- and post-storm nearshore profiles, as is done at several sites in this study. Storms are known to cause a great deal of subaerial beach disturbance (Fucella and Dolan, 1996; Komar, 1998; Lee et al., 1998) and might strip away thin sand layers overlying relict gravel, thereby exposing the relict units to erosion (Pearson, 1979). This paper does not identify specific controls on shoreline change. Instead, it demonstrates the physical concurrence and persistent locations of shore-oblique bars and gravel outcrops observed in the northern Outer Banks. It then quantitatively links these nearshore features and the variability of nearshore geology to the alongshore variability of shoreline change on a range of temporal and spatial scales.

REGIONAL SETTING

The survey areas mapped in this study are located in the nearshore and surf zone along the northern section of the North Carolina Outer Banks between Corolla and Oregon Inlet (Figure 3). For the purposes of this study, "surf zone" is defined as the area of breaking waves, and "nearshore" is defined as the region extending from the beach to the 12 m contour. This beach and nearshore, particularly near the Duck Field Research Facility, have been extensively studied (Hayes, 1979; Birkemeier et al., 1985; Fenster and Dolan, 1993; Plant and Holman, 1996; Lee et al., 1998; Holland et al., 2001). Historic meteorological data are available from the Army Corps of Engineers (http://www.frf.usace.army.mil/frfdata.html). The region behaves as a long, linear barrier beach and is generally oriented NNW-SSE but includes several small-scale changes in shoreline orientation. The beaches on the Outer Banks have a relatively straight and steep (1:10) foreshore and a planar (1:500) offshore region (Holland et al., 2001). The region is wave-dominated and microtidal. The semi-diurnal tides have a mean range of 0.97 m, and the variable wave climate has a mean annual significant wave height of 0.9 m and an annually averaged shore-normal direction. The net southerly alongshore transport of sand is very high in comparison to other regions along the Atlantic coast, as detailed in the introduction section. Like many barrier systems, the northern Outer Banks is subject to storm washover. Other major influences on this coast are alongshore current, hurricanes, and northeasters. The nearshore area often includes shore-parallel bars, but, as noted in the introduction section, bars may be absent and may occur as isolated clusters perpendicular or at oblique angles to the shoreline.

METHODS

Mapping techniques

In June 2002, a regional survey of the North Carolina Outer Banks (Figure 3) simultaneously collected nearshore bathymetry and acoustic backscatter data using an interferometric swath system (Submetrix series 2000) at a frequency of 234 kHz. This system allows confident interpretation of the spatial relationship of bathymetry to sediment distribution by enabling distinction between acoustic returns of high incident angles from seafloor sediments with high backscatter characteristics, and by eliminating the need to account for towfish layback artifacts. The system was mounted on the bow of an amphibious vehicle (Figure 4) and was used in conjunction with a motion sensor, compass, and real-time kinematic global positioning system to obtain horizontal and vertical precision of about 10 cm. Initial regional survey lines were shore-parallel and spaced approximately 100 m apart, resulting in 65% coverage of the bathymetry and the acoustic backscatter of the seafloor. For the later surveys, the study sites were mapped along lines with approximately 70 meter spacing, with an additional two shore-perpendicular tie lines in each survey area, resulting in 90% seafloor coverage.

Acoustic backscatter data were mosaicked using SonarWeb and categorized as sand, gravel, or mixed based on sediment grab samples obtained during field surveys. ArcView was used to delineate the perimeter of gravel outcrops and to calculate the areal extent of each sediment type for each survey and site.

Bathymetry was heave-corrected and processed using RTS2000 and Grid2000 software. Depth measurements were adjusted relative to mean low water based on the NOAA tide station at the FRF pier in Duck, NC. Depths were gridded using a 3 m sliding window, then smoothed and despiked. Grids were interpolated in Surfer software using kriging and a Gaussian filter to create surface and contour maps.

The shape of the 9 m isobath was determined to be a representative proxy for the location of shore-oblique bars, which are usually evident and discrete at that depth. To calculate the offshore distance of this isobath, the Digital Shoreline Analysis System (DSAS) (Thieler et al., 2003) was used to cast shore-perpendicular transects between the isobath and a recent shoreline calculated by averaging monthly shoreline positions between 1999-2003 (List and Farris, 1999). The distance to the 9 m isobath (Figure 5A) was also used to calculate the slope of the shoreface.

Survey locations and conditions

A regional survey covered the 40 km between Corolla and Oregon Inlet, North Carolina. The survey area began as close to shore as possible, generally in about 2 m water depth, and extended offshore a distance of 1 km to water depths reaching 14 m. Based on data from this regional survey, four smaller sites situated within a 15 km region between Southern Shores and southern Kill Devil Hills, North Carolina were selected for repeated surveys (Figure 3). Each study site was approximately 1 km long in a shore-parallel direction and extended approximately 1 km offshore.

Pre-survey conditions varied between each of the four surveys. Wave heights measured at the 8 m isobath ranged from 0.23 m to 2.1 m and tides from -0.7 m to 1.3 m. Incident wave direction varied between surveys. The June 2002 and May 2003 surveys were performed during and after typical spring weather, while the March 2003 survey followed a powerful northeaster on February 23, 2003. The final survey in this study occurred in November 2003, just after Hurricane Isabel on September 18, when storm surge reached 1.5 m and significant wave height reached 8.1m. These were record conditions for 27 years of monitoring at the USACE Field Research Facility in Duck, which is located 125 km north of the location of the eyewall's landfall.

Shoreline change datasets

Nearshore survey data were linked to shoreline change estimated by three metrics: shoreline variability, recent shoreline change rate, and long-term shoreline change rate. The shoreline variability (Figure 5B) was determined from a set of shoreline positions (mean high water contour) that were mapped monthly between 1999 and 2002 (List et al., submitted). To collect the data, two GPS units, each capable of three-dimensional measurements, were mounted on a small vehicle that was driven along the estimated mean high water contour seen on the beach. The foreshore slope is assumed to be uniform, and is extrapolated from the difference in horizontal and vertical positions of the two GPS units. The target elevation contour is then extracted from the foreshore topography. This ground-based method can capture short-term variability, unlike aerial photos in which shoreline change may be smaller than the error expected from digitizing (List and Farris, 1999). The standard deviation in shoreline position was calculated for points at 2 m spacing; those point values were then smoothed with a 1 km sliding window that averaged the values within that window. High standard deviations indicate a high variability in shoreline position, whereas low standard deviations indicate less short-term variability in shoreline position.

The recent (28-year) shoreline change end-point rates (Figure 5C) were calculated using the averaged shoreline position with another set of averaged monthly profiles that were collected by the Army Corps of Engineers. The profiles were surveyed once a month from May 1974 through January 1977 at 62 locations, each between 0.7 and 2.1 km apart.

The long-term shoreline change rates (Figure 5D) were calculated by North Carolina's Division of Coastal Management using the end point rate method (NCSU, 2003). The 1998 shoreline was digitized from aerial photographs. Most historic shorelines were obtained from aerial photographs taken between 1933 and 1962, but shoreline positions for the northernmost NC coast were obtained from an 1800s-era NOS T-sheet. These data have a point spacing of approximately 164 m along the coast.

Statistical analysis

Chi-square was calculated to determine whether or not a relationship existed between the presence of shore-oblique bars and the presence of gravel in the June 2002 dataset. To create the 2x2 contingency table (Table 1), each point along the shoreline was classified according to whether there was or was not gravel offshore and whether the 9 m isobath (a proxy for shore-oblique bars) was closer or farther offshore than the median distance to that isobath. A standard table of the cumulative distribution of chi-square given one degree of freedom was used to determine the probability of a greater chi-square value (Zar, 1999).

Cross-correlation analysis of the June 2002 dataset quantified the strength and the alongshore distance of the linear relationships between several features: offshore distance of the 9 m isobath (i.e., the presence or absence of a shore-oblique bar), shoreline variability, and long-term shoreline change. Although similar correlation methods have been used in nearshore geological research, this research presents its use in the surf zone and in distilling large and varied datasets into summary correlations. In contrast to correlation analysis, which explores the strength of the relationship between spatially concurrent pairs of the members of two data sets, cross-correlation supposes that there is a spatial shift at which the members of the two datasets have the strongest relationship; that is, in a cross-correlation function, the relationship may reach its absolute maximum at a non-zero lag. In this study, a negative lag between bathymetry and a shoreline change measurement indicates that the shoreline was affected to the south of the bathymetric feature; a positive lag indicates the shoreline change occurred to the north of the bathymetric feature. Positive correlation coefficient indicates that both parameters were increasing or decreasing together; negative correlation indicates that one parameter increased while the other decreased.

Each shoreline position point was linked with the perpendicular-offshore distance to the 9 m isobath distance and sediment type, as well as to the shoreline variability and the long-term and shoreline change rates. To accomplish these connections, DSAS was used to cast shore-normal transects from the averaged shoreline position at 20 m intervals. For the sparser long-term shoreline change data set, each transect was assigned to the nearest measurement using the 'Spatial Join' function in ArcView Geoprocessing Wizard, with the result that some adjacent transects share the same values for shoreline change rates.

Cross-correlations between dataset pairs were then calculated with MatLab's 'xcov' function using the 'coeff' scaling option to normalize the sequence so that the autocorrelations at zero lag were equal to one. A two-tailed test was chosen in order to examine correlations in both the negative and positive direction (at alongshore lags to both the north and the south). The resulting cross-correlations span 80 km, the total possible lag distance between paired datasets that are spatially shifted during the cross-correlation functions. However, only 4 km are displayed on the graphs, 2 km to both the north and the south, because causal relationships are not expected to involve features at a distance exceeding 4 kilometers, and because at greater spatial shifts, unrelated features such as discrete bar fields are paired. Spatial independence is assumed to be on the order of 300 m based on surf zone morphology (e.g., width of shore-oblique bars). Therefore, the effective sample size (at 300 m intervals) is one-fifteenth of the actual sample size (at 20 m intervals). Degrees of freedom were calculated as two less than the effective sample size for each analysis, and significance was determined using a standard table for the significance level of correlation coefficients (Table 2) (Snedecor and Cochran, 1967).

Relationships between the same three variables were also examined at each smaller focus area. Cross-correlation analysis was used to explore the spatial lag between variables. Although the values for the regional dataset were normally distributed, the values for each study site were not, so confidence limits were calculated based on Student's t-distribution. The effective sample sizes for the individual focus areas were too low to provide significant results. Instead, chi-square was calculated to examine the relationships between bathymetry and shoreline variability, both at spatially concurrent locations and at the alongshore lag determined by cross-correlation analysis. Although this test does not calculate the alongshore lag distance of correlation between variables, it is appropriate to use at the smaller sites because it assumes only that the values are normally, not randomly, distributed. To create the 2x2 contingency table, each point along the shoreline was classified as having shoreline variability higher or lower than the regional average, and by whether the vertical gradient between two adjacent points was steeper or flatter than the regional average, assuming that a steeper gradient indicates the presence of a bar field rather than a planar shoreface. It was not possible to calculate the chi-square value for Southern Shores, as none of the samples in that area were classified as having high shoreline variability, nor were shore-oblique bars or outcrops present in the nearshore.

The length and irregularity of the 28-year shoreline change data impede its use in cross-correlation analysis. It is displayed for visual reference but is not used in any quantitative calculations of correlation or lag distance. The long-term shoreline change datasets are not as robust as the others, and the higher distance between values makes spatial correlation difficult for the 1-km scale of the study sites.

RESULTS

Regional observations of nearshore morphology, sediment distribution, shoreline variability, and long-term shoreline change rates are described below. The regional cross-correlation results are also shown. The characteristics of each study site during each survey period are then detailed, and cross-correlations between their features are enumerated.

Regional observations

Within the 40 km regional survey area, there are extensive planar sand stretches with triangular patches of gravel (Figures 6, 7) and isolated clusters of shore-oblique bars (Figure 8). Three fields of alternating shore-oblique bars and troughs, as illustrated by the distance of the 9 m isobath from shore (Figure 5A) and the regional bathymetry (Figure 8), were mapped. The barred region in Kitty Hawk and Kill Devil Hills is approximately 5.5 km long. Eleven km farther south, in Nags Head, a second bar field extends for 1.1 km alongshore. A third group of bars extends from 2.5 to 6 km south of Nags Head. South of this barred area, the shoreface slope gradually increases southward towards Oregon Inlet, to a slope of 0.012 (Figure 5A).

Between Southern Shores and Kitty Hawk, the shoreline variability (Figure 5B) is low, within the second (3.9-6.5 m), and predominantly the first (0-3.9 m), quartile. In contrast, along a 4.5 km section between Kitty Hawk and Kill Devil Hills, shoreline variability is much higher (mean 5.2 m) and has a large range (2.2-9.7 m). Short-term shoreline variability tends to increase as cross-shore slope increases, as seen on a regional scale in the area north of Corolla (J. List, pers. comm., April 2004) and between Kill Devil Hills and Oregon Inlet (Figures 5A, 5B). This correlation cannot be attributed to steady erosion, because even when linear change rates (the steady rates of erosion) are removed from the shoreline variability data, the shoreline variability curve does not change (Table 3) (J. List, pers. comm., May 2004).

There are also several intriguing correlations between the bathymetry and shoreline change data sets (Figures 5A, 5C, 5D). The long-term shoreline change rate curve is similar to the changes seen between 1974 and 2002, with the exception of the area near Oregon Inlet, where erosion has increased over the last century but has decreased during the past few decades. Within the 15 km region encompassing the four focus areas, the long-term changes over 75-year and 28-

year time scales have matching patterns of erosion and accretion (Figures 5C, 5D). Like the pattern seen for shoreline variability, long-term shoreline change increases both as the shoreface slope increases southward from Kill Devil Hills to Oregon Inlet and where the shoreface slope is fairly constant between Southern Shores and Kitty Hawk.

Data collected in June 2002 were cross-correlated with existing datasets to examine regional trends. At a regional scale, there were high correlations between bathymetry and both shoreline variability and long-term shoreline change. The results were significant at the 99% confidence level, indicating that there is only a 1% chance of concluding incorrectly that there is a relationship between the paired datasets.

For the 40 km region, shoreline variability and the distance to the 9 m isobath have a correlation value of -0.40 at 220 m lag (Figure 9), indicating that an area with a shallow slope (a long distance between the shoreline and the 9 m isobath) is associated with an area of low shoreline variability at a point 220 m to the north (Figure 10). When the shoreline variability dataset is smoothed alongshore with a 1500 m sliding window, the magnitude of the correlation value increases to -0.48 but the alongshore lag shifts northward (Figure 9), so that an area with a shallow slope is instead associated with an area of low shoreline variability at a point 280 m to the north (Figure 10).

The long-term change rate and the distance to the 9 m isobath have a correlation of 0.59, at a lag of -280 m (Figure 11). These correlation values are very strong, and the short lag distance demonstrates a tight spatial coupling between shallow slopes and long-term accretion immediately to the south (Figure 10). Shoreline variability and long-term shoreline change are also correlated, but at somewhat of a distance: the maximum correlation of –0.47 occurs at an alongshore lag of -800 m (Figure 12). This inversely correlated offset indicates that an area of shoreline with high short-term variability is associated with an area that is 800 m to the south and has high long-term erosion (Figure 10).

Based on the data from the initial regional survey, four smaller study areas were selected for repeated surveys (Figure 3, Table 4). Each focus area contained different feature attributes including bar position and orientation, sediment distribution, long-term shoreline change, and shoreline variability (Table 3). The unique characteristics of the four areas, described below, offer opportunities to examine nearshore morphology, sediment distribution, shoreline variability, and long-term shoreline change on a smaller spatial scale throughout the 16-month survey period.

Convex, planar shoreface

SOUTHERN SHORES

Morphology of shoreface

The northernmost focus area, located in Southern Shores (hereafter SS), lies within a planar sandy section in the northern part of the regional survey area. It did not have any shore-oblique bars evident during any of the survey periods (Figures 13, 14A), and maintained a fairly uniform alongshore slope with a shore-parallel bar and a cross-shore slope of about 0.010 (Figure 14A). This area behaves as a classic example of seasonal coastal beach behavior (Wright and Short, 1984; Lee et al., 1998; Carter and Woodroffe, 1994). The summer (June 2002) shoreface was the steepest of the surveys, with the 9 m isobath 800 m from shore. During the March and November surveys, the 9 m contour was farthest seaward (900 m from shore) and had a few irregularities in an overall linear shape. The May 2003 position was also as expected, closer towards shore in the transition from a stormy winter to a lower-energy summer position.

Sediment Distribution

The SS site has a thick muddy sand layer that is distributed uniformly and continuously across the survey area, a determination based on acoustic reflectance (Figure 15), sediment grab samples (Figure 6), and shallow sub-bottom data (Miselis and McNinch, 2002). According to seismic data collected in June 2002 (Table 3), the sand layer has an average thickness of 0.41 m^3/m^2 (Miselis and McNinch, 2002).

Shoreline Variability

Shoreline variability measurements in the planar SS site have a low range of values (2.01 to 4.41 m) (Figure 16A), which are mostly within the 25th percentile (mean 3.05 m, standard deviation 0.55 m). The maximum correlation between bathymetry and shoreline variability is 0.51 at a -140 m lag (Figure 17A), meaning that the distance to the 9 m isobath is inversely correlated to the short-term variability of a point on the shoreline 140 m to the south. More specifically, an area with a steep cross-shore slope (a short distance to the 9 m isobath) is associated with an area with high shoreline variability 140 m to the south (Figure 18A).

Long-term shoreline change

The long-term change rate is low (mean 0.18 m/yr, standard deviation 0.06 m/yr) with a low range of values (0.06 – 0.27 m/yr). The long-term change rate and the distance to the 9 m isobath have a maximum correlation of 0.39 at a lag of 220 m (Figure 19A), indicating that areas with a shallow slope (a long distance to the 9 m isobath) are associated with areas of long-term accretion about 220 m to the north (Figure 18A). There is also a secondary peak in the correlation results: a coefficient of –0.37 at a lag of –100 m (Figure 19A). This indicates that an area with a steep slope (a short distance to the 9 m isobath) is associated with an area of long-term erosion 100 m to the south (Figure 18A).

Shore-oblique bar areas

This section summarizes general trends evident in the barred areas. The following sections include site-specific details on survey locations, shore-oblique bar morphology and angles, and surface sediment distribution and thickness.

Morphology of shoreface and shore-oblique bars

The three southernmost study sites all include shore-oblique bars and troughs. All of the shore-oblique bars have similar characteristics. Within the 40 km survey, all of the shore-oblique bars point towards the northeast or east, at angles ranging from 48° to 87° (Table 3, Figure 8). These bars are seen at the landward limit of the survey lines, at 3.5 m depth; the data do not reveal whether the bars are attached to the subaerial beach. At the 9 m isobath, these bars may extend up to 1100 m offshore and be between 200 m and 1 km wide with cross-shore gradients of up to 0.016 (Figure 5A). The troughs that lie adjacent to the shore-oblique bars have a smaller width range, about 200-500 m. The bars and troughs have amplitudes up to 3 m and are asymmetric in an alongshore (cross-bar) direction. Troughs can be distinguished within 250 m of the subaerial shoreface, at depths of 4 m. They have a cross-shore slope of approximately 0.011, and the 9 m isobath is located at a distance of 800-900 m from shore.

The southern edge of every shore-oblique bar, where bars are wide and in depths of more than 7 m, was in a nearly identical position in every survey (Figure 14). The shallower portions of shore-oblique bars change position and orientation closer to shore, but they never occupy a wholly new space; that is, each location of a given bar overlaps its previous position. The main body appears to remain in place at depths of more than seven meters, with the shallower portion shifting to a new location between surveys. Over the 16-month period, changes in trough locations mirrored those of the shore-oblique bars.

Sediment Distribution

In the three study sites with shore-oblique bars, a thin, irregular layer of sand overlies a gravelly layer, as determined by acoustic reflectance (Figure 7), sediment grab samples (Figure 6) and shallow sub-bottom data (Miselis and McNinch, 2002). The overlying sand layer varies in thickness by 0-1.5 m (Miselis and McNinch, 2002). An in-depth discussion of the stratigraphy is beyond the scope of this paper and will be the subject of a subsequent report (Miselis and McNinch, submitted), but it is important to note that thickness and continuity of the surficial sand is not uniform along this region or even within each study site.

Acoustic backscatter data also show several gravel patches with shore-parallel ripples of 30-50 cm wavelengths (Figure 6C). Each patch is triangular in shape with the apex pointing towards shore and the base widening in an offshore direction (Figure 7). The surficial exposure of the individual patches continues in an offshore direction, where one larger exposure is visible 1.5 km offshore (Williams et al., 2000). The smaller patches may first appear as close as 200 m to the shoreline in depths as shallow as 4 m below MLW. In repeated surveys, the perimeter of the exposed patches, at their shoreward pointed tips, move towards and away from shore (Figure 20). Overall, however, the locations of these features are fairly stable on a hundreds-meter scale. This is particularly evident towards the wider seaward edge, which was mapped almost 1 km from shore in 11 m depth MLW.

Changes in surface sediment distribution were visible in all three shore-oblique bar sites, where the gravel exposure spread alongshore and across-shore between June 2002 and March 2003 and migrated slightly southward (Figure 20). These changes reflect changes in the shore-oblique bar and trough shapes as discussed in the following sections. Discrete triangular patches exposed in June 2002 and, to a lesser extent, in May 2003, degraded to patchier exposures seen post-nor'easter (March 2003) and post-hurricane (November 2003). In comparison to the previous sidescan surveys, the area of exposed gravel was reduced by 50-89% between May and November 2003 (Table 3). In all three study sites with shore-oblique bars, the gravel that was visible in the November survey was exposed over a much wider area, was farther offshore, and was visible only as scattered patches rather than as well-defined triangular areas.

The position, shape, and changes of the gravel patches are closely tied to the morphology of the shore-oblique bars (Figure 21). A chi-square test of the June 2002 regional survey data shows that there is a relationship, with a p-value < 0.001, between shore-oblique bars and the presence of gravel (Table 1). All shore-oblique bars observed in June 2002 had an associated gravel patch located in a trough alongside a shore-oblique bar (Figure 22). Each shore-oblique bar had width and length proportional to that of the associated trough, always lay south of a gravel patch, and sometimes framed the north edge of the patch as well. The gravel exposures mirror trough shape and movement; for example, troughs that are wider in an alongshore direction and shorter in their across-shore length are associated with wider, shorter gravel patches. The location of gravel is confined to the troughs (Figures 23, 24). Despite the presence of similar morphologic forms in the study areas, the sediment distribution and bathymetry varies seasonally but not uniformly between the discrete regions.

Shoreline variability

The shore-oblique bars are strongly correlated to shoreline change measured at several scales, including monthly shoreline variability, long-term (65-year) change, and recent (28-year) change. This is evident at regional and study-site scales both graphically and through cross-correlation analysis of June 2002 data. Shoreline variability is also higher in areas with shore-oblique bars than in areas with a planar shoreface. All of the shore-oblique barred areas surveyed in June 2002 are along stretches of beach where the shoreline variability ranks in the highest quartile (6.5-15.9 m) for the 40-km area (Figure 16).

Long-term shoreline change

The two areas in the 40 km region that have the highest long-term erosion rates also have shore-oblique bars. One of these regions lies between Kitty Hawk and southern Kill Devil Hills. The other region is near Oregon Inlet and may be attributable to widely observed shoreline dynamics caused by inlet processes, such as sediment bypassing and wave refraction around the ebb tidal delta (Hayes, 1980; FitzGerald, 1984).

KITTY HAWK

Morphology of shoreface and shore-oblique bars

The Kitty Hawk (KH) site is approximately 5 km southeast of SS and has both a shore-oblique bar and an associated trough on the southern edge of the bar. Within this study site, the 9 m isobath is centered about 800 m offshore, but its irregular contour ranges from 480 m to 1050 m offshore, producing a cross-shore slope that ranges between 0.008 and 0.019 (Figure 14B). Bathymetric surveys (Figure 25) show that in June 2002, the axis of the shore-oblique bar was at an 86° angle to the shoreline and, at 800 m from shore, had a width of 383 m as measured along the 9 m contour line. By March 2003, it had rotated northward to 76° and the northern edge of the bar, as defined by the 9 m isobath, had moved 154 m northward, while the southern edge of the bar had moved 154 m southward, widening the bar by 308 m; this position was the same in

May 2003. By November 2003, the bar had rotated sharply to the north and was at a 37° angle to shore; it had also widened by 158 m, with the northern edge moving an additional 54 m northward and the southern edge moving 104 m southward.

Sediment Distribution

Sand thickness at this site varies, but averages 0.46 m (Miselis and McNinch, 2002). This gravel was exposed in some areas of the survey site (Figure 26), and the total surface area covered by sand varied between each survey; in June 2002, 83% of the surface was covered in sand, 79% in March 2003, only 68% in May 2003, and in November 2003, the sand was very patchy and covered 88% of the surface.

Shoreline Variability

Shoreline variability in this area (Figure 16B) is high (mean 4.71 m, standard deviation 1.40 m) with a wide range (2.18 – 8.11 m). Shoreline variability and bathymetry have a correlation coefficient of 0.46, with a lag of 540 m (Figure 17B), indicating an area of high shoreline variability at a point 540 m north of an area with a shallow cross-shore slope (Figure 18B). The two parameters also have a high inverse correlation, with a coefficient of –0.43, at a distance of –660 m (Figure 17B), indicating that an area of low shoreline variability at a point 660 m south of an area with a shallow cross-shore slope (Figure 18B). The chi-square value at concurrent locations is 0.476 ($p < 1$) and at lag-shifted locations is 3.07 ($p < 0.10$).

Long-term shoreline change

The long-term change rate is fairly high, 1.04 m/yr (standard deviation 0.24 m). The long-term change rate and bathymetry are inversely correlated (Figure 19B), with a maximum coefficient of -0.63 at a lag of -700 m, and a secondarily high correlation of 0.60 at a lag of –260. These values indicate that in relation to an area of shallow slope, such as a shore-oblique bar, there is erosion at a distance 700 m south and accretion at a distance of 260 m to the south (Figure 18B).

NORTHERN KILL DEVIL HILLS

Morphology of shoreface and shore-oblique bars

The Northern Kill Devil Hills site (KDHN) is located 1 km south of KH and has a shore-oblique bar just north of a trough. Within this study site, the 9 m isobath is centered about 720 m offshore, but its irregular contour ranged from 560 m to 890 m offshore, producing a cross-shore slope that ranged between 0.010 and 0.016 (Figure 14C). Bathymetric surveys (Figure 27) show that in June 2002, the shore-oblique bar was at a 66° angle to the shoreline and, at 700 m from shore, had a width of 215 m as measured by the 9 m contour line. By May 2003, the shore-oblique bar had rotated northward to 56°, lengthened 75 m offshore, and widened by 70 m through the northward movement of the bar's northern edge, as defined by the 9 m isobath. The shoreface was steepest in November 2003. By then, the bar had rotated eastward to 74° and had shortened by 170 m. Despite the changes in length and angle, the bar did not move northward or southward, as measured at the 9 m isobath.

Sediment Distribution

The irregular layer of surface sand has an average thickness of 0.35 m layer (Miselis and McNinch, 2002). The total surface area covered by sand, rather than gravel, varied between each survey (Figure 28); in both June 2002 and May 2003, 76% of the surface was covered in sand, and in November 2003, the sand was very patchy and covered 95% of the surface.

Shoreline Variability

The shoreline variability in this area is high (mean 5.06 m, standard deviation 1.13 m) and has a wide range (2.65 – 8.02 m). In an exception to the generality that shoreline variability increases in areas with a steep shoreface, the shoreline variability in KDHN decreases onshore of the northernmost of two shore-oblique bars, but, in contrast to the other barred sites, remains low onshore of the trough that is sited between the two shore-oblique bars (Figure 16C). Shoreline variability and the distance to the 9 m isobath have a maximum correlation coefficient of -0.58 at a lag of 220 m and a secondary peak in correlation (0.51) at a lag of –220 m (Figure 17C). These results indicate that in relation to an area with a shallow slope, such as a bar, there is an area of low shoreline variability 220 m to the north and an area of high shoreline variability 220 m to the south (Figure 18C). The chi-square value at concurrent locations is 7.311 ($p < 0.001$) and at lag-shifted locations is 0.35 ($p < 1$).

Long-term shoreline change

The long-term change rate in this area is low (0.31 m/yr, standard deviation 0.17 m/yr). The long-term change rate and the distance to the 9 m isobath have a maximum correlation coefficient of -0.50, at a lag of -980 m. There is a secondary peak at –700 m, with a correlation coefficient of 0.41 (Figure 19C). These values indicate that in relation to an area of shallow slope, there is an area of high long-term erosion 980 m to the south, and an area of long-term accretion 700 m to the south (Figure 18C).

SOUTHERN KILL DEVIL HILLS

Morphology of shoreface and shore-oblique bars

The Southern Kill Devil Hills site (KDHS) is situated 1.3 km south of KDHN and includes three shore-oblique bars, each flanked on both the north and south sides by a trough. Within this study site, the 9 m isobath is centered about 750 m offshore, but its irregular contour ranged from 555 m to 1095 m offshore, producing a cross-shore slope that ranged between 0.008 and 0.016 (Figure 14D). The shore-oblique bars at this site varied in magnitude both with respect to their morphology and with respect to each other (Figure 29). In June 2002, the shore-oblique bars had an average angle of 70° and, along the alongshore axis, had widths of 50 m, 70 m, and 200 m, north to south respectively. In March 2003, the average bar angle was 55°, and bar widths had changed: the northernmost bar had expanded 50 m northward, the middle one had expanded 30 m southward, and the southernmost one had narrowed, with its northern edge moving southward 135 m. The shoreface slope at this site was flattest in May 2003. By May 2003, their angle had moved slightly north to 51°; the northernmost bar had expanded northward 70 m, the middle bar had lengthened by 190 m and expanded 155 m northward and 20 m southward, and the southernmost bar was no longer distinguishable at 9 m depth. The November 2003 shoreface was the steepest. The average bar angle was slightly eastward at 57°; the northernmost bar matched its March 2003 position, the middle bar had shortened by 230 m and its northern edge had moved 245 m southward, and the southernmost bar was once again evident but very narrow, about 20 m wide and located in its March 2003 position.

Sediment Distribution

Surficial gravel is also evident at this site, and the irregular sand layer has an average thickness of 0.39 m (Miselis and McNinch, 2002). Sand covered about the same amount of the site's surface during all of the surveys (Figure 30): 76% of the surface in June 2002, 75% in March 2003, 77% in May 2003, and 79% in November 2003. The exposed gravel at this site was located between the shore-oblique bars that flank the trough, but was not centered within the trough. Instead, it was exposed at the thalweg and lined only the southern half of the bathymetric trough, spreading southward as the seafloor rises. This contact was not well defined in November

2003, when the post-hurricane survey documented a much patchier exposure of gravel across the seafloor than was seen in any of the previous surveys.

Shoreline Variability

The shoreline variability in KDHS (Figure 16D) is high (mean 5.13 m, standard deviation 1.74 m) and has a wide range (2.67 – 9.61 m). It is lower directly onshore of the shore-oblique bars and troughs, and peaks just south of the bar field. Shoreline variability and the distance to the 9 m isobath have a maximum correlation coefficient of -0.55 at a lag of 600 m (Figure 17D), indicating that an area with a shallow slope is highly correlated with an area of low shoreline variability located 600 m to the north (Figure 18D). The chi-square value at concurrent locations is 0 ($p < 1$) and at lag-shifted locations is 2.70 ($p < 0.20$).

Long-term shoreline change

The long-term change rate in this area is moderate (mean 0.89 m, standard deviation 0.33 m). The long-term change rate and the distance to the 9 m isobath have a maximum correlation coefficient of -0.51 at a lag of 680 m (Figure 19D), indicating that an area with a shallow slope is associated with an area of long-term erosion located 680 m to the north (Figure 18D).

DISCUSSION

Despite a high level of energy in the surf zone, and the presumed dominance of alongshore transport, both shore-oblique bars and gravel areas are remarkably persistent in both morphology and location. Shore-oblique bars are strongly correlated to both short-term variability and long-term change on a regional scale, but their presence does not entirely account for all of the alongshore variability. The temporal and spatial variations in erosional hotspots probably contribute to the alongshore variability in shoreline position and further complicate shoreline change measurements. Although shore-oblique bars have some similarities to previously-described nearshore bar morphologies, their morphology and stability are unique. Shoreline change prediction models that account for the existence of shore-oblique bars and sediment heterogeneity might be more representative of real-world surf zone dynamics and thereby more powerful.

Inter-survey stability of shore-oblique bars

Throughout the 16-month survey period, individual shore-oblique bars displayed only a few major changes in morphology and location, most of which occurred shoreward of the 7 m isobath. The inter-survey alongshore movement or widening of the bars, as measured at the 9 m contour, was never more than a few hundred meters, and the southern edge of most shore-oblique bars held a fairly constant position throughout the survey period. The greatest inter-survey change was 245 m, when the northern edge of the KDHS bar (Figure 14D) migrated southward between May 2003 and November 2003. In the two Kill Devil Hills sites (Figure 14C, 14D), the positions of the shore-oblique bars were in similar locations during all of the surveys, but were widest and expanded farthest offshore during the May 2003 survey, and were shortest in November 2003. The shore-oblique bars always pointed towards the north, with angular inter-survey changes of less than 15° with one exception: the KH bar had changed by 41° between May 2003 and November 2003.

The migrations and metamorphoses of the shore-oblique bars (Figure 14) are sometimes, but not always, synchronous. For example, all bars migrated northward and their angles increased towards the north between June 2002 and March 2003; they were at the same angles when surveyed in May 2003. However, their independent behavior is illustrated by the changes between May 2003 and November 2003. During that time period, the bars shortened in both KDHN and KDHS, shifted southward in KDHS, and simply narrowed in KDHN. Some changes in orientation were also evident, such as the northward rotation (41°) of the KH bar, and the eastward rotation of the bars in KDHN (18°) and KDHS (6°).

These changes, the most impressive seen during the 16-month survey period, were preceded by a category two hurricane. Sediment movement in response to storm energy is expected and has been well documented in other studies (Niedoroda and Tanner, 1970; Aubrey et al., 1982; Lippman and Holman, 1990). However, the stability of the discrete bars (Figure 14), still in similar positions after such a large energy event, is surprising. The stability suggests that shore-oblique bars either weathered the energy events intact, remaining present and in fairly consistent locations; or, possibly, that the bars are first destroyed by disturbances and then redevelop. More frequent surveys would be needed to determine which if either of the possibilities is true, because storm recovery may occur within five days of the event (List and Farris, 1999), and the majority of storm recovery may even occur within 12 hours (Fucella and Dolan, 1996).

Sediment heterogeneity

As demonstrated by a chi-square test and by visual inspection of the bathymetry and sediment distribution, the locations and extent of seafloor gravel is closely tied to the locations and size of shore-oblique bars and troughs, an observation shared with several studies that document the affiliation of persistent shore-oblique bars with relict channels (Browder and McNinch, 2003; McNinch, 2004). Like the shore-oblique bars, the location and perimeter of the gravel areas (Figure 20) were also remarkably persistent despite high-energy events. For the first three survey periods, the majority of the gravel in KH and KDHN was seen between the shoreline and the 9 m isobath. The November 2003 survey, which followed Hurricane Isabel, exhibited smaller, more disparate gravel areas than in any other survey.

Based on their inter-survey stability, the gravel patches exposed in three regions of the nearshore are believed to be outcropping parts of an underlying gravel layer rather than scattered deposits overlying the sand. This idea is supported by shallow seismic data showing a hard, acoustically-reflective surface underlying thin sand deposits (Figure 31) (McNinch, 2004; Miselis and McNinch, submitted) and by Boss et al. (2002), whose location map shows that the outcrops in the Northern Outer Banks appear to be situated above an old channel of the paleo-Roanoke

River. This interpretation is further supported by Browder and McNinch (2003) and McNinch (2004), who documented a high correlation of gravel outcrops with underlying relict fluvial channels along the Virginia and North Carolina coast.

Given the high alongshore sand transport on this coast, the variation in gravel outcrop exposure is probably not due to lack of sediment input. Instead, the sand is probably an active layer that migrates atop the gravel stratum to produce variations in gravel outcrops. For example, as seen in the post-storm surveys, the changes in gravel outcrop perimeters (Figure 20) likely resulted from the movement of sand from the upper and lower beach into the surf zone, which buried the shallower sections of the gravel outcrops and parts of the nearshore exposures. The wave ripples in the gravel probably form as the surface gravel exposures are reworked by winter surface waves (Cacchione et al., 1984) and bottom boundary layer conditions (Murray and Thieler, 2004). While this paper does not address the controls on sediment distribution, the evidence of persistent and surficial sediment heterogeneity in the nearshore may help to further the development of sediment transport models and our understanding of the mechanisms driving the formation and maintenance of sorted bedforms.

Spatial relationship between bathymetry and shoreline variability

On a regional scale, short-term variability in shoreline position is higher in areas with a steep shoreface or shore-oblique bars (Figure 9). At individual survey sites, however, the correlation results and the lag distances at which these occur are inconsistent. For example, at both KDHN and KDHS (Figure 17), the shoreline variability is lower just north of shore-oblique bars, and in SS, the shoreline variability is higher just south of areas with a lower slope. This increased variability may result from differences in incident wave energy, which is higher when it reaches the shoreline along steep slopes because the energy is not dissipated as far from shore. The maximum correlation between trough position and high shoreline variability occurs at a small alongshore offset that is generally no farther than the width of the shore-oblique bar in the area. This inverse correlation, however, does not hold true for all of the smaller survey sites; in KH, the shoreline variability is low to the south of the shore-oblique bar. The dissimilarly positive-southward correlation in KH may result from the great width of the bar (849 m), which is three times the width of the second-largest bar, located in KDHN.

The alongshore lags can probably be attributed to three things. First, the oblique angle of incident waves, which at their strongest arrive from the northeast during the winter, reach the shore-oblique bars at a point farther northward than the point where they reach the shoreline. Second, the shore-oblique angle of the troughs may redirect incident wave energy along their axes. Third, due to the positional shifts of shore-oblique bars and exposed areas of gravel over time, a given point on the shoreline is sometimes connected to a shore-oblique bar and sometimes to a trough.

More perplexing is the result of smoothing regional shoreline variability alongshore, which resulted in an inverted correlation of increased magnitude between shoreline variability and bathymetry (Figure 9). Like the results in KH, the shoreline variability in this case also proves to be lower just south of areas with a steep shoreface. The increased correlation may reflect the existence of large length scales that dominate shoreline variations in the northern Outer Banks, estimated between 1 km (Plant and Holman, 1996) and 1.5 km (J. List, pers. comm., 2004). Smoothing the shoreline variability values over 1.5 km might also mitigate the effect of small perturbations in the alongshore trend, further increasing the correlation. The southward lag of low variability may result from features acting at longer length scales. For example, physical attributes that may exert an influence on shoreline change, such as underlying geology, nearshore bathymetry, or migrating hotspots, may be larger or have an effect that is farther-reaching than the length scale considered for this study. It is important to acknowledge that affinities between nearshore features and shoreline change, and the control that one may exert on another, may occur at a range of temporal and spatial scales. It is also important to keep in mind the limited spatial nature of the reoccupied survey sites. The seasonal seafloor changes were observed in small sections along the coast and may not be representative of the regional shoreline. For example, a study site with a high erosion rate may be only a small eroding section of a beach that experiences overall accretion.

Spatial relationship between bathymetry and long-term shoreline change

The relationship between shore-oblique bars and long-term shoreline change is complex. Long-term erosion rates vary alongshore with the presence of shore-oblique bars in a 4.5 km section between Kitty Hawk and Kill Devil Hills. The major peaks in shoreline erosion line up with areas of shore-oblique bars (Figure 5), and the cross-correlation values (Table 2, Figure 9) also demonstrate that regionally, areas of high long-term change have shore-oblique bars. Not all of the shore-oblique bars are associated with high long-term shoreline change, however; in Kill Devil Hills there are several shore-oblique bars, but long-term change is fairly low. Further, shore-oblique bars are not found directly offshore of all areas of high long-term change. Long-term erosion increases southward between Southern Shores and Kitty Hawk, where shoreface slope is fairly constant and there are no shore-oblique bars; and south of Nags Head, where the bathymetric slope steepens and no shore-oblique bars are present, although short-term variability is also high.

Regionally, the long-term shoreline change rate displays overall accretion just south of areas with shore-oblique bars, a relationship reflected in KDHS. In SS, KH, and KDHN, however, shallow slopes correlate with long-term erosion at various distances southward. The maximum correlations between bathymetry and long-term shoreline change are seen at alongshore lags ranging from 960 m southward to 680 m northward, and the smaller study sites exhibit their maximum correlations at higher alongshore lags than for the regional analysis. The range of alongshore lags, as well as the southward offset of long-term shoreline erosion in relation to high shoreline variability, probably reflects the influence of temporally variable physical features or alongshore processes. One possibility is the presence of migrating erosional hotspots. When viewed on a regional scale, the areas of shore-oblique bars are almost directly offshore of areas identified as erosional shoreline hotspots (Miselis and McNinch, 2002; Schupp et al., 2002; McNinch, 2004). This offset may also be related to underlying geology, a phenomenon seen on the Atlantic coast of Delaware in which relict sediments were exposed in paleofluvial channels that approached the modern shoreline at oblique angles (Honeycutt and Krantz, 2003), which is true in the Outer Banks as well (Boss et al., 2002; Browder and McNinch, 2004). In Delaware, these oblique angles are believed to have resulted in higher shoreline change not onshore of the paleo-sediments but rather where the outcrop met the shoreline (Honeycutt and Krantz, 2003). Additionally, exposure of the underlying sediments may alter shoreface shape and sediment supply, according to Belknap and Kraft (1985), who studied the effects of exposed paleo-fluvial channels in Delaware. Sediment thickness should also be considered; Miselis and McNinch (in prep.) demonstrate that alongshore variations in nearshore sand volume correlate with long-term shoreline change.

Unique morphology and stability of shore-oblique bars

The shore-oblique bars described in this manuscript appear to differ from the bar features documented in a number of Atlantic coast studies (Niedoroda and Tanner, 1970; Aubrey et al., 1982; Swift et al., 1985; McBride and Moslow, 1991; Konicki and Holman, 2000; Schwab et al., 2000; Caballeria et al., 2002). Previously-described features, which include shoreface-attached sand ridges, transverse bars, and rippled scour depressions (see McNinch, 2004 for a review of several forms), may appear to have some morphologic similarities to the shore-oblique bars described in this study, but their locations, size, spacing, formation, and possible influence on shoreline change appear to be quite different from the shore-oblique bars described here. For example, the shoreface sand ridges described by McBride and Moslow (1991) are also linear sand bodies oriented at an oblique angle to the shoreline, but they are seen in deeper water, are much larger, and have sharper angles between the shoreline and their long axis. Furthermore, according to McBride and Moslow (1991), shoreface ridges are believed to have evolved from relict ebb tidal deltas of historic inlets, whereas the historic tidal inlets along this coast are north of Duck and south of Manteo (McBride, 1986), far from the observed shore-oblique bars. Shore-oblique bars also have similar morphology to the transverse bars studied by Konicki and Holman (2000), which also persisted for days to months, but those bars migrated alongshore and disappeared between seasons and storms; the forms described in this study are fairly stable temporally (over 1.5 years) and spatially (on the scale of 100 m alongshore), with smaller-scale positional shifts. The formation of shore-oblique bars also appears to be unrelated to the transverse-bar and rip beach state described by Wright and Short (1984), which develops along accretionary shorelines out of pre-existing beach cusps; the Outer Banks shore-oblique bars occur on a retreating shoreline and are not known to be associated with standing rip currents. Nor are these bars the non-rhythmic attached bar described by Lippman and Holman (1990), which are considered to be unstable; the shore-oblique bars are quite stable both temporally and spatially. Unlike all of the previously studied forms, the shore-oblique bars described here were surveyed in the shallow surf zone and have persistent locations and morphology.

Of the linear nearshore features described by others, shoreface RSDs are the most similar to shore-oblique bars. The morphologic forms are shore-normal, asymmetric, floored by ripples of coarse shell hash and gravel, and sometimes separated by sand ridges. However, they differ in their location and magnitude; the sorted bedforms described elsewhere develop just outside the fair-weather surf zone and are much longer (several km) and narrower (less than 100 m) than the Outer Banks features (Murray and Thieler, 2004). The behavior of RSDs suggests an explanation for the bar-associated sediment distribution in this study. RSDs are believed to control the distribution, texture, and composition of surficial sediments and inner-shelf bathymetry at Wrightsville Beach (Thieler et al., 2001b), while underlying geology may control the shoreface profile shape (Thieler et al., 1995). These two postulations are supported by the association of shore-oblique bars with gravel-bottomed troughs at the northern Outer Banks sites in this study, and by the presence of steeper slopes in areas with shore-oblique bars and troughs. The maintenance of gravel outcrop locations may be similar to that of sorted bedforms and rippled scour depression, as postulated by Murray and Thieler (2004) and observed in New Zealand, where the area of coarse sediment creates a turbulent environment that inhibits fine-sand settling, so that fines are deposited in areas already covered in fines, creating a positive feedback (Green et al., 2004).

Implications of results for predictive shoreline change models

Several mathematical models, including SBEACH and GENESIS, are widely used to predict beach behavior and to design and evaluate the feasibility of coastal engineering projects. These models include some oversimplified assumptions and some important omissions, resulting in their failure to capture and model the complexity of the poorly understood nearshore system. Reviews of such shortcomings have been compiled by several authors (Young et al., 1995; Thieler et al., 2000) and, as they relate to this study, are presented below.

GENESIS (Hanson and Kraus, 1989) is used to calculate long-term shoreline change due to coastal engineering projects that may alter alongshore sediment transport and to develop regional sediment budgets. The model assumes that a depth of closure exists, and that there is no offshore loss or gain of sediment. It also assumes that the beach profile remains unchanged, so that beach change is described only in terms of shoreline position (Hanson, 1989). The model also makes an assumption and several omissions that cannot be reconciled with the features documented in this study. It assumes that the shoreface bathymetry is smooth, and it neglects shoreface geology, sediment attributes such as grain size, the effects of bedforms and bars on sediment transport, and the effects of surface roughness and bedforms on wave energy (Thieler et al., 2000). Evidence presented in this study illustrates that the shoreface bathymetry is not of consistent slope and suggests that outcropping strata, heterogeneous sediment sizes, sorted bedforms, and shore-oblique bars should in fact be considered in long-term shoreline change predictions.

Another numerical model, SBEACH (Larson and Kraus, 1989), is used to predict storm-induced beach and dune erosion and bar formation and movement. The model assumes that the beach profile changes only in response to cross-shore processes that result from breaking waves; alongshore processes are assumed to be uniform and are not used in the analysis. The model also assumes that there is no net change in sand volume, and that both an equilibrium shoreface profile and a closure depth exist. The model neglects shoreface geology, grain size variability, the effects of bedforms and bars on sediment transport, and the effects of surface roughness and bedforms on wave energy (Thieler et al., 2000). All of these omissions may reduce the predictive success of the model; evidence presented in this study indicates that underlying and outcropping strata, heterogeneous sediment sizes, sorted bedforms, and shore-oblique bars are all relevant to both shoreline erosion and to bar movement.

CONCLUSIONS

Evidence of the relationship between nearshore morphology and shoreline change

Results from seafloor mapping and cross-correlation analysis of shoreline change demonstrate the connection of surf zone bathymetry and sediment distribution to both short-term and long-term shoreline change. This relationship is demonstrated through the following findings:

1. The locations of shore-oblique bars and gravel outcrops are spatially correlated. All gravel outcrops observed in the study region were located in a bathymetric trough alongside a shore-oblique bar, had width and length proportional to that of the associated trough, and mirrored trough shape and movement. Shore-oblique bars always lie south of outcrops and sometimes bound them to the north as well.
2. Despite the occurrence of two high-energy events, shore-oblique bars, and their associated gravel outcrops, are remarkably persistent in their number, location, and morphology. However, they may exhibit small asynchronous variations in width, length, distance, and angle, usually in depths of more than 7 m.
3. Areas with shore-oblique bars and gravel outcrops are highly correlated with on-shore areas of high short-term shoreline variability and high long-term shoreline change rates.
4. The relationship of nearshore and surf-zone morphology to shoreline change can be quantified through cross-correlation of regional bathymetry with shoreline change data sets.

Rethinking shoreline change predictions

Clearly, the dynamic nearshore system is complicated, and there are several factors that need to be evaluated when exploring the relationship between shoreline change and nearshore morphology. For example, pre-existing topography and stratigraphic resistance to erosion probably play important roles in the complex dynamics of surf-zone and shoreline change. This study does not explain the mechanisms by which shoreline change is controlled, but it demonstrates that although currents and waves may dominate alongshore and cross-shore sediment transport, these parameters do not account for all shoreline change. Cross-correlation results presented here show that shore-oblique bars and seafloor sediments correlate with shoreline change on several temporal and spatial scales. Shoreline change models might improve their predictive accuracy through incorporation of the observations presented here, such as the presence of sediment heterogeneity, a thin and discontinuous layer of surficial sand, persistent shore-oblique bar features, and the possible influence of underlying geology on shoreline change.

Future Research

This research raises many interesting questions. The shoreface and the seabed appear to respond to storms and seasons in various ways. Therefore, it is important to consider the small-scale and short-term changes seen in the surf zone and beach in response to seasonal changes, low-energy conditions, and high-energy events. Through testing of regional-scale assumptions on localized features, an improved understanding of shoreface dynamics may be developed. Closer study of the correlation between incident wave energy and shoreline configuration might also yield interesting results. For better spatial correlation, areas at least 1.5 km long should be identified for repeated surveys. To develop models for temporal correlation between shoreline change and shore-oblique bar movement, smaller intervals between surveys would be required. Further understanding of these dynamics would be enhanced by comparison between simultaneous surveys of surf zone bathymetry and shoreline position. This would reveal any connection of shore-oblique bars extending up onto the beach as cusps. Future studies might also investigate how shore-oblique bars are formed, why they have persistent locations and morphology, and how they may influence sediment transport and shoreline change.

TABLE 1. Results of chi-square test for a regional relationship between shore-oblique bars and nearshore gravel outcrops in June 2002. Points are grouped according to whether gravel was present or absent, and according to their location (closer or farther to shore) relative to the median distance to the 9 m isobath.

Number of points	Closer than median distance to 9 m isobath	Farther than median distance to 9 m isobath	Total
Gravel absent	649	887	1536
Gravel present	273	34	307
Total	922	921	1843

Degrees of Freedom = 1

$\chi^2 = 222.9$

$p < 0.001$

TABLE 2. Results of regional and survey site cross-correlation tests including alongshore lag and number of samples tested.

Relationship	Measurement	Northern Outer Banks	SS	KH	KDHN	KDHS
Number of samples		1843	74	99	83	87
Degrees of freedom (assuming 300 m interval for spatial independence)		121	3	5	4	4
Correlation coefficient at the 80% confidence level		0.117	0.687	0.551	0.608	0.608
Correlation coefficient at the 95% confidence level		0.178	0.878	0.755	0.811	0.811
Bathymetry and long-term shoreline change	Cross-correlation	0.59	0.39	0.63	0.50	0.51
	Lag (m)	-280	220 (secondary peak at -100)	-700 (secondary peak at -260)	-960 (secondary peak at -700 m)	680
	Student's t-test (2-tailed): t-value	8.034	0.725	1.740	1.085	1.156
	p-value	0	0.5463	0.157	0.359	0.3335
Bathymetry and shoreline variability	Cross-correlation	-0.40	0.51	0.46	-0.58	-0.55
	Lag (m)	220	-140	540 (secondary peak at -660)	220 (secondary peak at -220)	600
	Student's t-test (2-tailed): t-value	-4.798	1.015	1.111	-1.338	-1.284
	p-value for t-test:	0.000	0.417	0.329	0.273	0.291
	chi-squared test	453.73	n/a	0.476	7.311	0
	p-value for chi-squared test:	0.001	n/a	1	0.001	1
	Lag-shifted, chi-squared test	2.42	n/a	3.07	0.35	2.70
	p-value for lag-shifted chi-squared test:	0.20	n/a	0.10	1	0.20
Bathymetry and shoreline variability, smoothed over 1500 m	Cross-correlation	-0.49				
	Lag (m)	-280				
Shoreline variability and long-term shoreline change	Cross-correlation	-0.47				
	Lag (m)	-800				

TABLE 3. Quantification of site features during each survey period.

	SS	**KH**	**KDHN**	**KDHS**
Gravel June 2002	0%	9%	7%	18%
Gravel March 2003	0%	13%	no data	11%
Gravel May 2003	0%	16%	14%	10%
Gravel Nov 2003	0%	8%	5%	2%
Sand June 2002	100%	83%	76%	76%
Sand March 2003	100%	79%	no data	75%
Sand May 2003	100%	68%	76%	77%
Sand Nov 2003	100%	88%	95%	79%
Average bar angle, June 2002	0	86	66	70
Average bar angle, March 2003	0	78	no data	55
Average bar angle, May 2003	0	78	56	51
Average bar angle, Nov 2003	0	37	74	57
Average sand thickness, June 2002	0.41	0.46	0.35	0.39
DCM long-term shoreline change rate (raw, m/yr)	0.18	1.07	0.31	0.89
DCM Long-term shoreline change, (smoothed, m/yr)	0.17	1.06	0.33	0.87
Standard deviation in shoreline position	2.74	4.11	3.39	2.45
Linear rate (m/yr)	1.51	-0.76	-0.84	0.64
Standard deviation with linear rate removed	2.12	4.02	3.24	2.34

TABLE 4. Geographic bounds (UTM Zone 18, meters) of survey site limits.

	Northing	Easting
Northern Outer Banks, June 2002	4005925	432330
	4005925	433100
	396750	450425
	3967650	449150
Southern Shores	3998000	435025
	3998350	435925
	3997400	436300
	3997000	435400
Kitty Hawk	3993050	437250
	3993525	438150
	3992300	438750
	3991850	437825
Northern Kill Devil Hills	3990850	438400
	3991300	439150
	3990350	439750
	3989850	438900
Southern Kill Devil Hills	3988750	439650
	3989175	440450
	3988075	441025
	3987625	440250

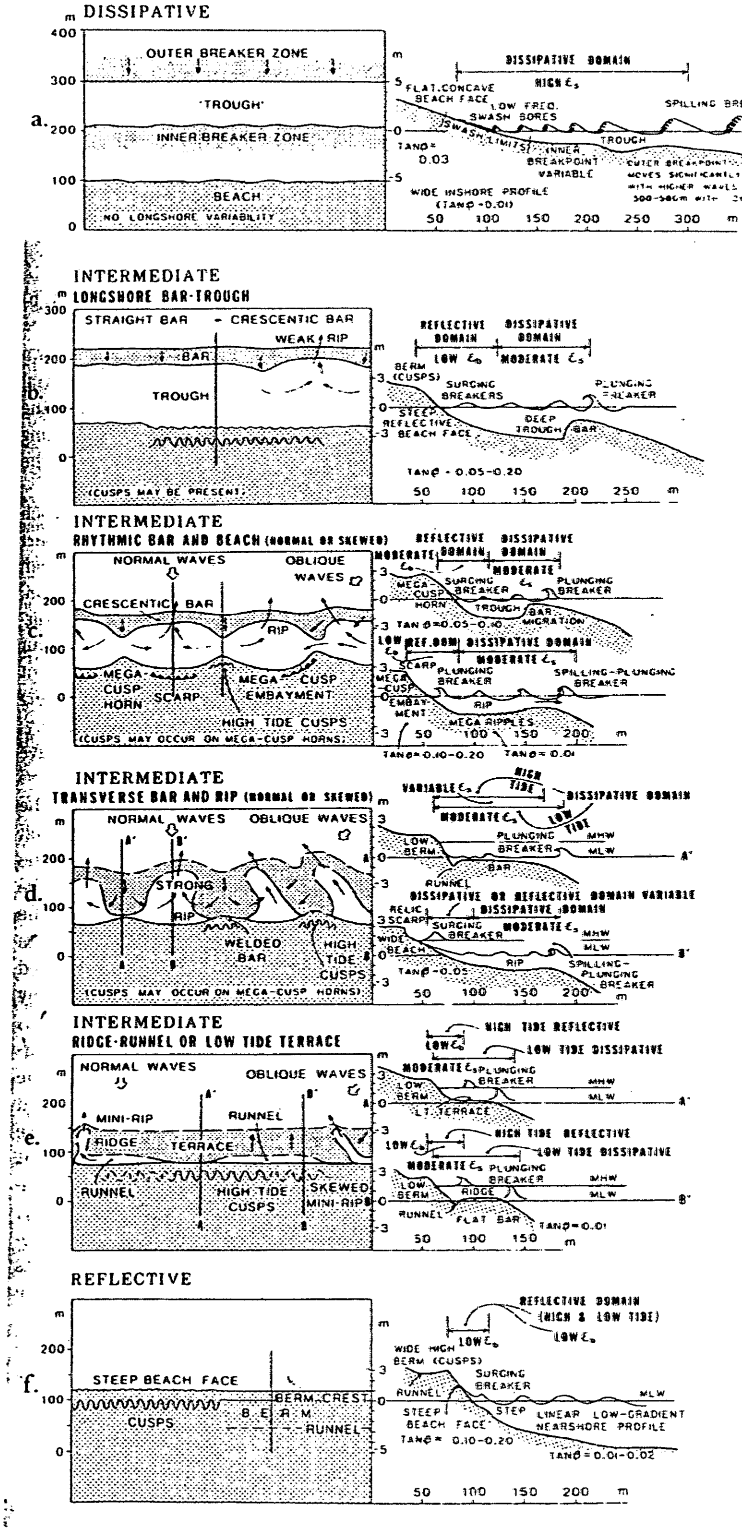


Fig.2. Plan and profile configurations of the six major beach states.

Figure 1. Categorization of six beach types, including four surf-zone bar morphologies (after Wright and Short, 1984).

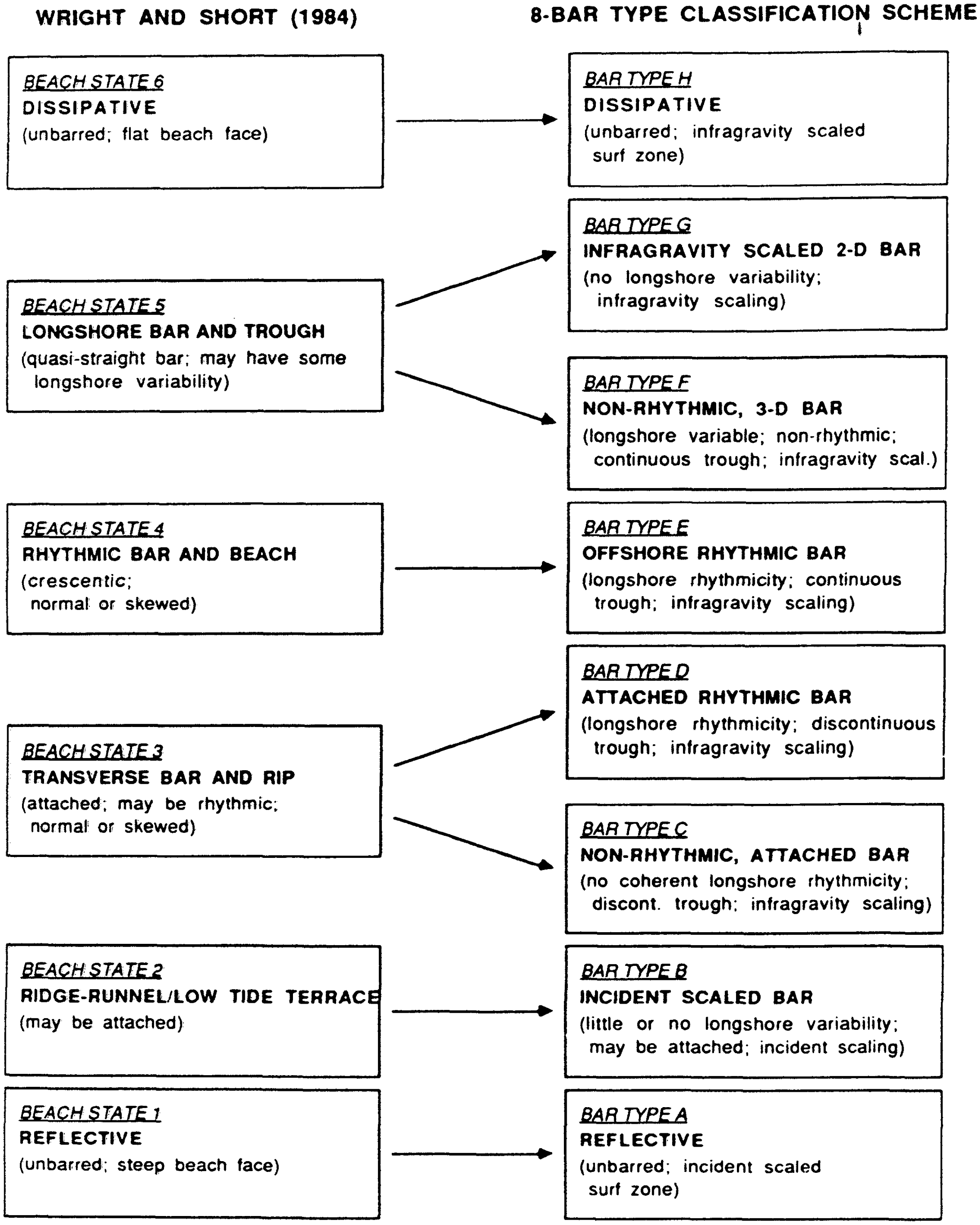


Fig. 1. Classification scheme of *Wright and Short* [1984], shown on the left-hand side. Our classification scheme is presented on the right-hand side. Comparisons between the two models are indicated with arrows between similar morphologic bar states.

Figure 2. Expanded classification scheme of surf-zone bar morphologies.

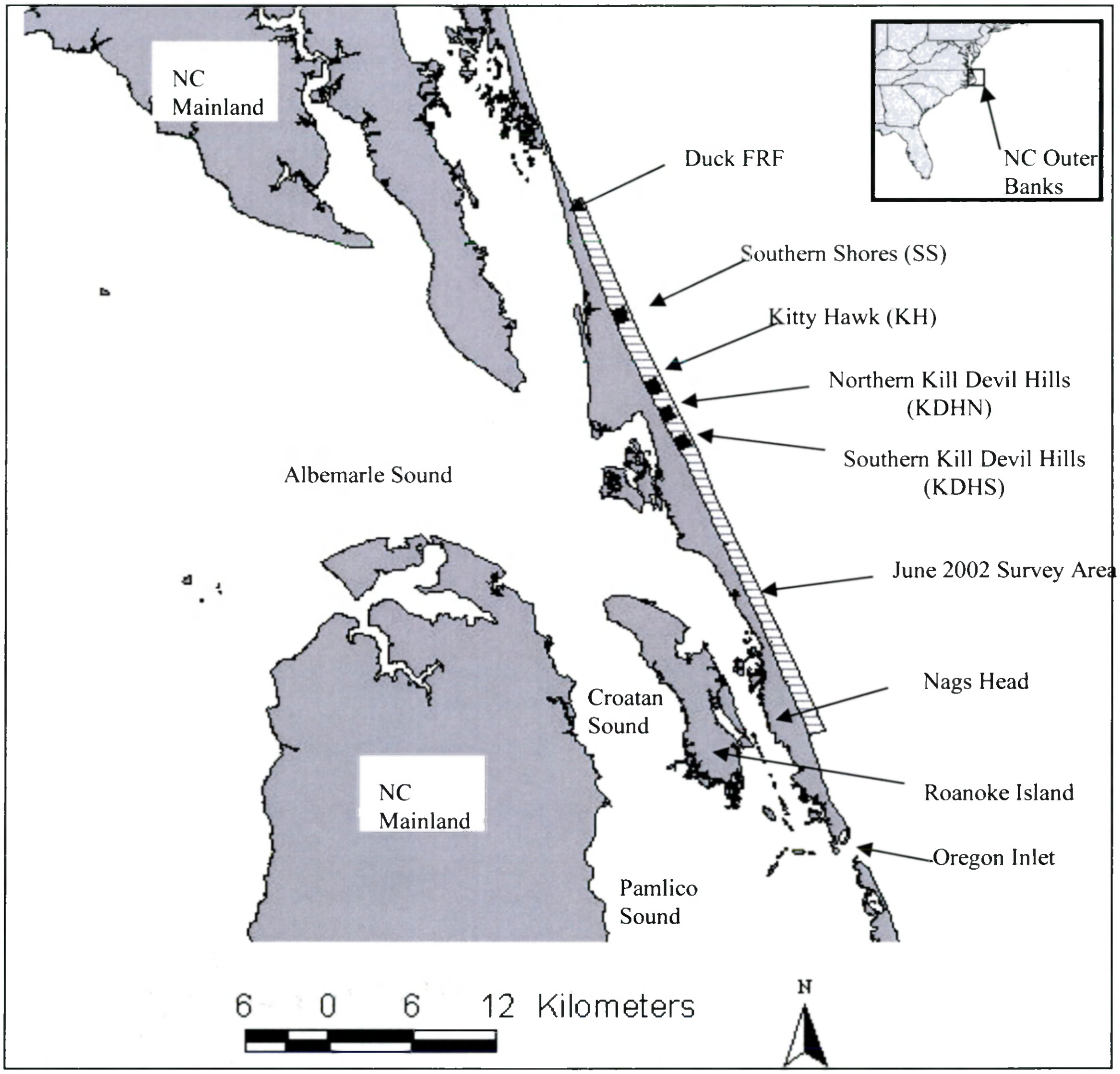


Figure 3. Location map of regional survey and study sites for repeated surveys in the northern Outer Banks, North Carolina.

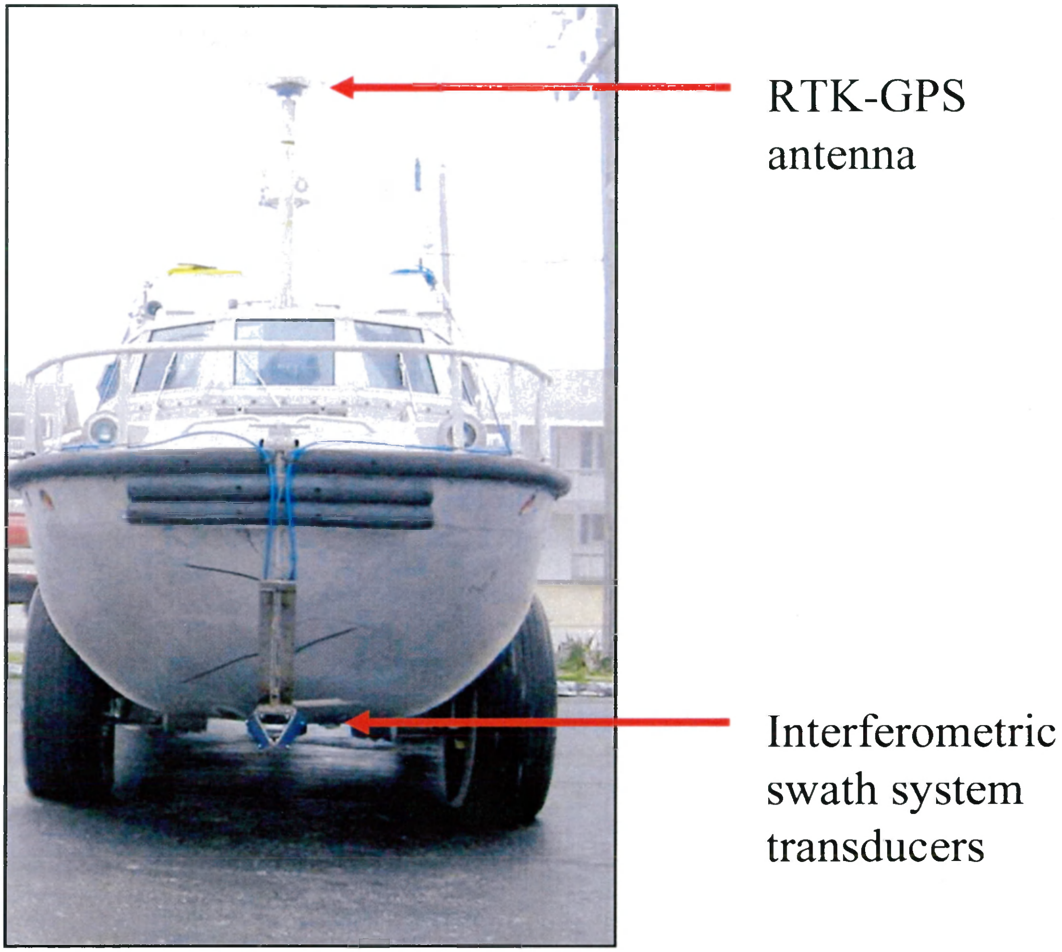


Figure 4. Equipment was mounted to an amphibious vehicle, which provided a stable survey platform in the rough surf zone. Some equipment is not visible; the motion sensor is mounted in the hull, the compass in the cabin, and the chirp sub-bottom profiler attached to the boom on the deck.

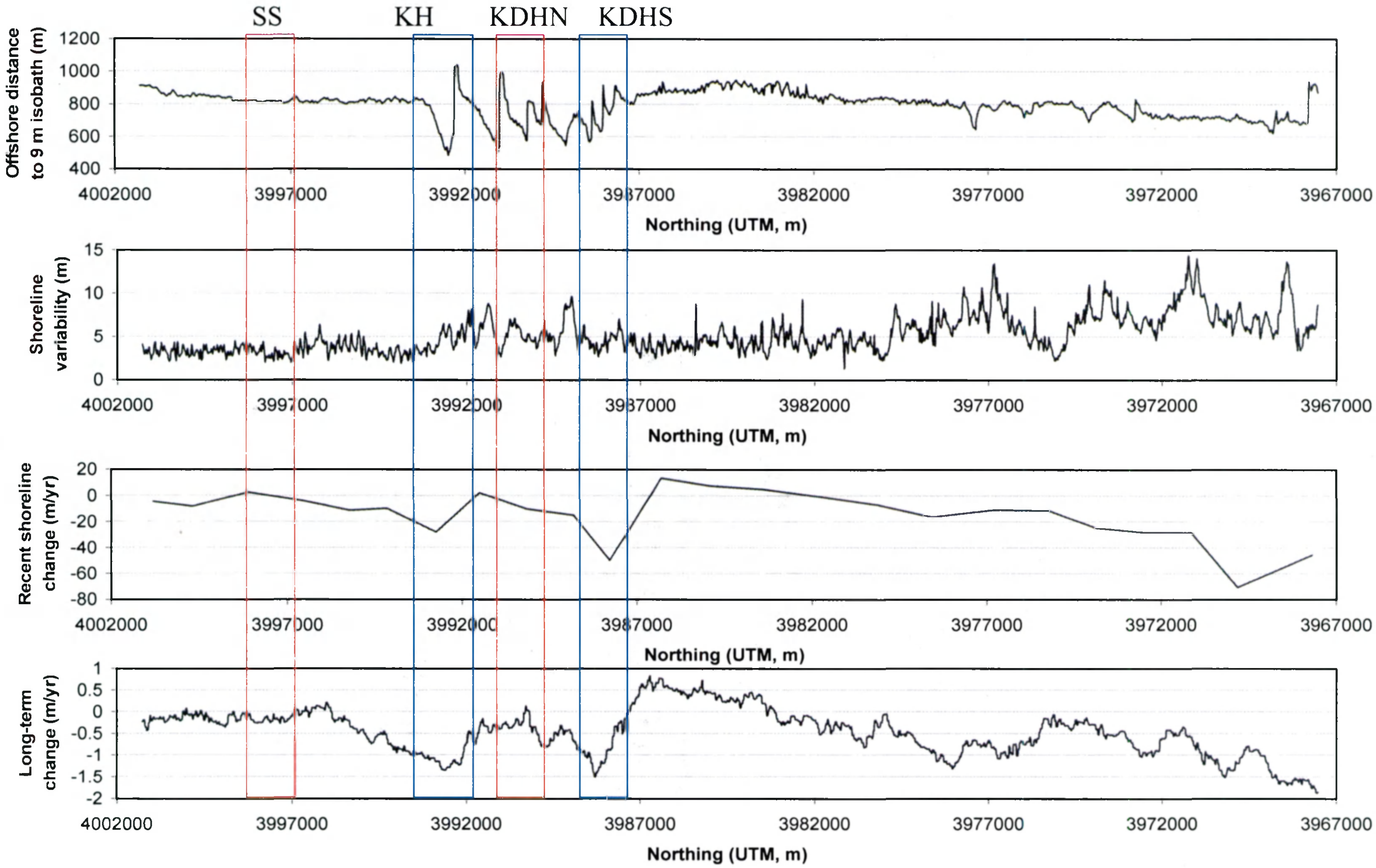


Figure 5. Measurements along the northern Outer Banks of the offshore distance of the 9 m isobath as surveyed in June 2002 (A), shoreline variability (1999-2003) (B), recent (1975-2002) shoreline change (C), and long-term (1933-1998) shoreline change (D). These graphs include the region between Corolla and Oregon Inlet. Colored rectangles delineate smaller sites selected for repeated surveys.

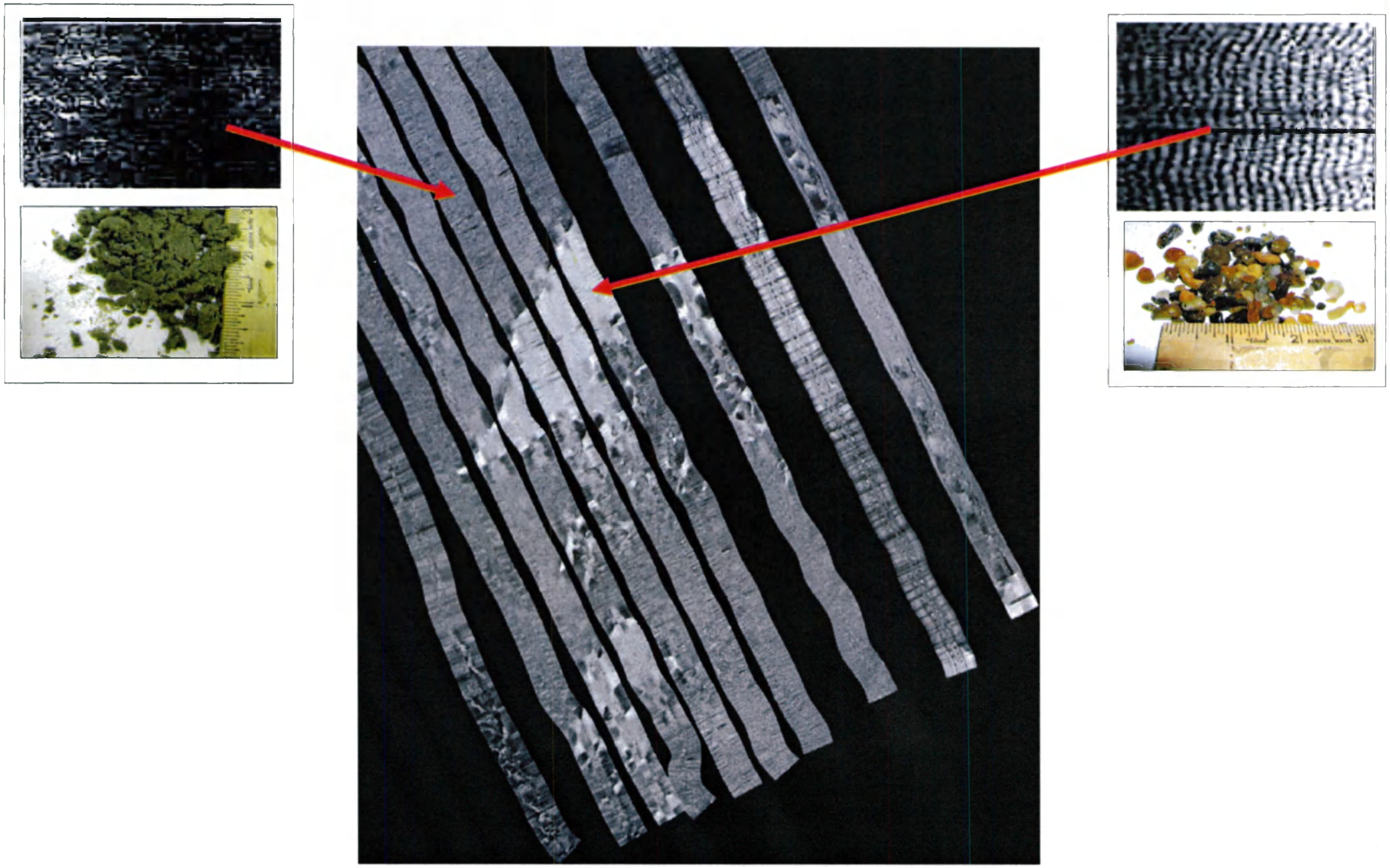


Figure 6. Typical gravel outcrop shape (A) and ground-truthed sediments: muddy sand (B) results in a lower backscatter, indicated by dark areas of the image; gravel (C) is associated with trough-perpendicular ripples and results in higher backscatter, indicated by light areas of the image. This sidescan sonar data was collected in Kitty Hawk in June 2002.

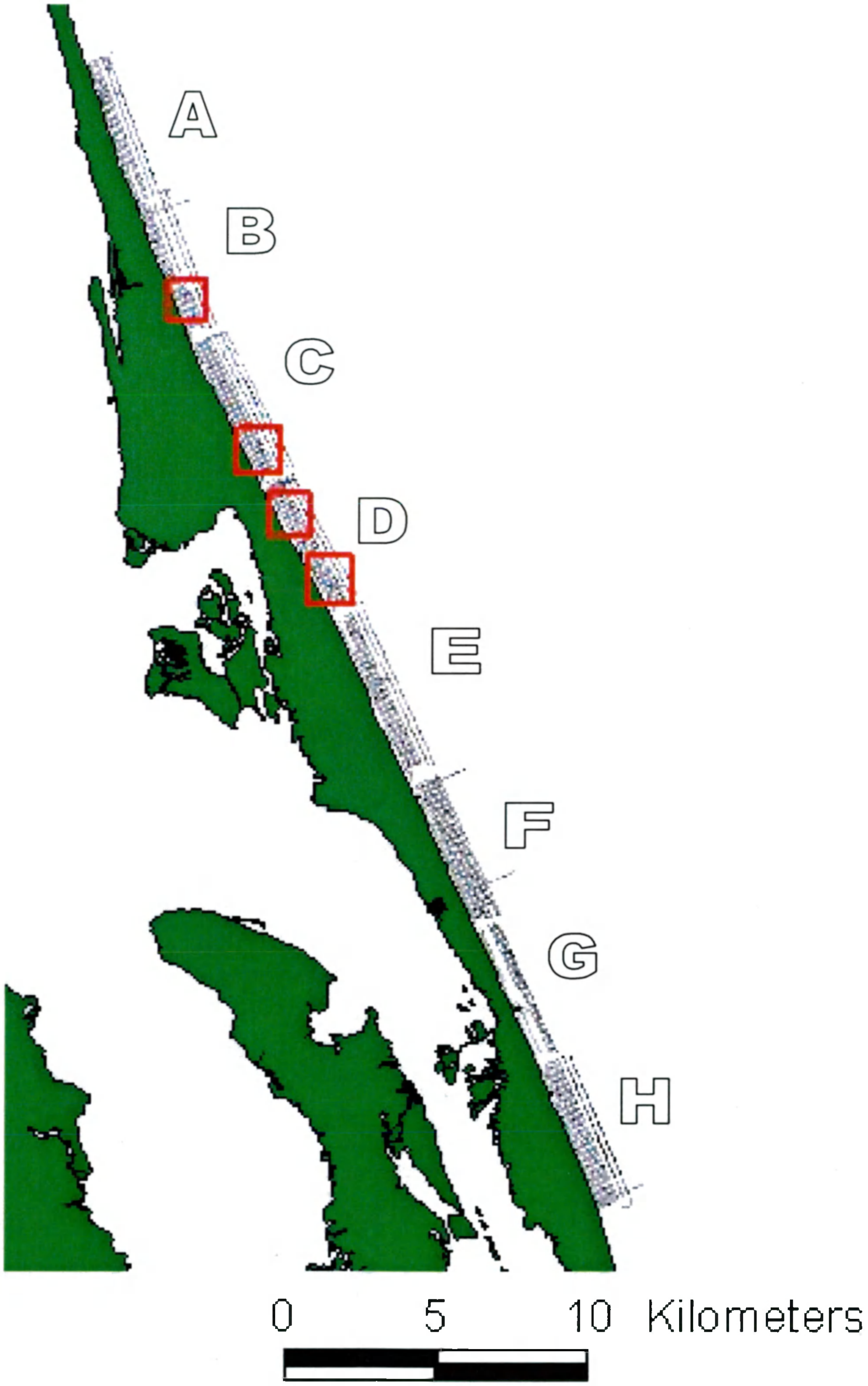


Figure 7. Acoustic reflectance map of the northern Outer Banks in June 2002, with smaller survey sites delineated. The following eight figures, each with an alongshore length of 5 km, show the same acoustic data on a larger scale.

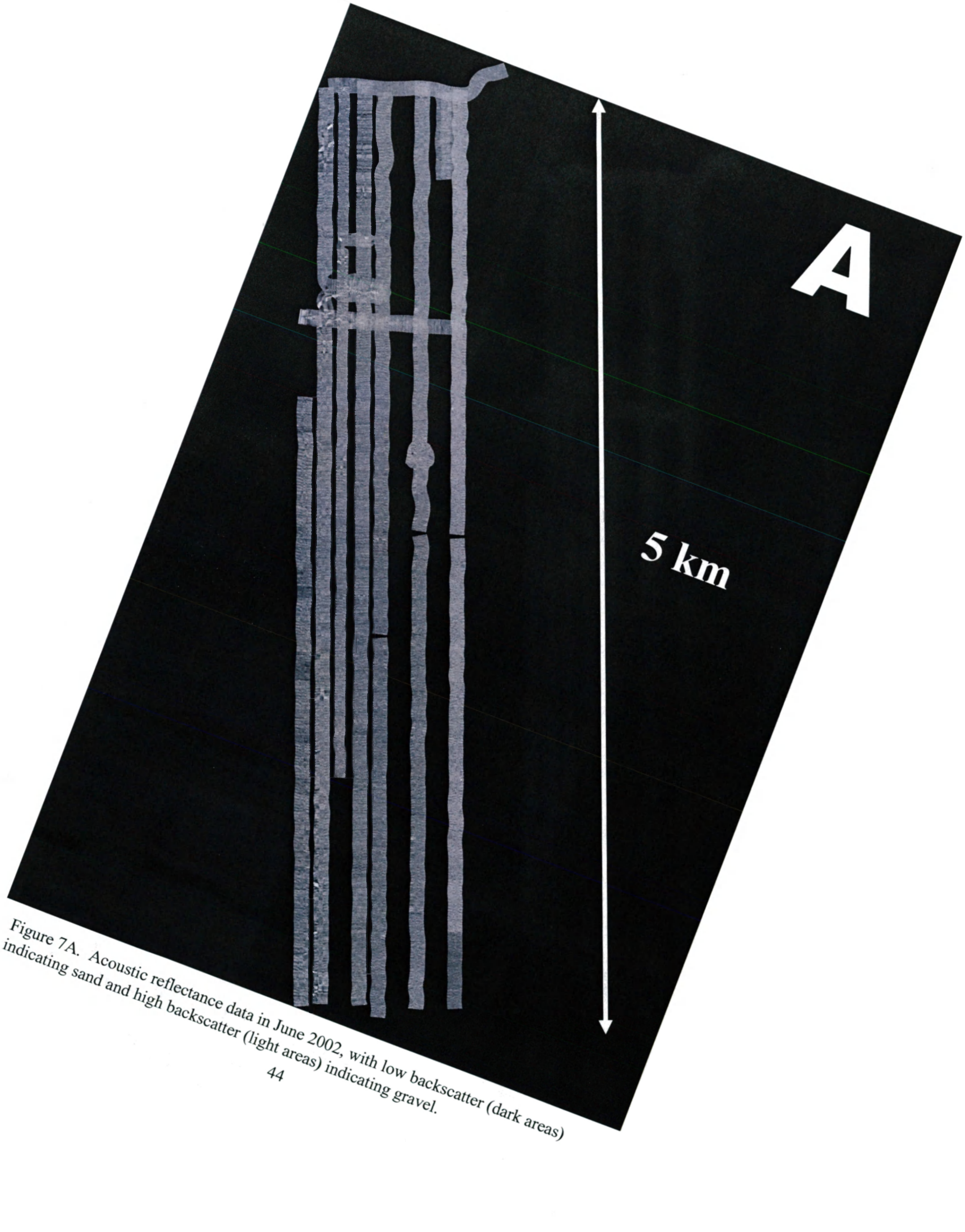


Figure 7A. Acoustic reflectance data in June 2002, with low backscatter (dark areas) indicating sand and high backscatter (light areas) indicating gravel.

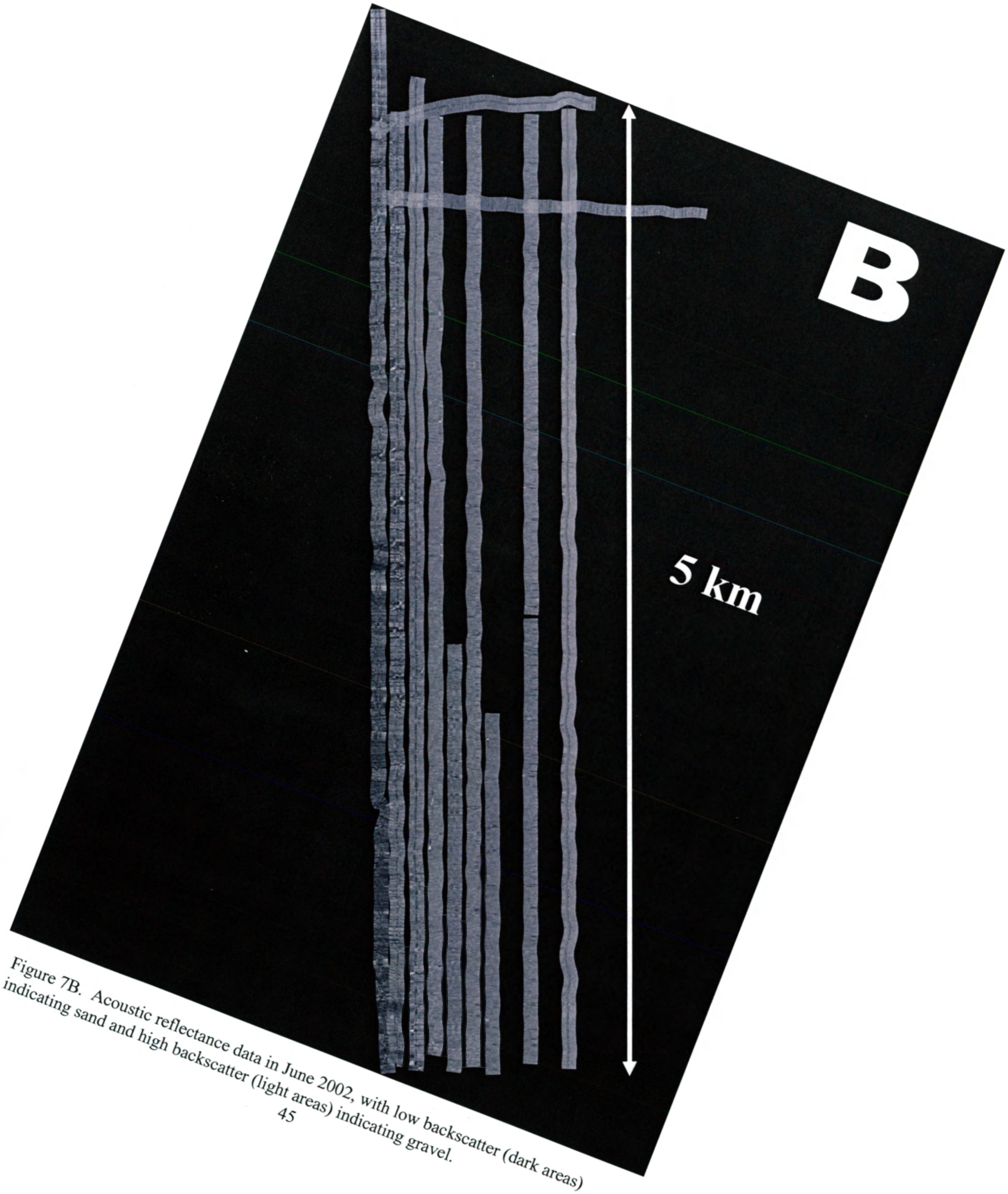


Figure 7B. Acoustic reflectance data in June 2002, with low backscatter (dark areas) indicating sand and high backscatter (light areas) indicating gravel.

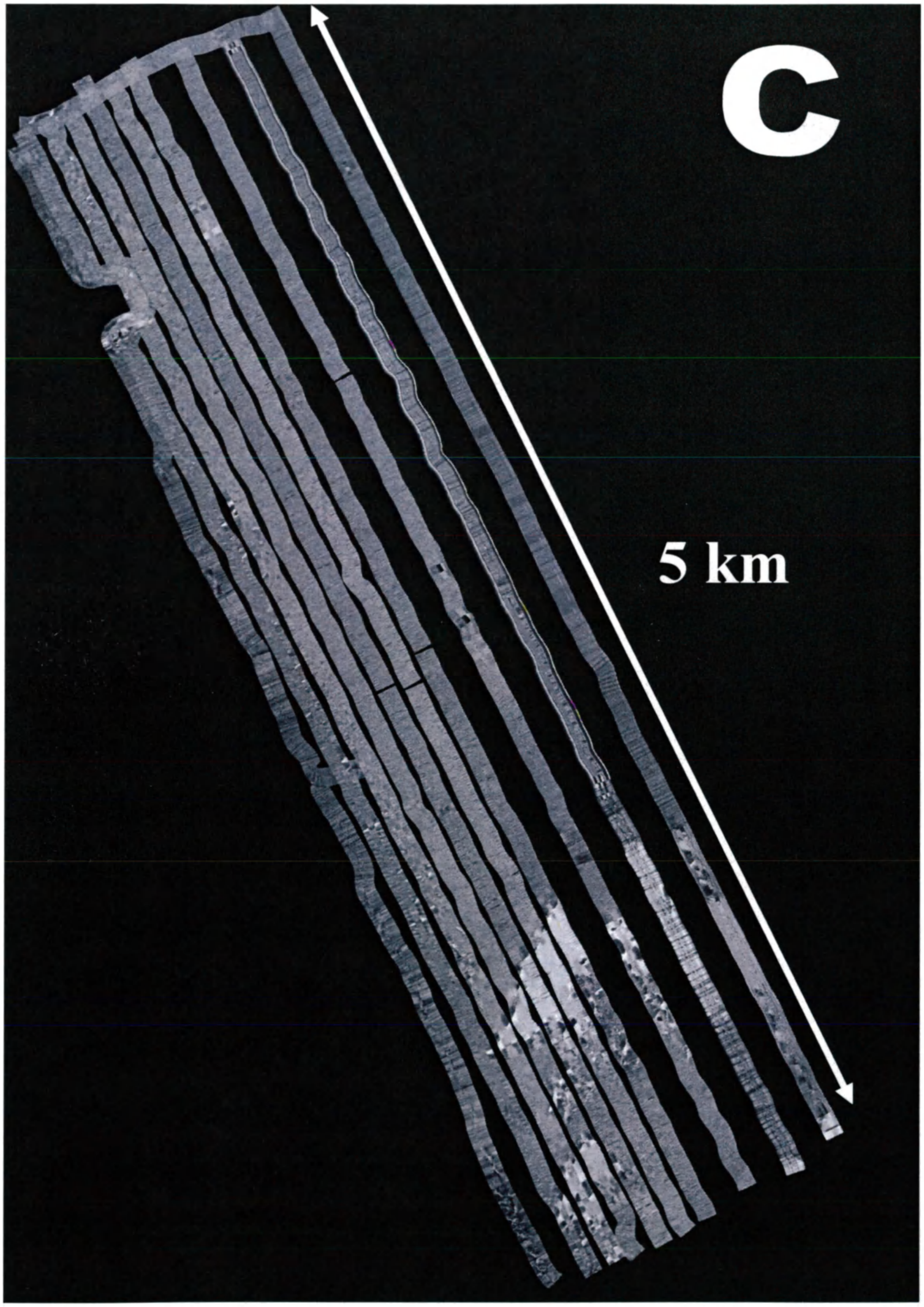


Figure 7C. Acoustic reflectance data in June 2002, with low backscatter (dark areas) indicating sand and high backscatter (light areas) indicating gravel.

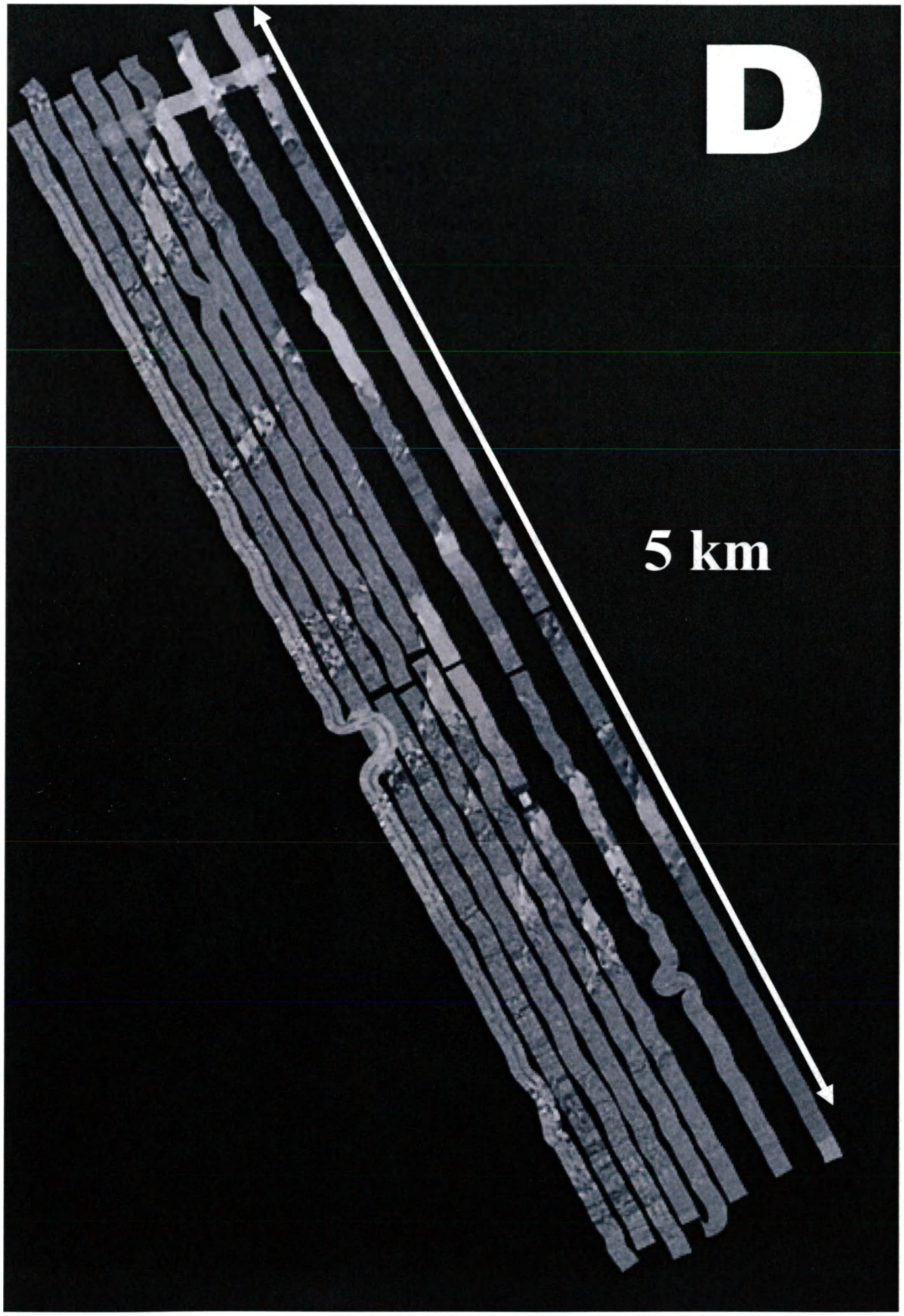


Figure 7D. Acoustic reflectance data in June 2002, with low backscatter (dark areas) indicating sand and high backscatter (light areas) indicating gravel.

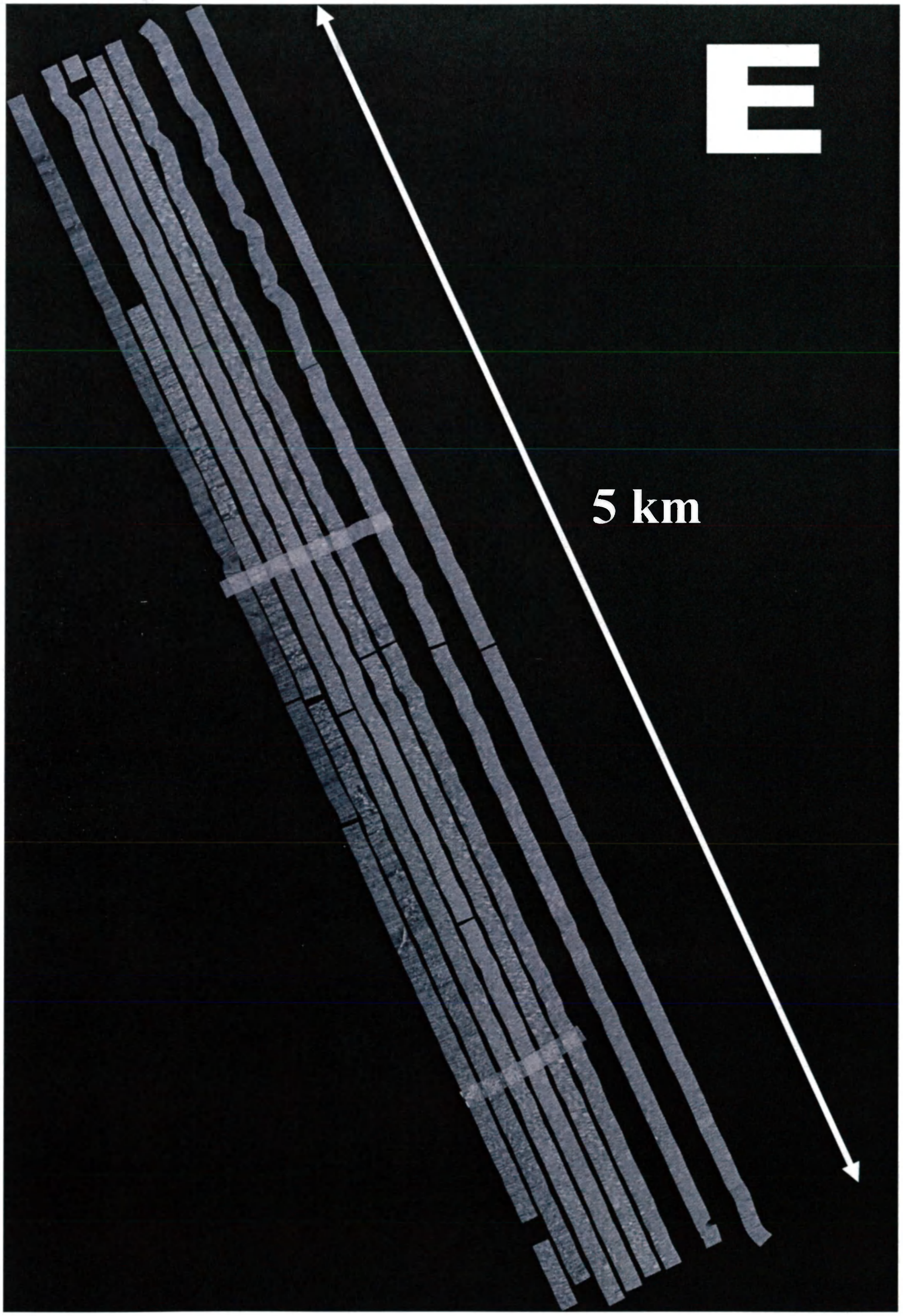


Figure 7E. Acoustic reflectance data in June 2002, with low backscatter (dark areas) indicating sand and high backscatter (light areas) indicating gravel.

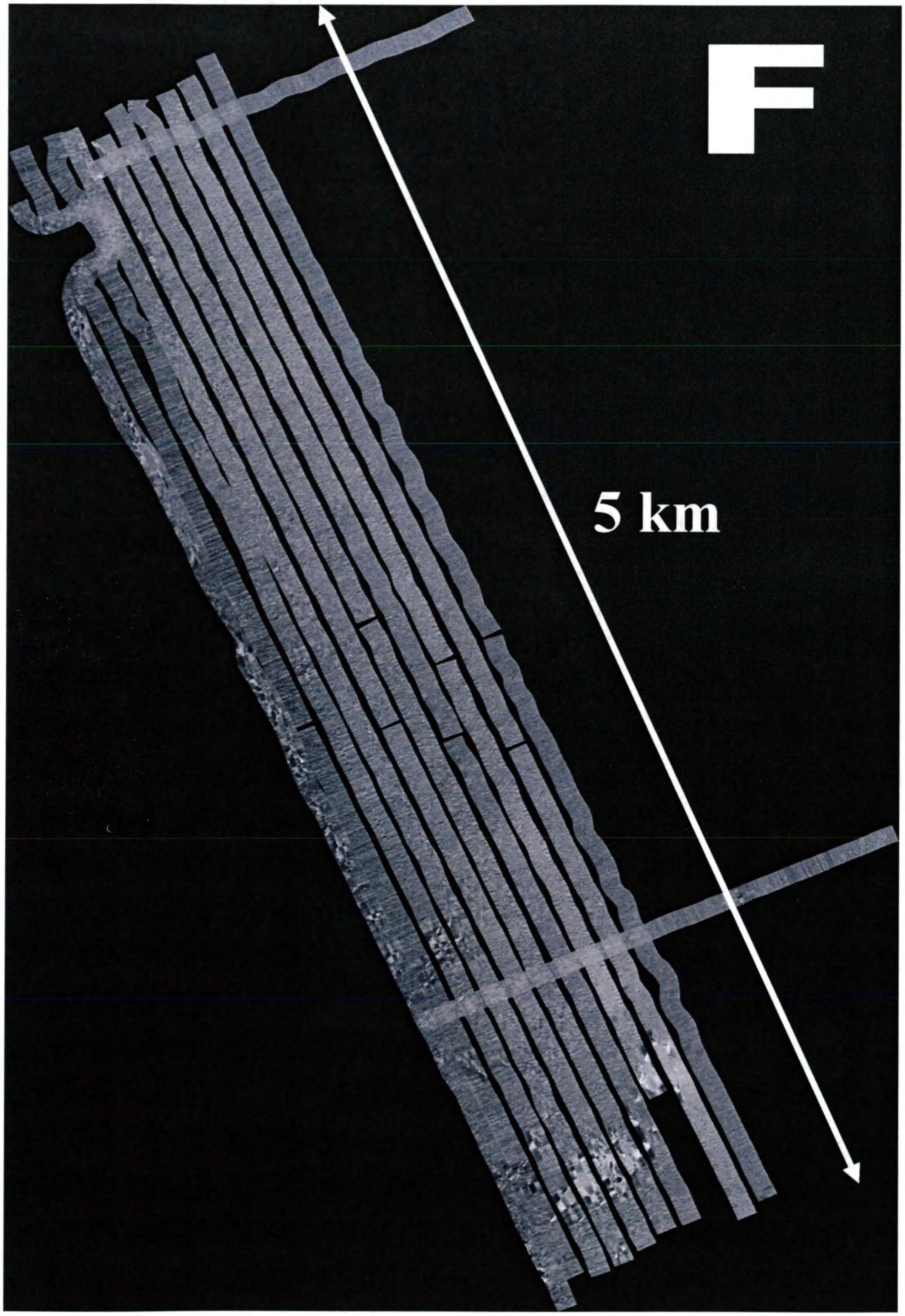


Figure 7F. Acoustic reflectance data in June 2002, with low backscatter (dark areas) indicating sand and high backscatter (light areas) indicating gravel.

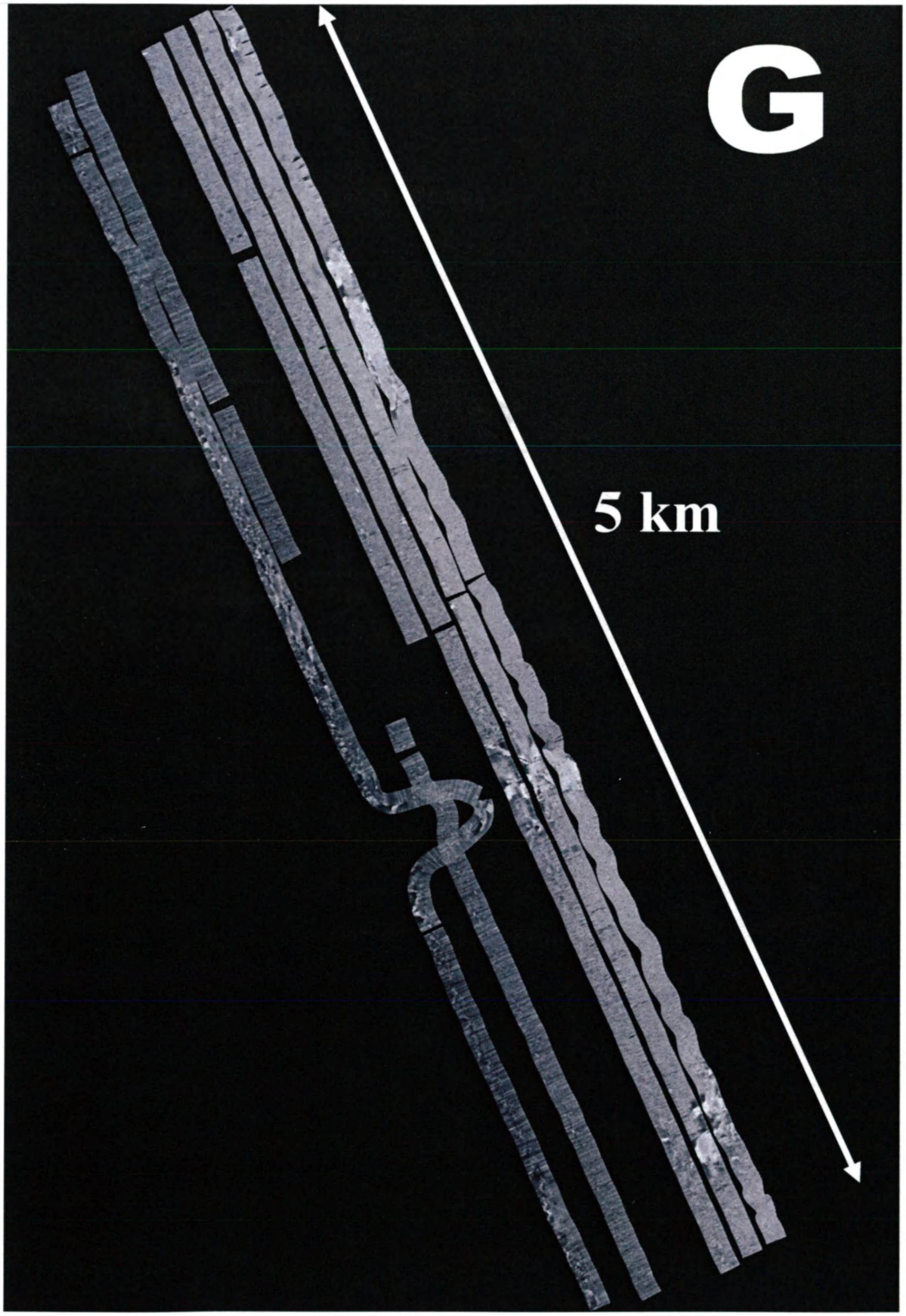


Figure 7G. Acoustic reflectance data in June 2002, with low backscatter (dark areas) indicating sand and high backscatter (light areas) indicating gravel.

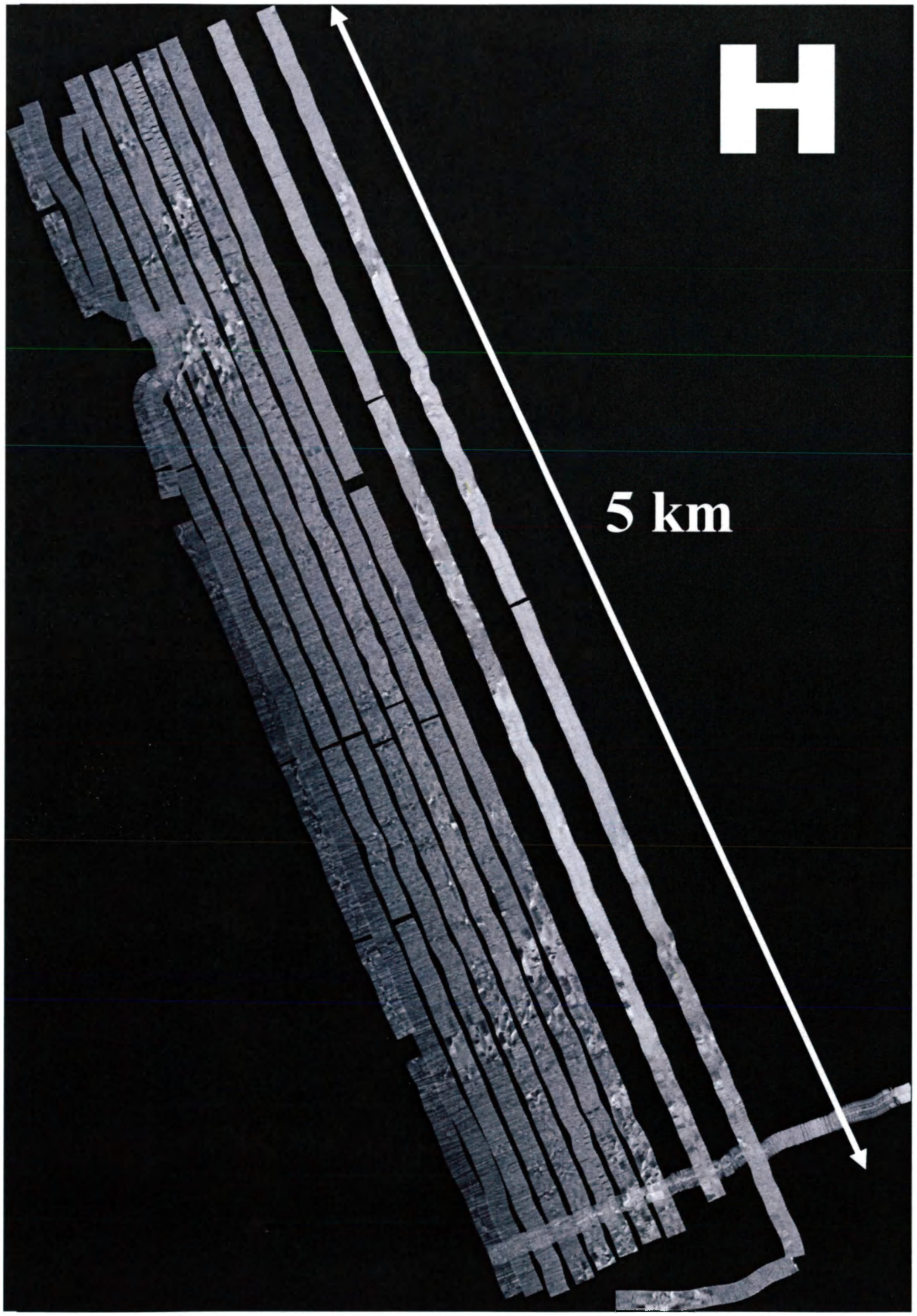


Figure 7H. Acoustic reflectance data in June 2002, with low backscatter (dark areas) indicating sand and high backscatter (light areas) indicating gravel.

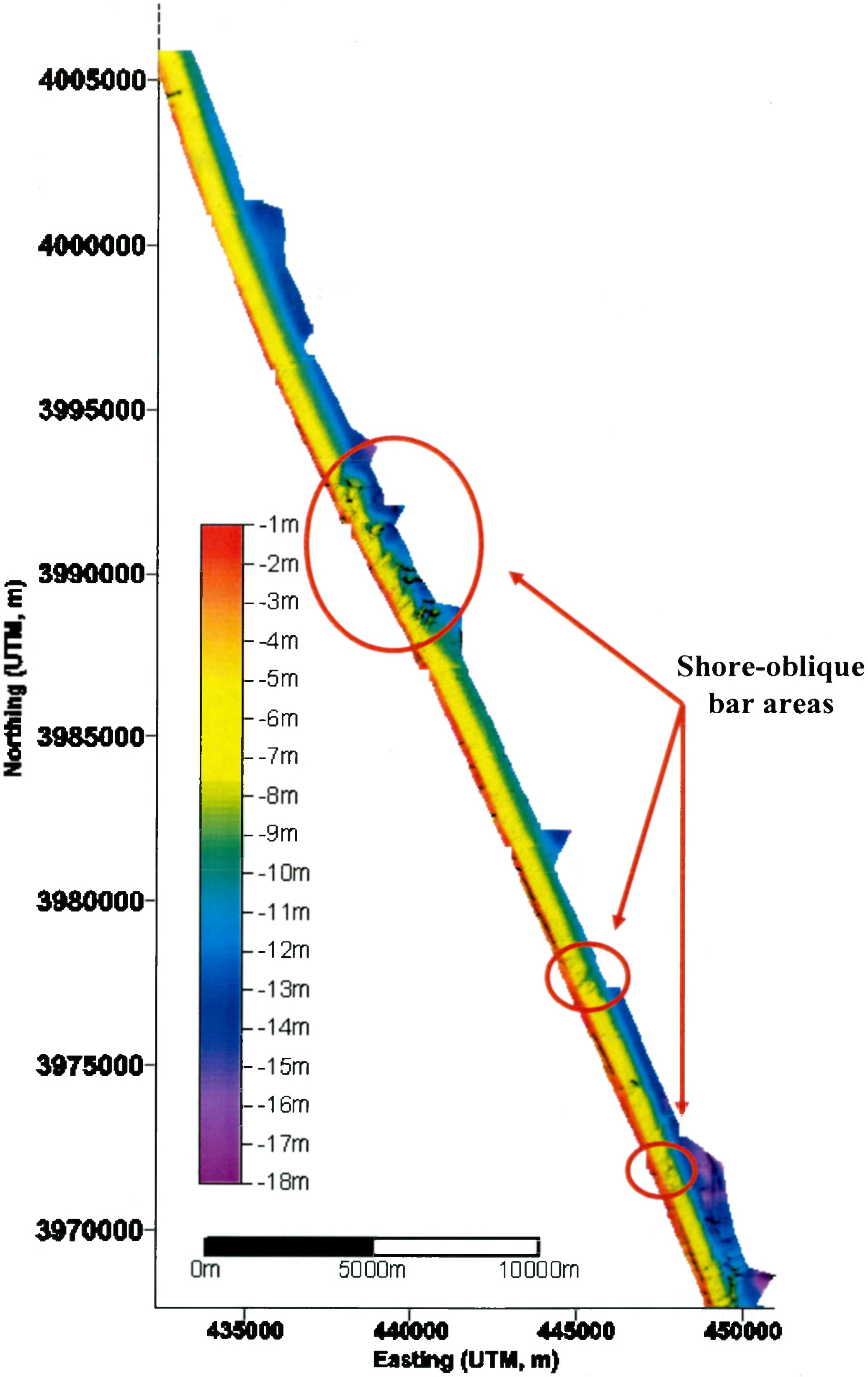


Figure 8. Map of northern Outer Banks bathymetry in June 2002. Red ellipses identify areas with shore-oblique bars.

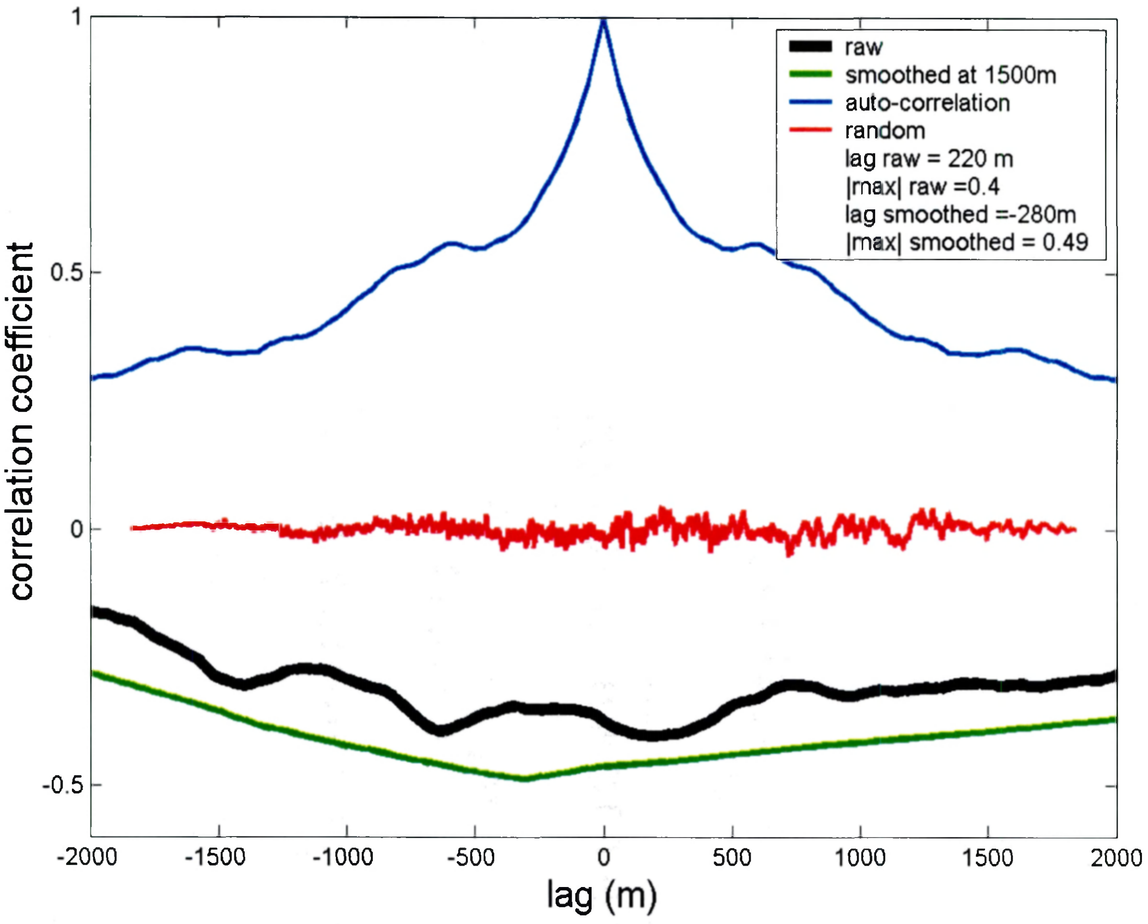


Figure 9. June 2002 survey alongshore lag and cross-correlation between bathymetry and shoreline variability for the regional survey area. The green line is the cross-correlation using a shoreline variability dataset smoothed with a 1500 m sliding window. Of the 40 km lag possible, only 2 km is displayed.

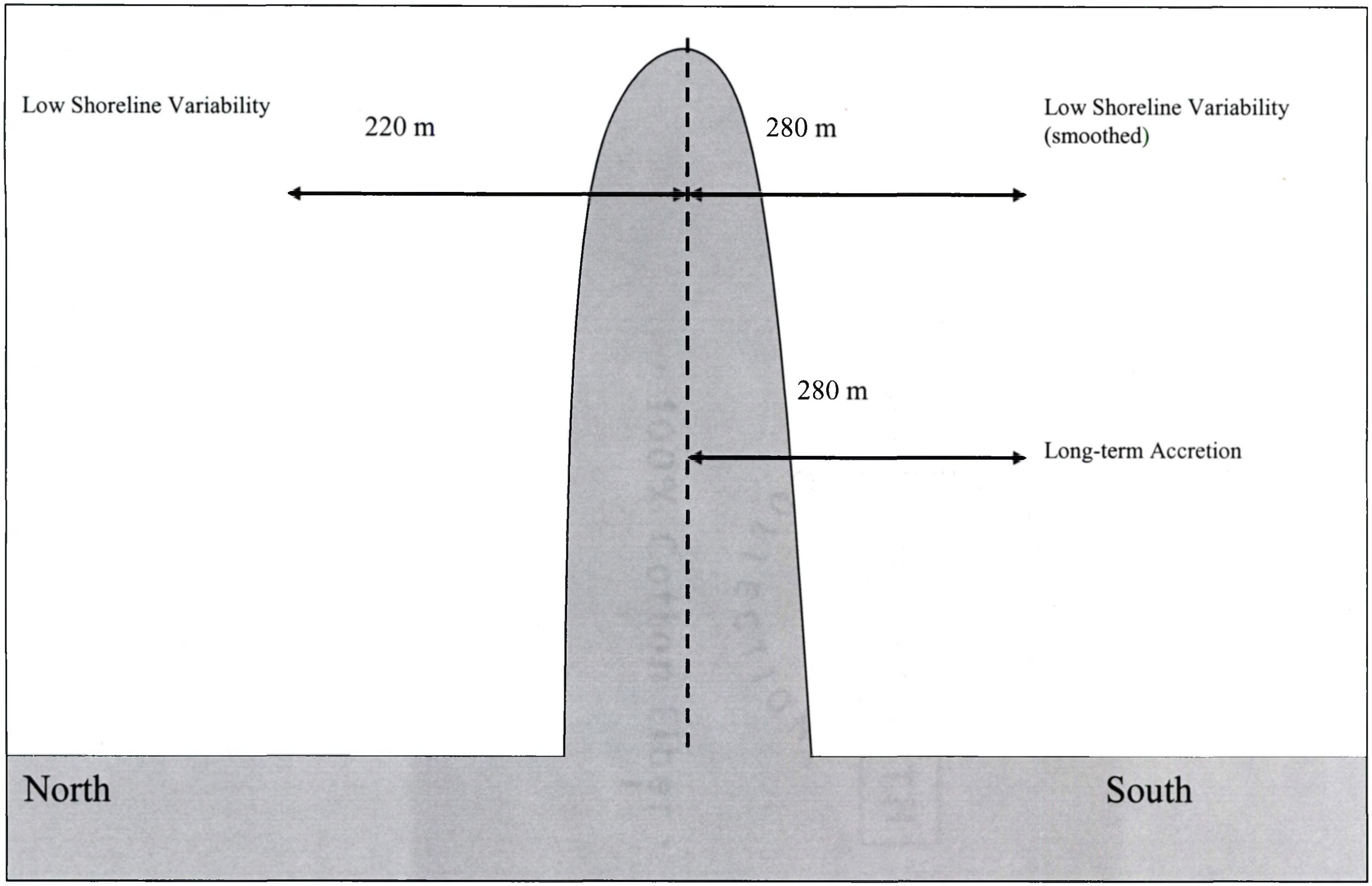


Figure 10. Conceptual diagram illustrating the spatial relationship of an area with shallow slope (represented as the long axis of a bar) to the alongshore lag at which it is maximally correlated with shoreline variability and long-term shoreline change, for the northern Outer Banks.

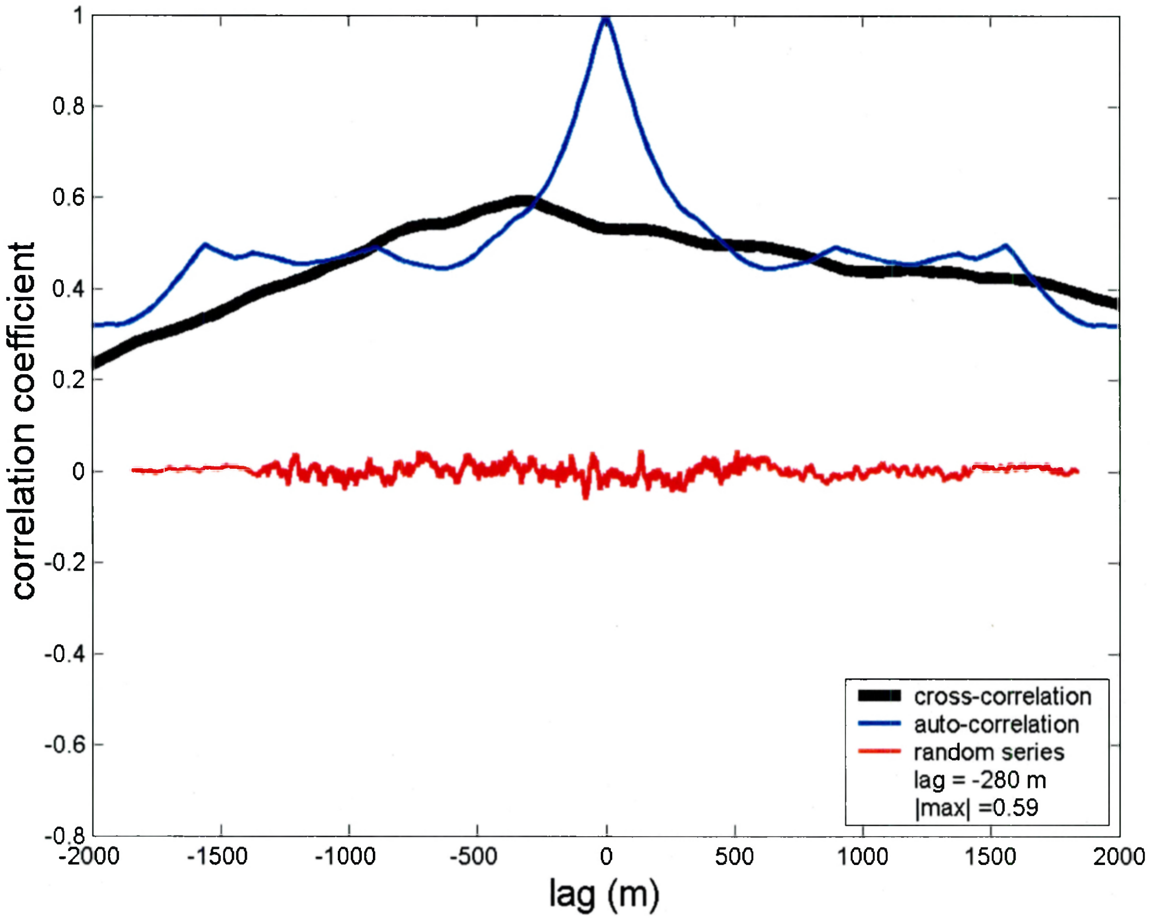


Figure 11. Cross-correlation and alongshore lag between bathymetry and long-term shoreline change for the regional survey area. Of the 40 km lag possible, only 2 km is displayed.

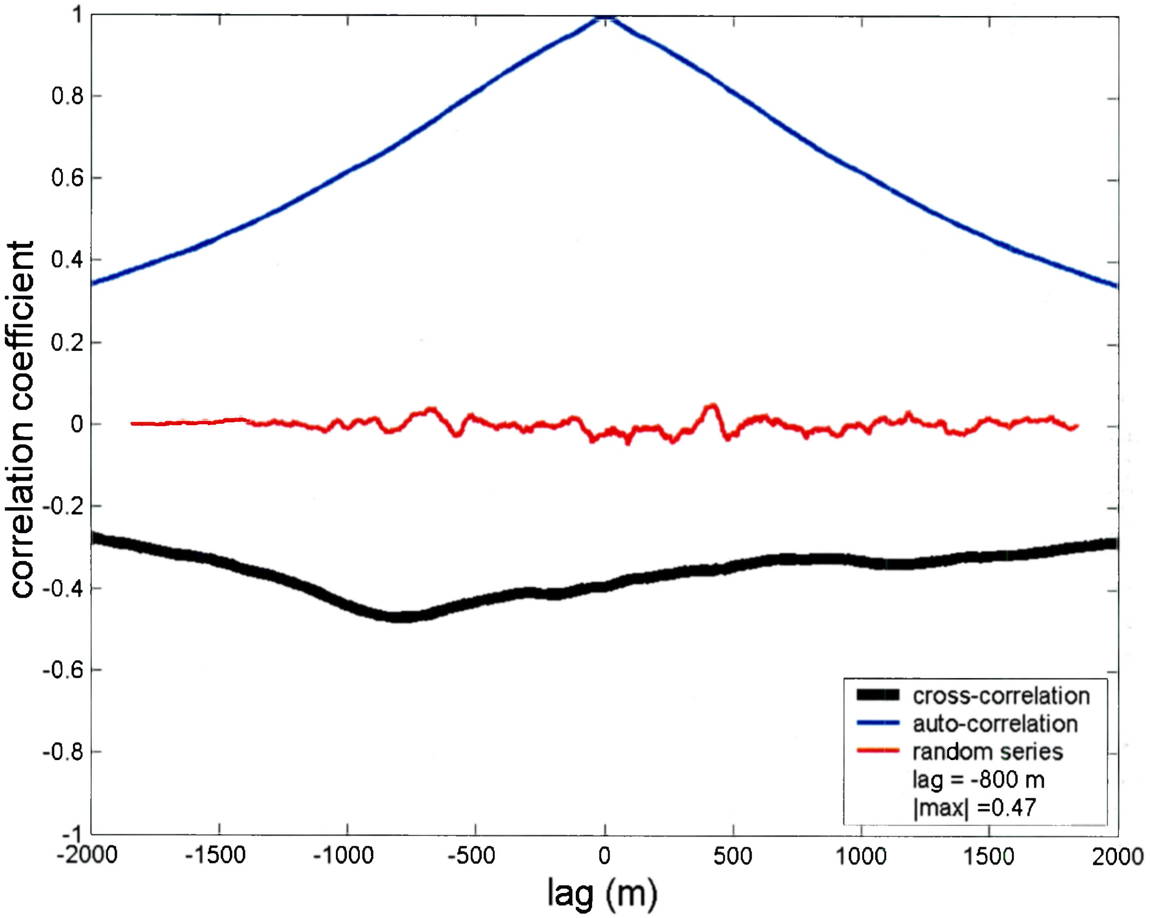


Figure 12. June 2002 survey alongshore lag and cross-correlation between shoreline variability and long-term shoreline change for the regional survey area. Of the 40 km lag possible, only 2 km is displayed.

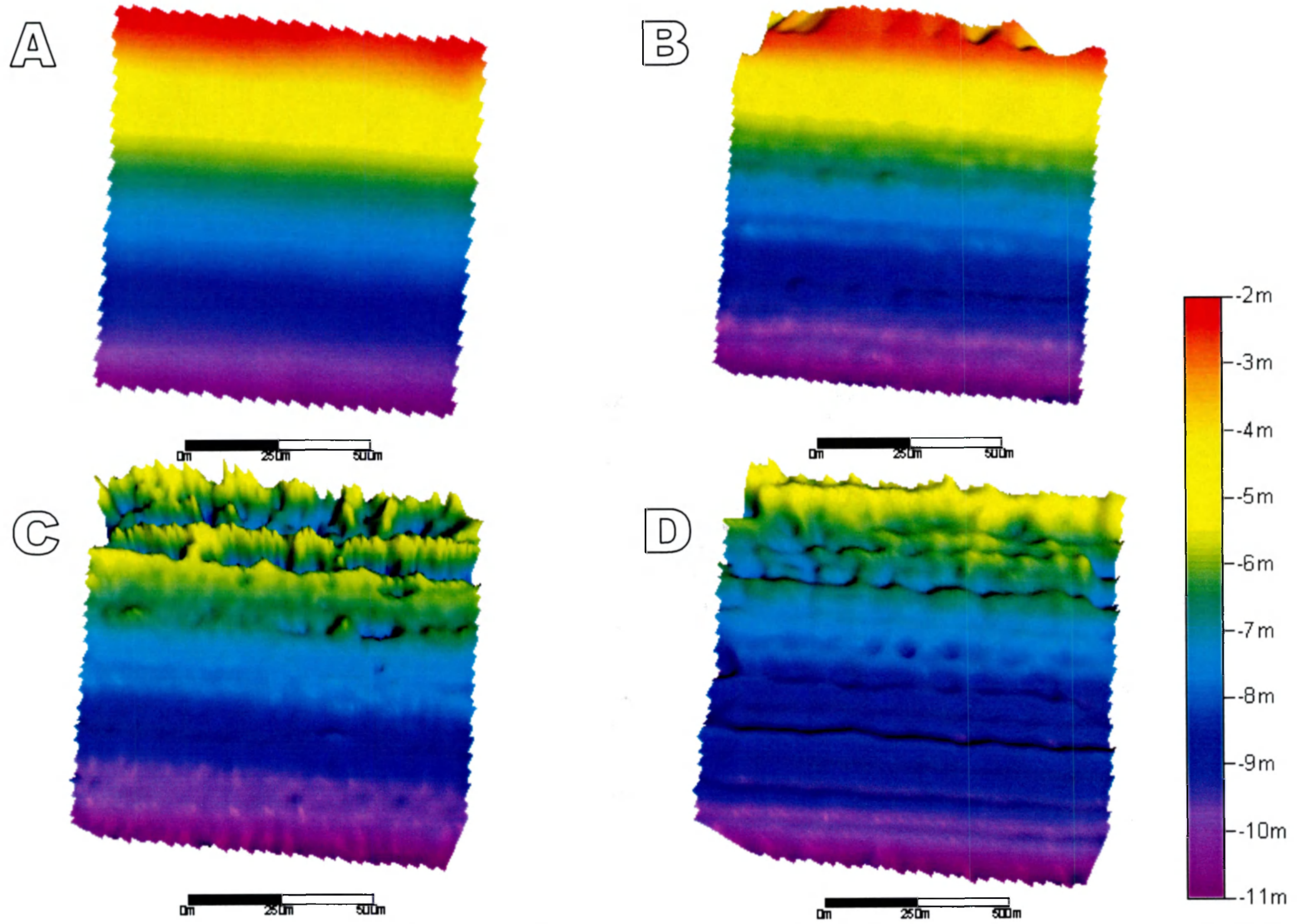


Figure 13. Surface map of Southern Shores bathymetry in June 2002 (A), March 2003 (B), May 2003 (C), and November 2003 (D). Depths are in meters relative to MLW.

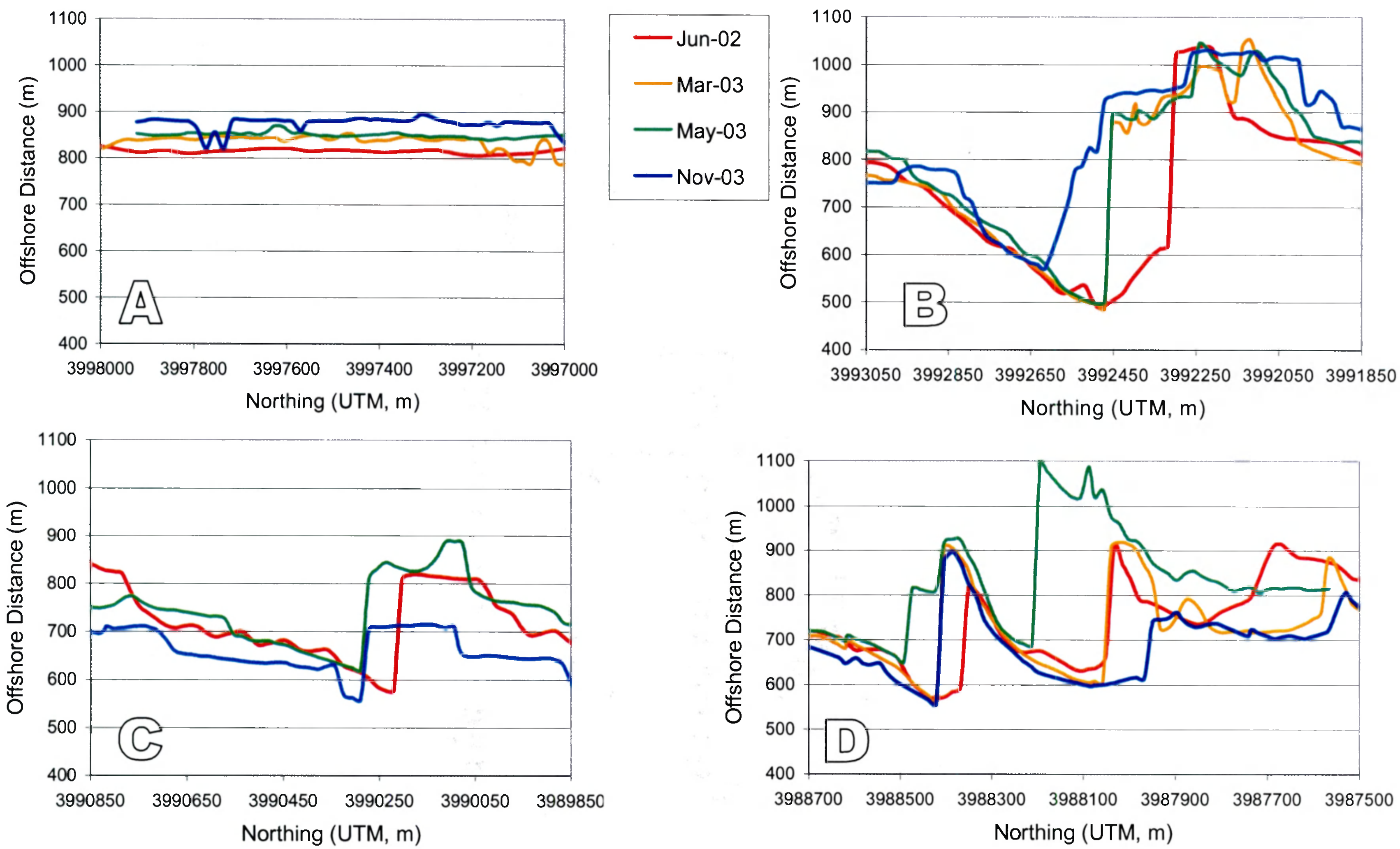


Figure 14. Offshore distance to the 9m isobath for the four study sites: Southern Shores (A), Kitty Hawk (B), northern Kill Devil Hills (C), and southern Kill Devil Hills (D).

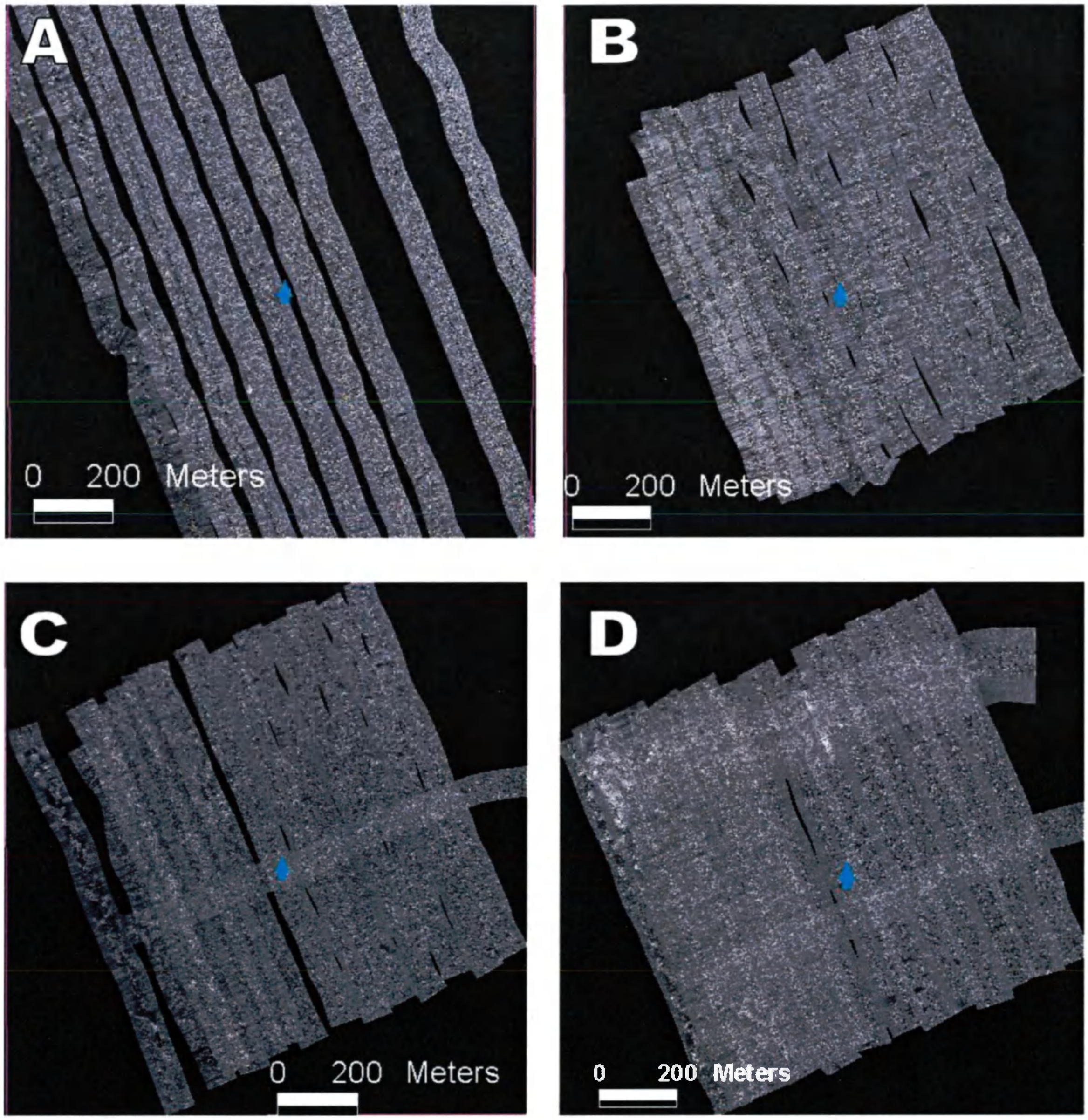


Figure 15. Acoustic reflectance map of Southern Shores in June 2002 (A), March 2003 (B), May 2003 (C), and November 2003 (D). The blue arrow is in the same geographic location in each image. Low backscatter (dark areas) indicates sand; high backscatter (light areas) indicates gravel.

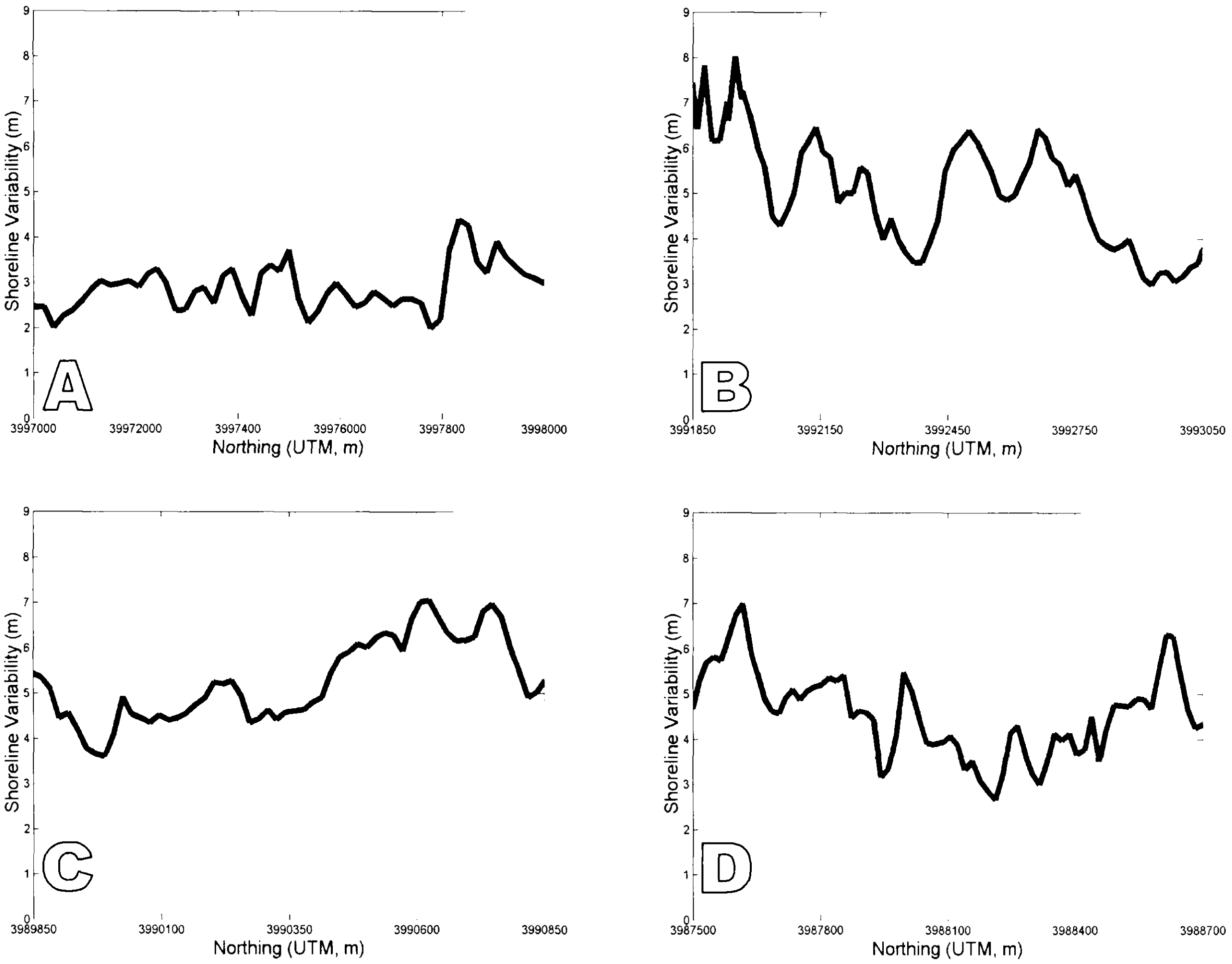


Figure 16. Shoreline variability for the four study sites: Southern Shores (A), Kitty Hawk (B), northern Kill Devil Hills (C), and southern Kill Devil Hills (D).

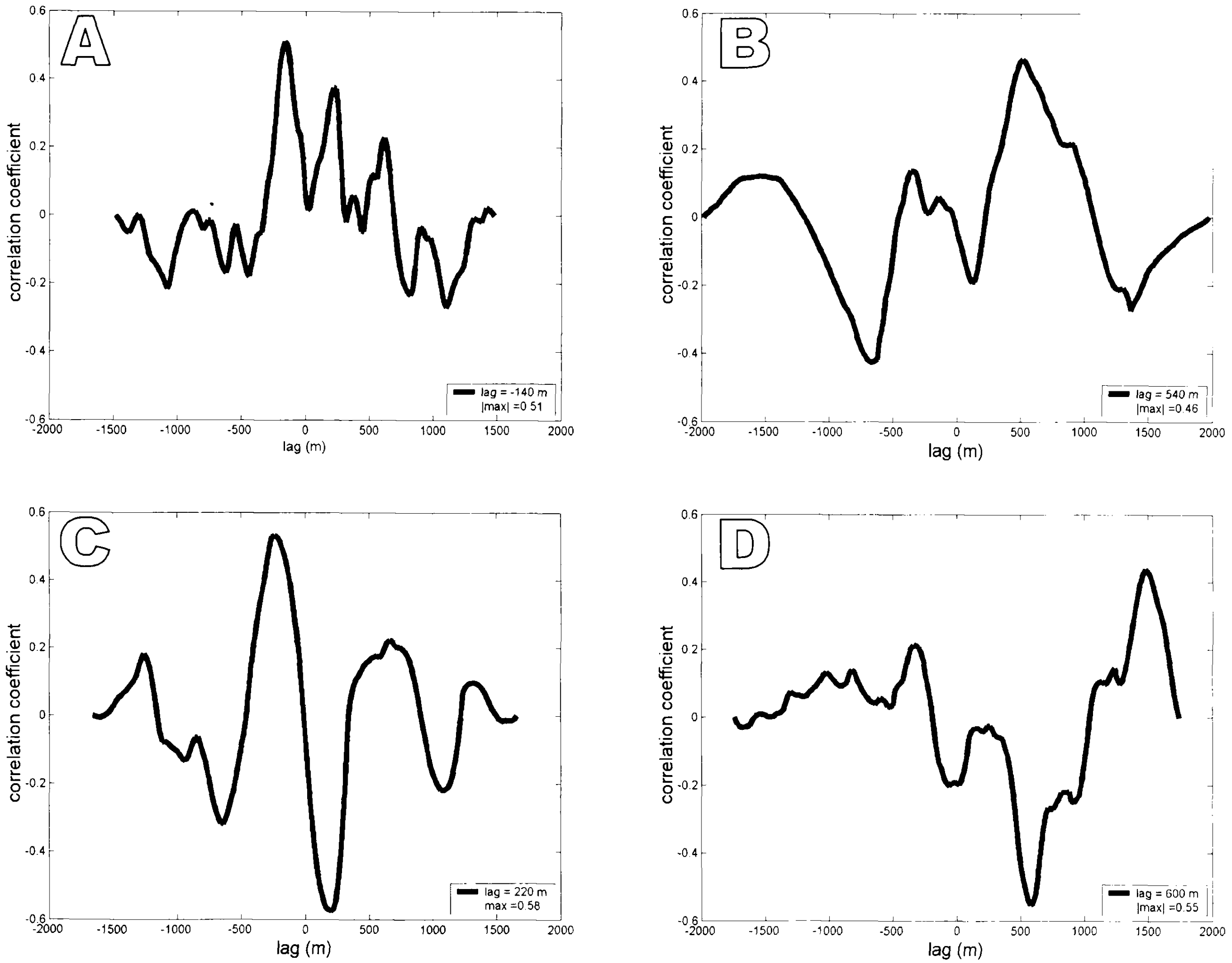


Figure 17. June 2002 survey alongshore lag and cross-correlation between bathymetry and shoreline variability for Southern Shores (A), Kitty Hawk (B), northern Kill Devil Hills (C), and southern Kill Devil Hills (D).

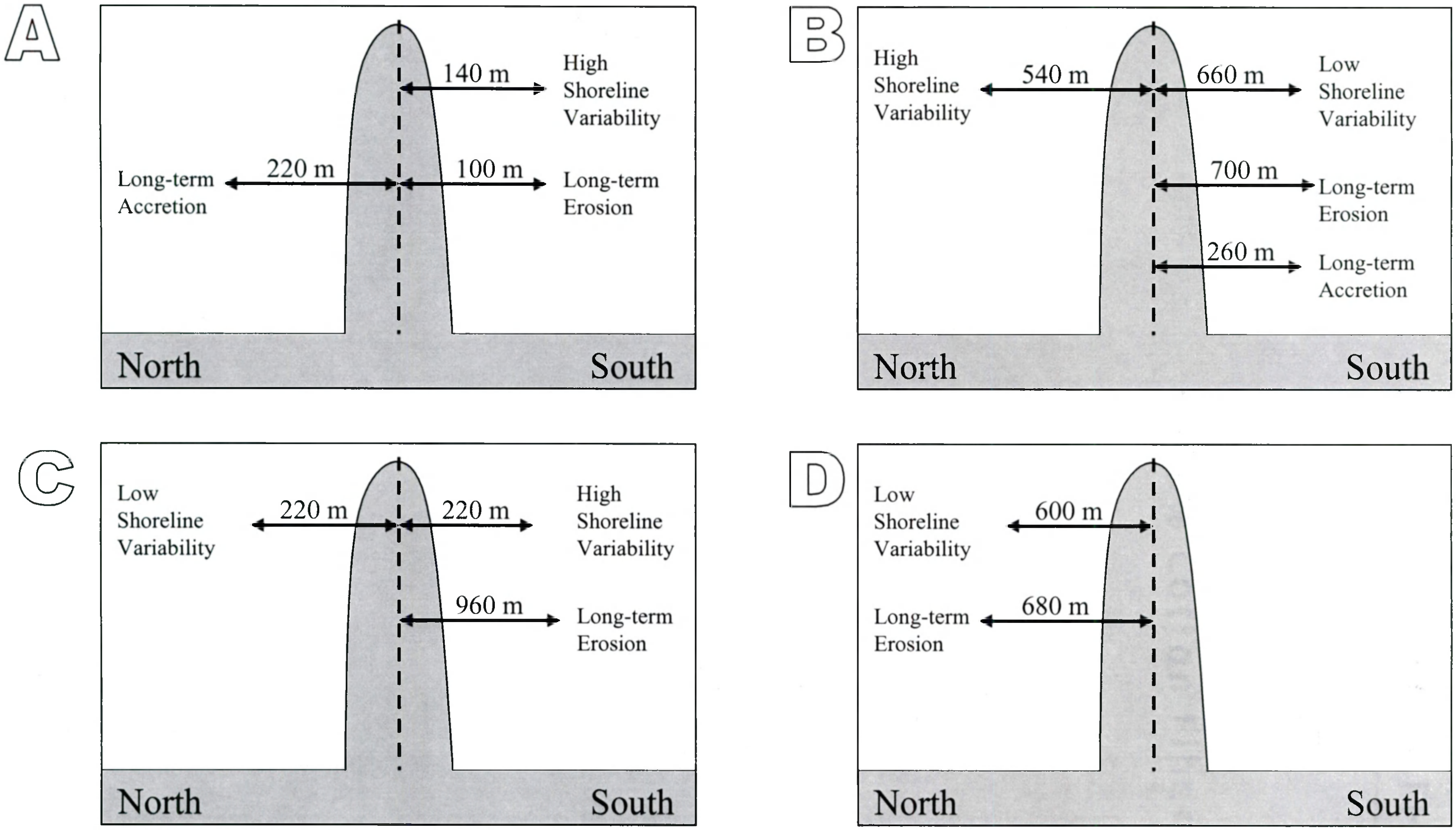


Figure 18. Conceptual diagram illustrating the spatial relationship of an area with shallow slope (represented as the long axis of a bar) to the alongshore lag at which it is maximally correlated with shoreline variability and long-term shoreline change, for Southern Shores (A), Kitty Hawk (B), northern Kill Devil Hills (C), and southern Kill Devil Hills (D).

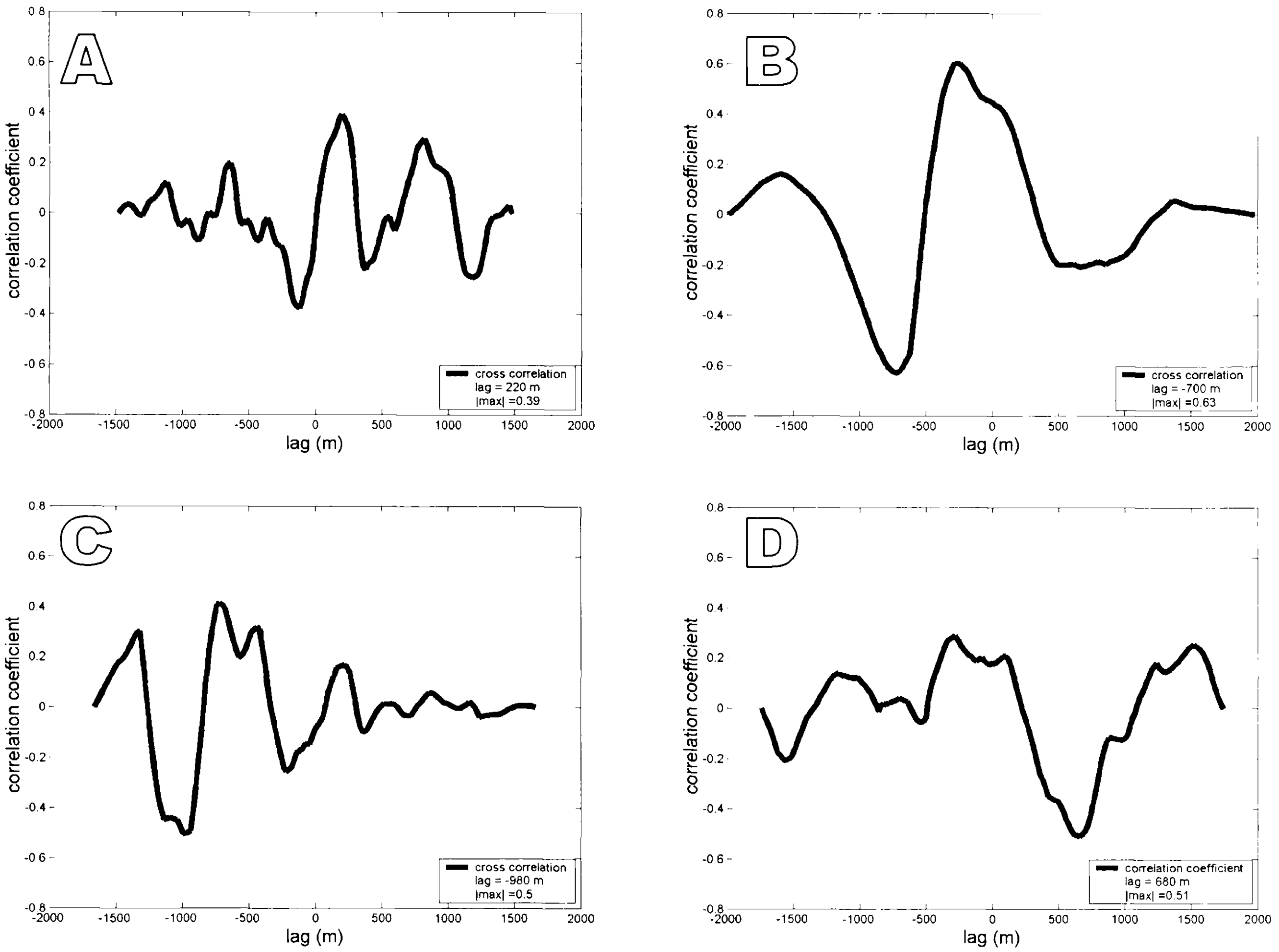
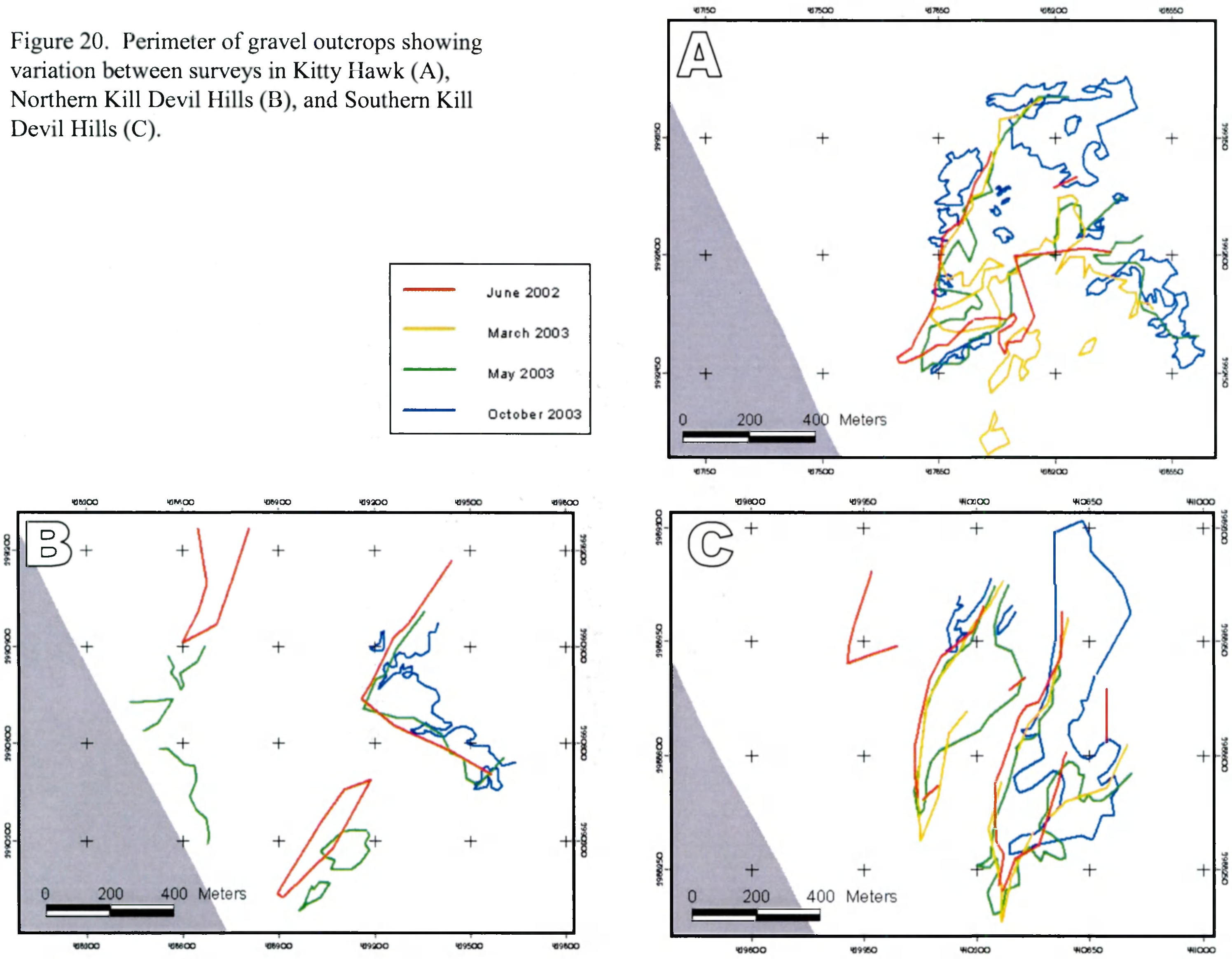


Figure 19. June 2002 survey alongshore lag and cross-correlation between bathymetry and long-term shoreline change for Southern Shores (A), Kitty Hawk (B), northern Kill Devil Hills (C), and southern Kill Devil Hills (D).

Figure 20. Perimeter of gravel outcrops showing variation between surveys in Kitty Hawk (A), Northern Kill Devil Hills (B), and Southern Kill Devil Hills (C).



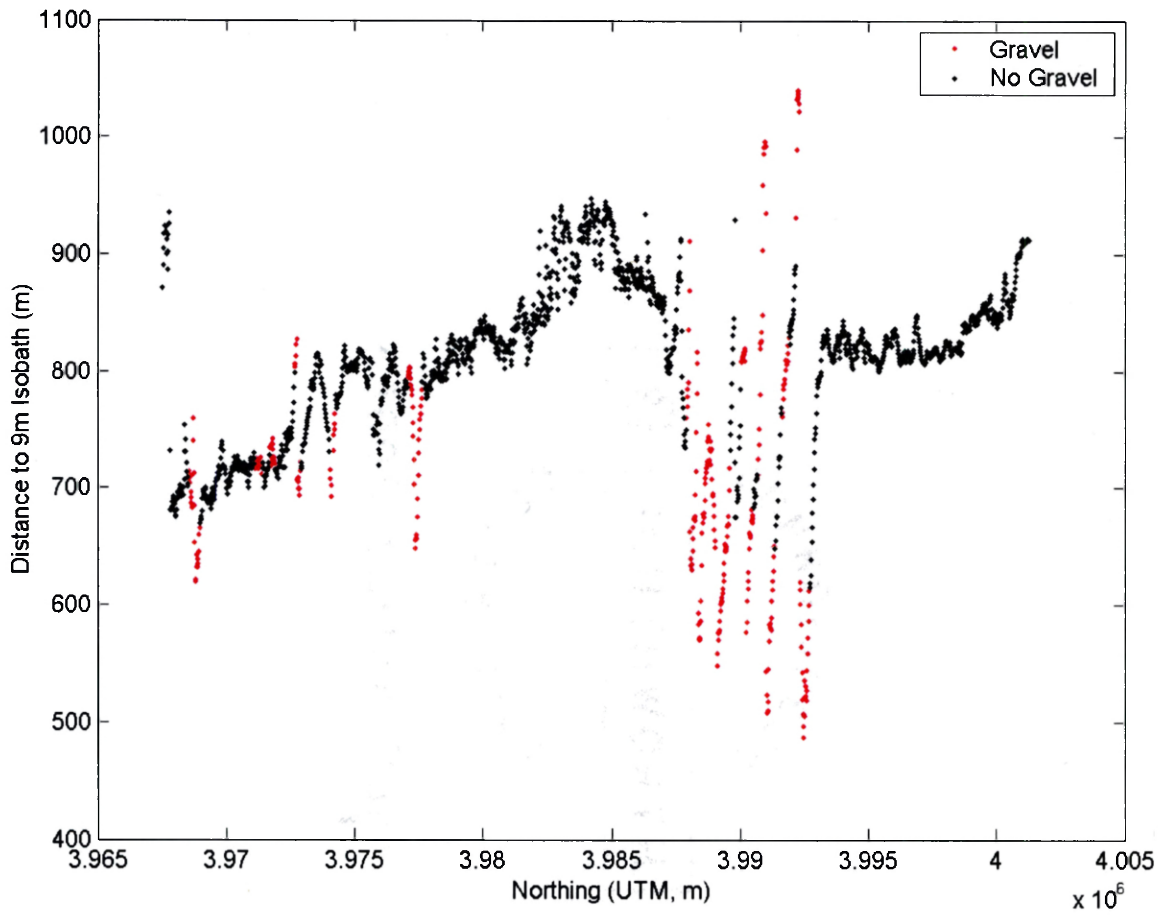


Figure 21. Regional alongshore concurrence of gravel outcrops and shore-oblique bars in June 2002.

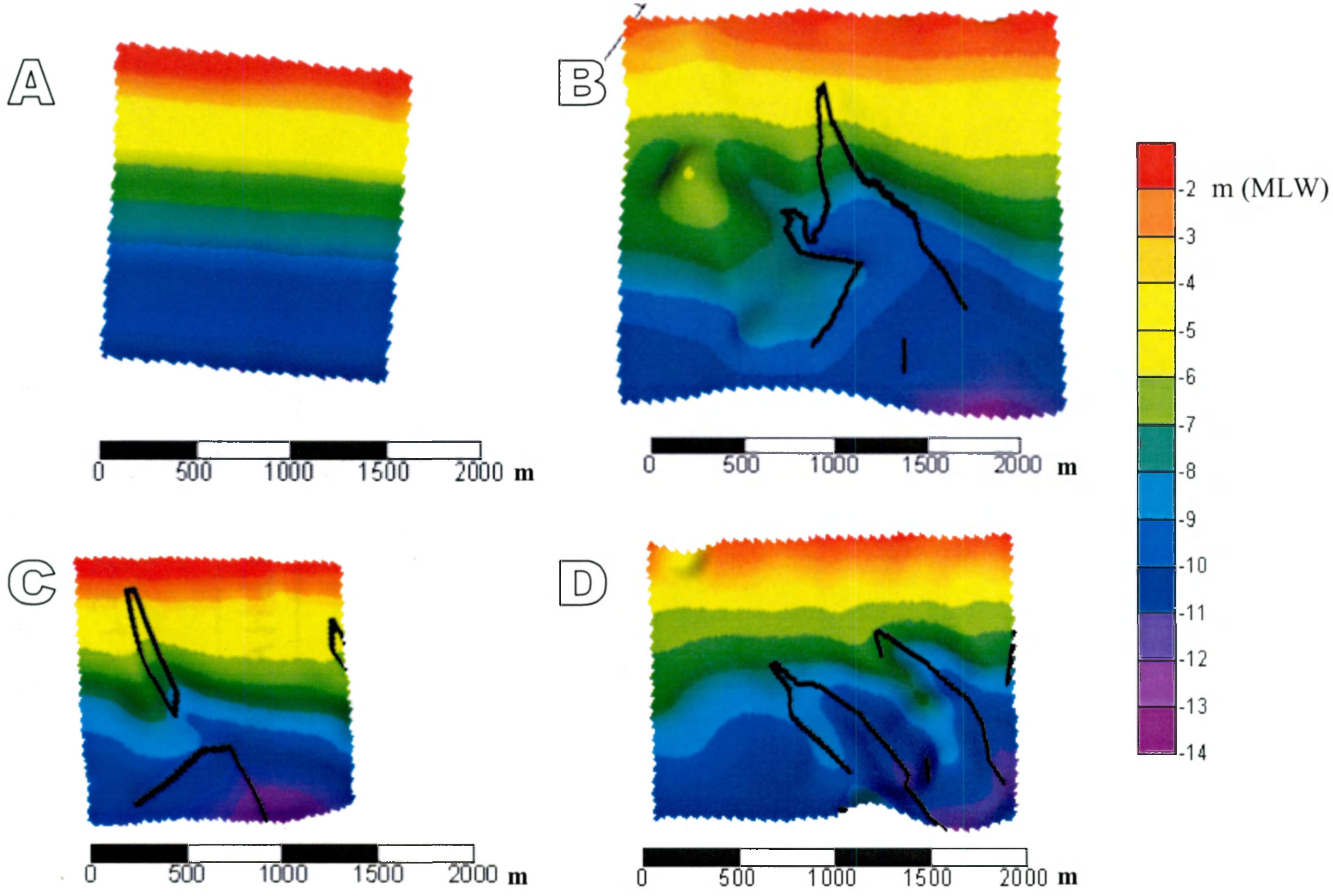


Figure 22. Surface map of bathymetry in June 2002 with overlaid perimeter of gravel outcrop visible in trough between shore-oblique bars in Southern Shores (A), Kitty Hawk (B), northern Kill Devil Hills (C), and southern Kill Devil Hills (D). Depths are in meters relative to MLW.

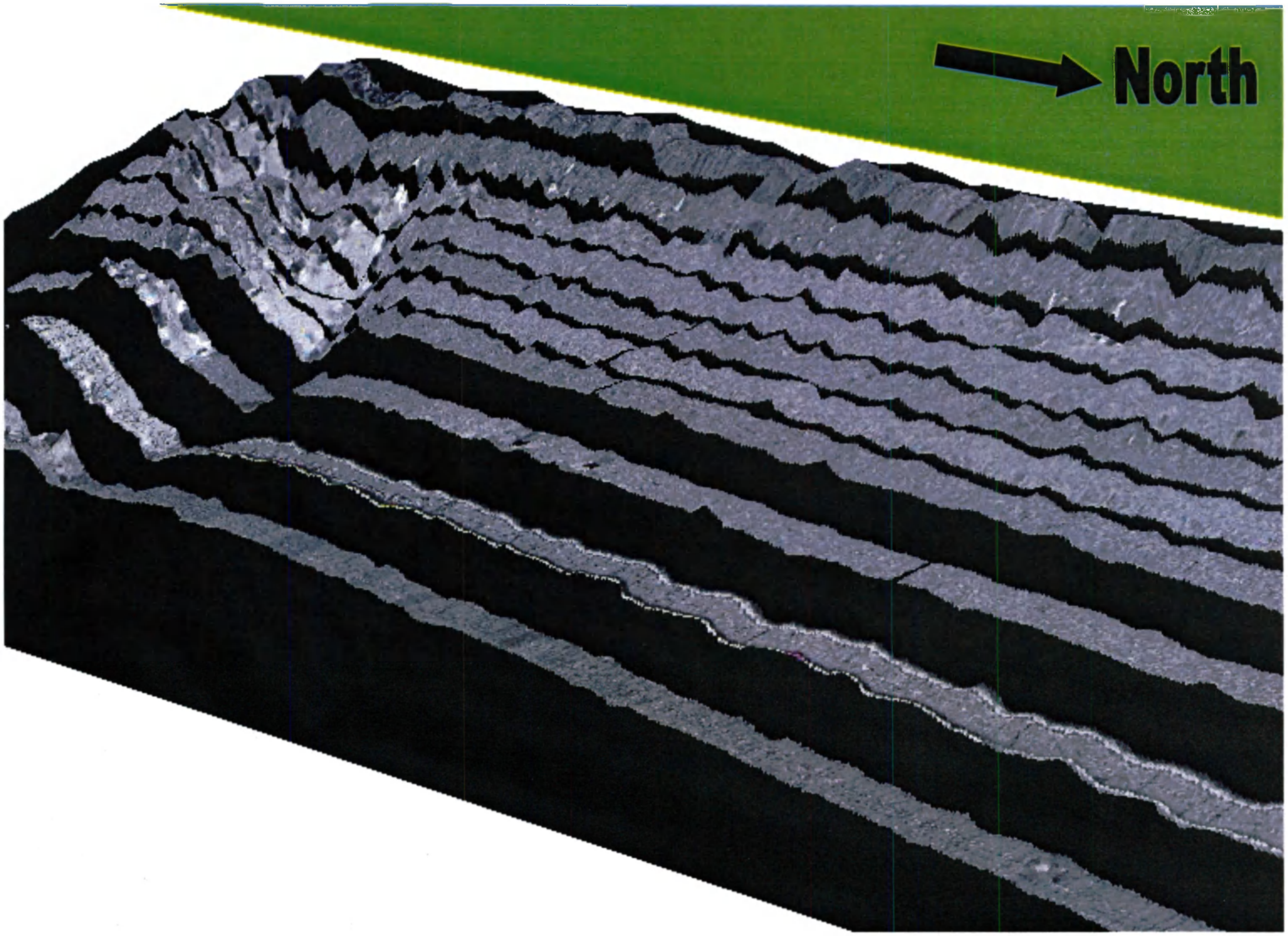


Figure 23. Acoustic reflectance data draped over bathymetric surface (vertical exaggeration = 30) in Kitty Hawk, June 2002. Low backscatter (dark areas) indicates sand and high backscatter (light areas) indicates gravel. Gravel is confined to the troughs.

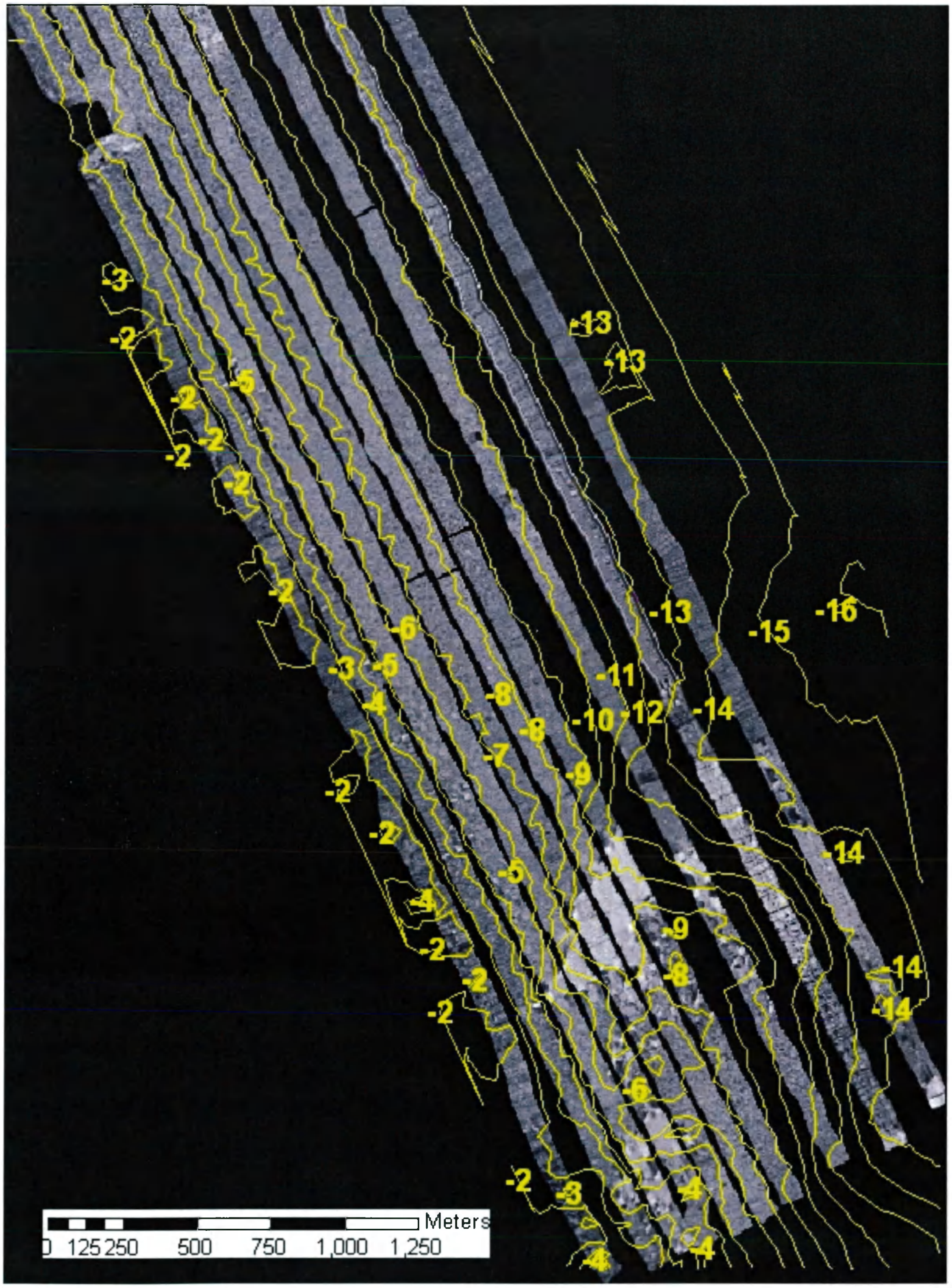


Figure 24. Acoustic reflectance data and depth below MLW (m) in Kitty Hawk, June 2002. Low backscatter (dark areas) indicates sand and high backscatter (light areas) indicates gravel. Gravel is confined to the troughs.

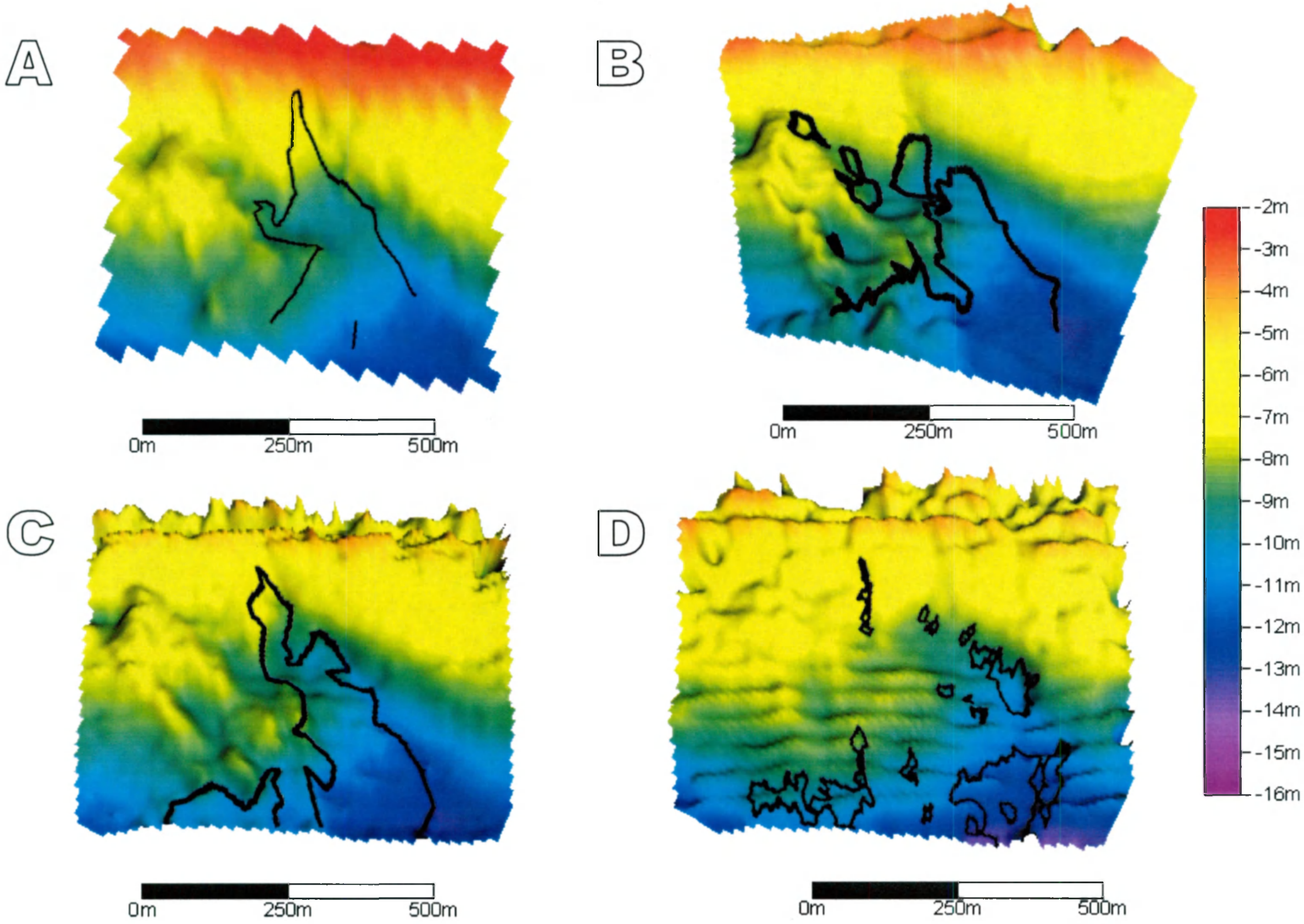


Figure 25. Surface map of Kitty Hawk bathymetry, with overlaid perimeter of gravel outcrop visible in trough between shore-oblique bar, in June 2002 (A), March 2003 (B), May 2003 (C), and November 2003 (D). Depths are in meters relative to MLW.

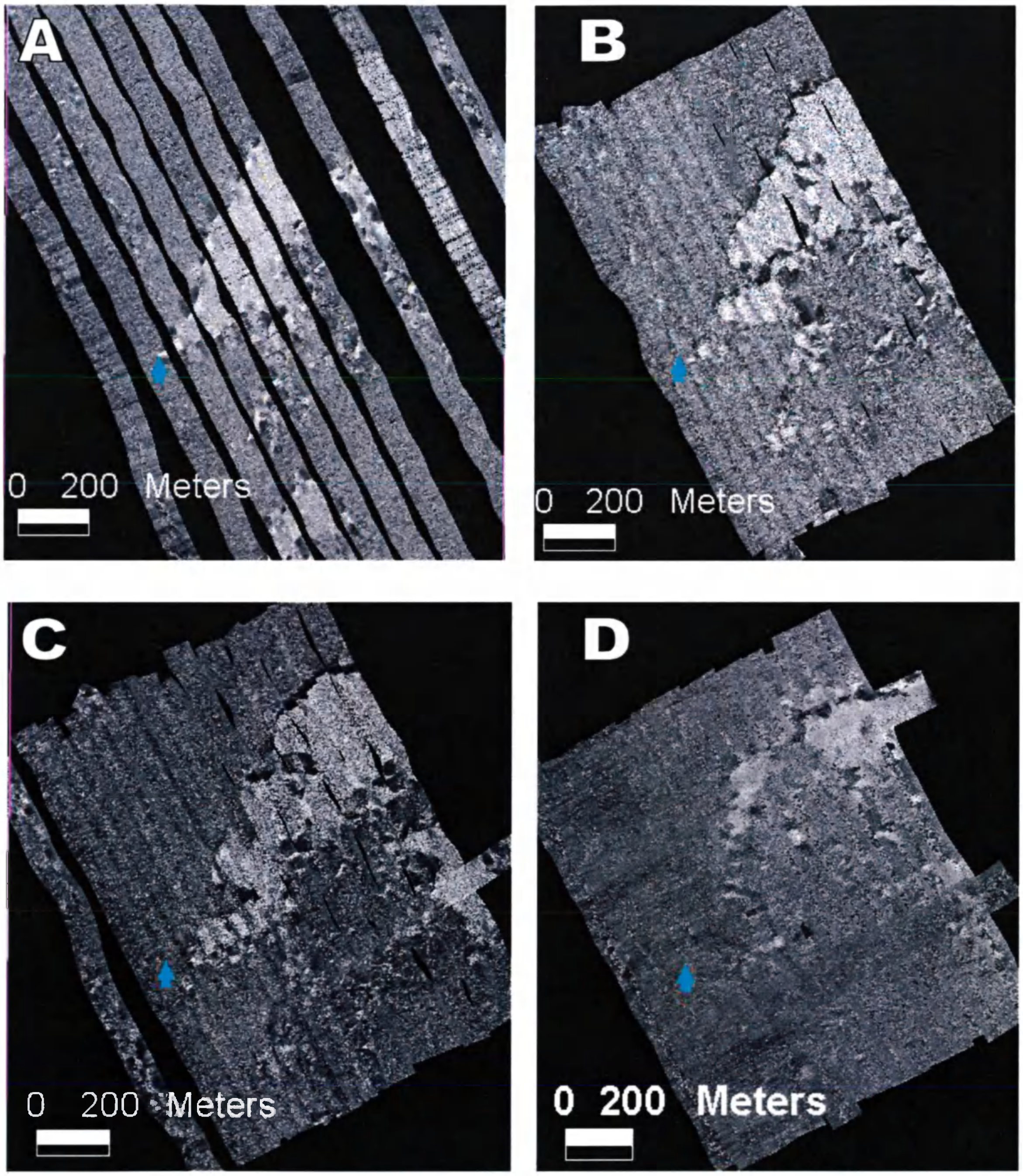


Figure 26. Acoustic reflectance map of Kitty Hawk in June 2002 (A), March 2003 (B), May 2003 (C), and November 2003 (D). The blue arrow is in the same geographic location in each image. Low backscatter (dark areas) indicates sand; high backscatter (light areas) indicates gravel.

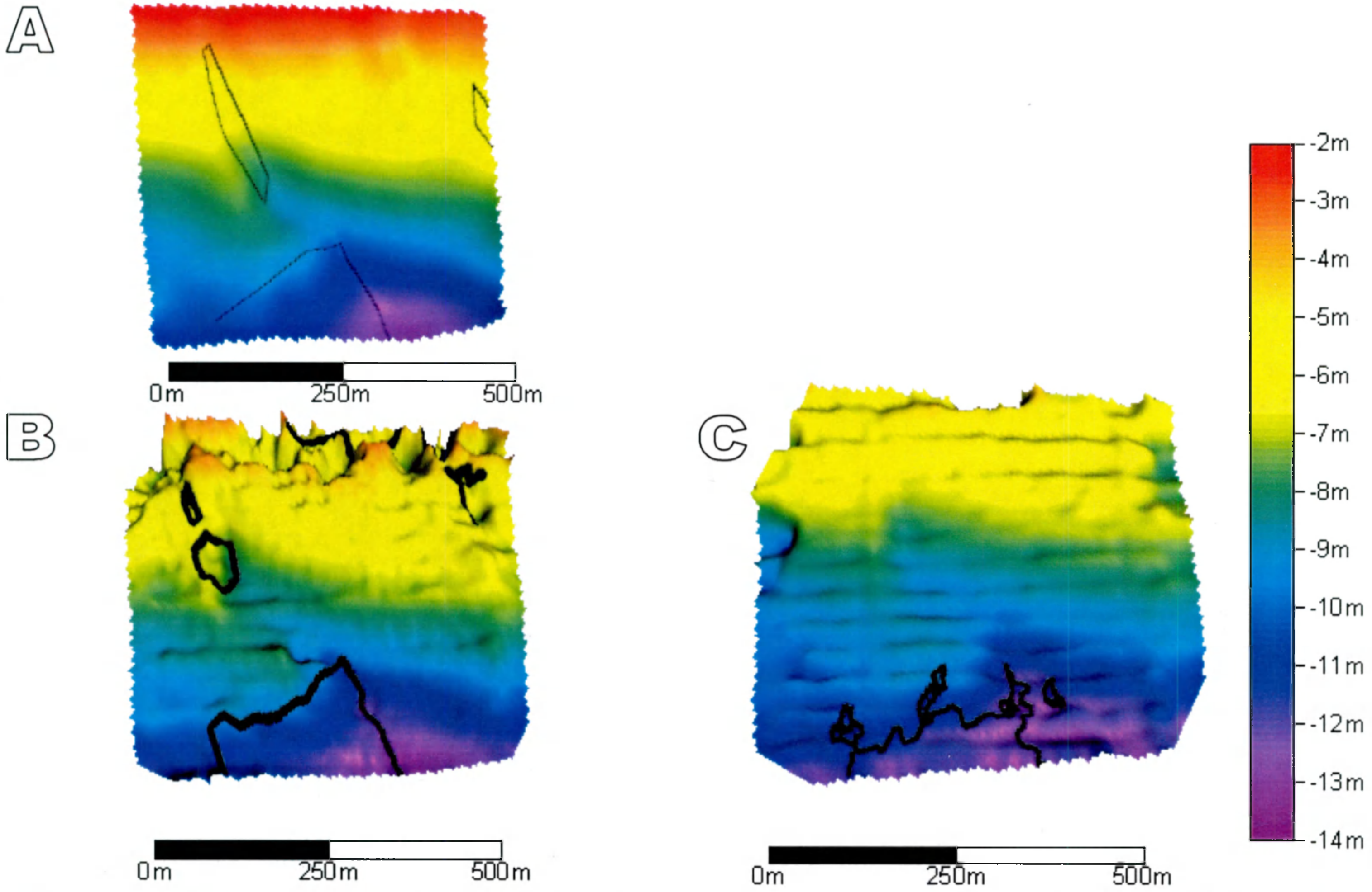


Figure 27. Surface map of northern Kill Devil Hills bathymetry, with overlaid perimeter of gravel outcrop visible in trough between shore-oblique bar, in June 2002 (A), May 2003 (B), and November 2003 (C). No data were collected in March 2003. Depths are in meters relative to MLW.

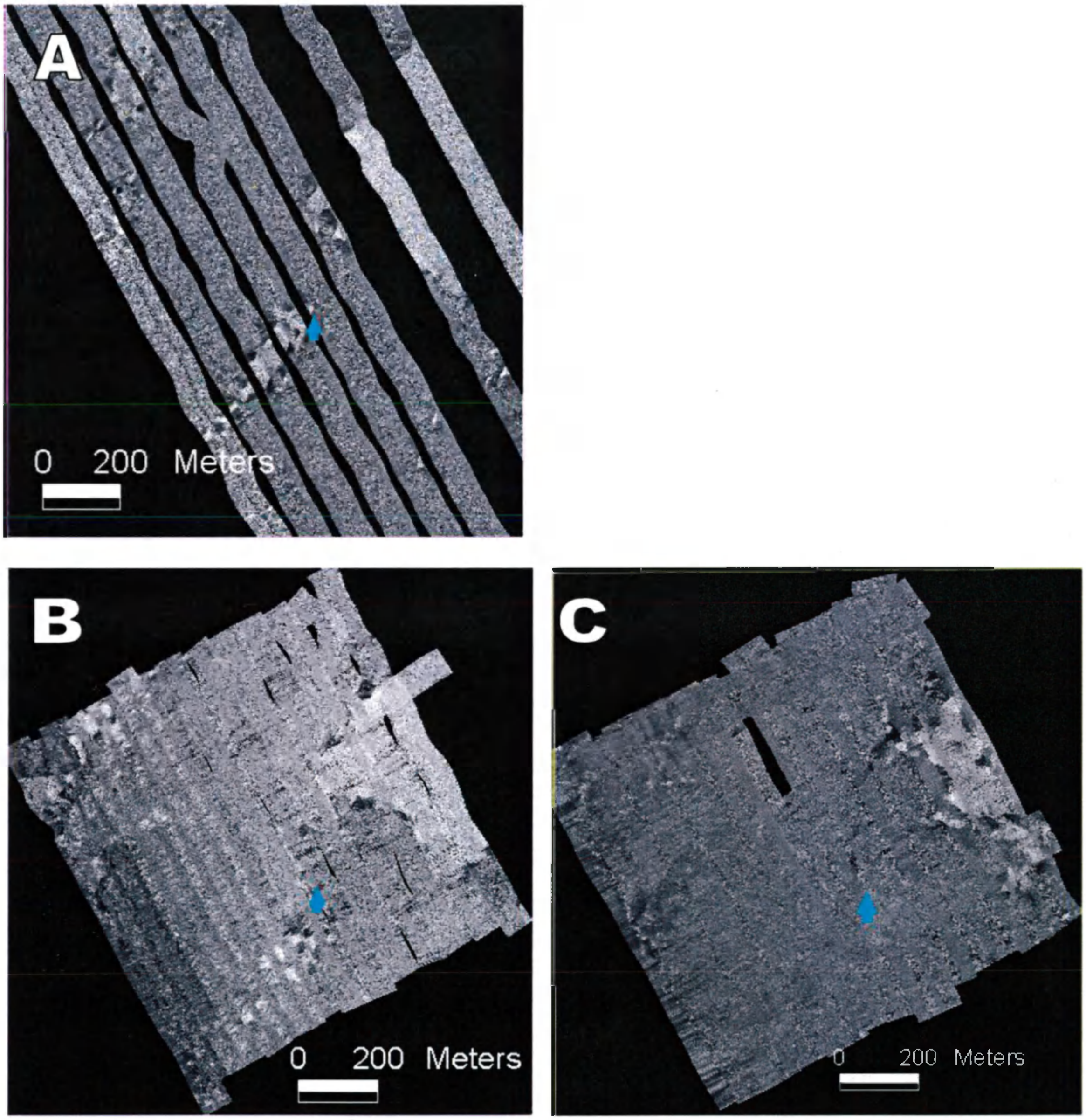


Figure 28. Acoustic reflectance map of northern Kill Devil Hills in June 2002 (A), May 2003 (B), and November 2003 (C). The blue arrow is in the same geographic location in each image. No data were collected in March 2003. Low backscatter (dark areas) indicates sand; high backscatter (light areas) indicates gravel.

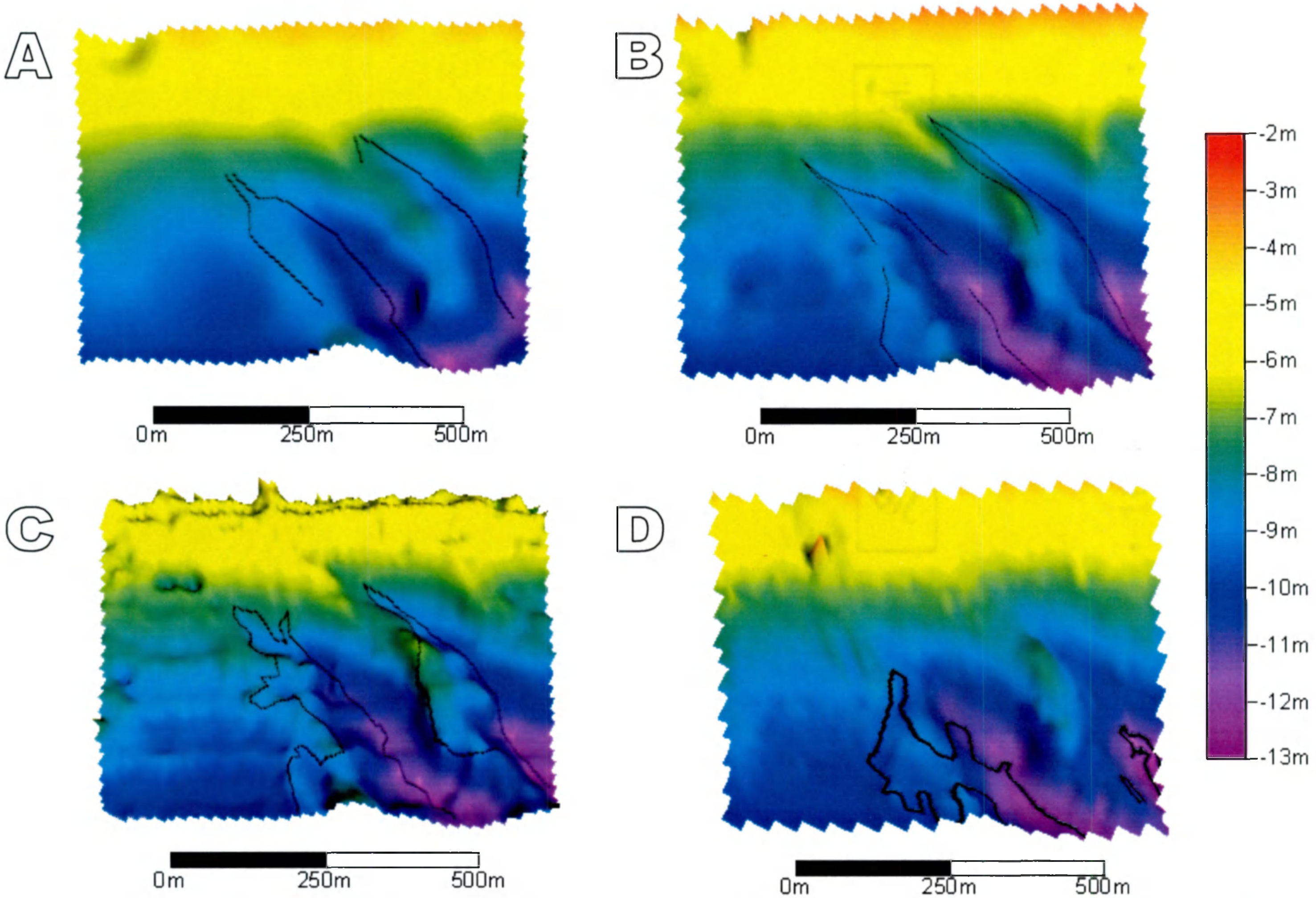


Figure 29. Surface map of southern Kill Devil Hills bathymetry, with overlaid perimeter of gravel outcrop visible in trough between shore-oblique bar, in June 2002 (A), March 2003 (B), May 2003 (C), and November 2003 (D). Depths are in meters relative to MLW.

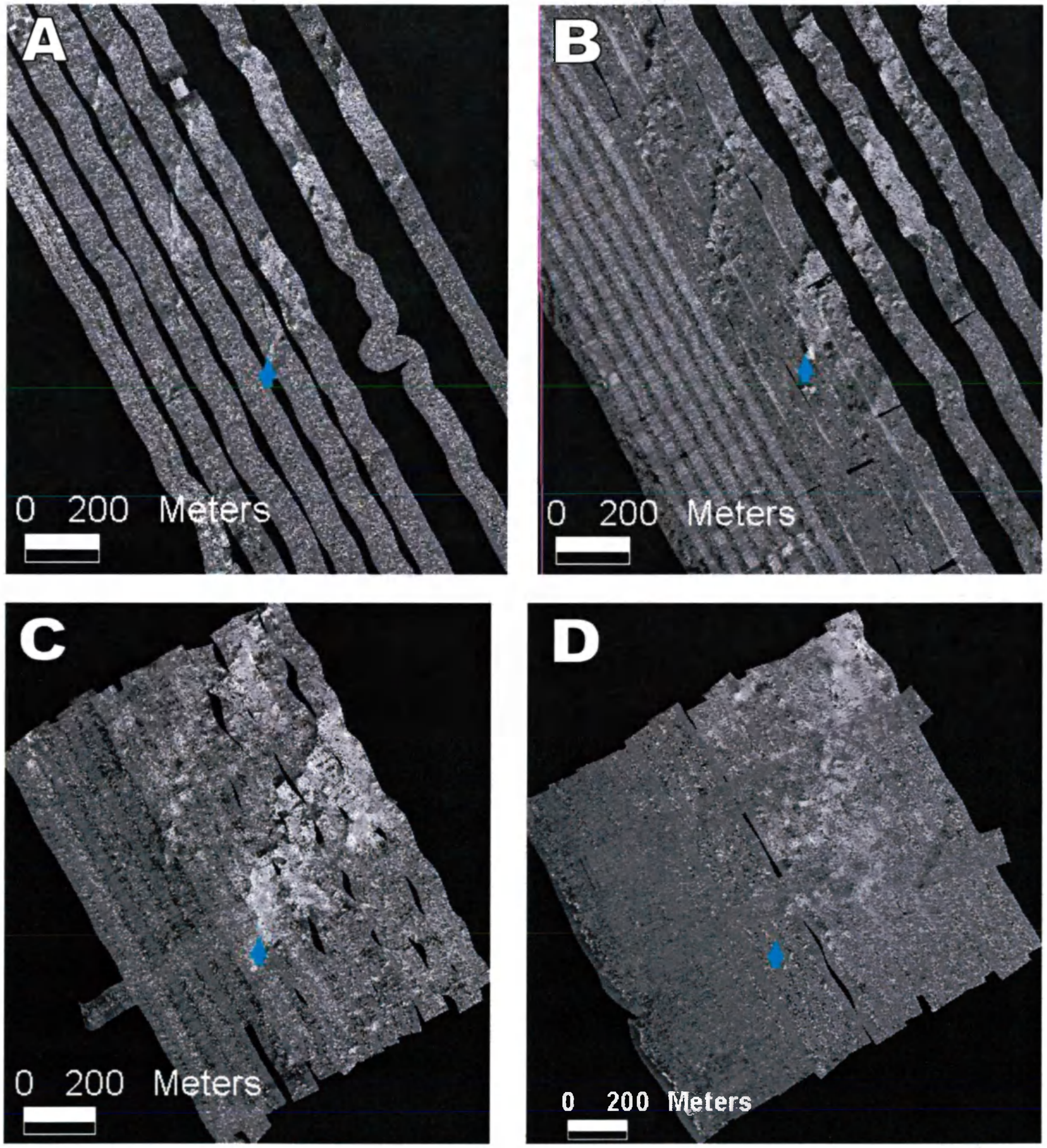


Figure 30. Acoustic reflectance map of southern Kill Devil Hills in June 2002 (A), March 2003 (B), May 2003 (C), and November 2003 (D). The blue arrow is in the same geographic location in each image. Low backscatter (dark areas) indicates sand; high backscatter (light areas) indicates gravel.

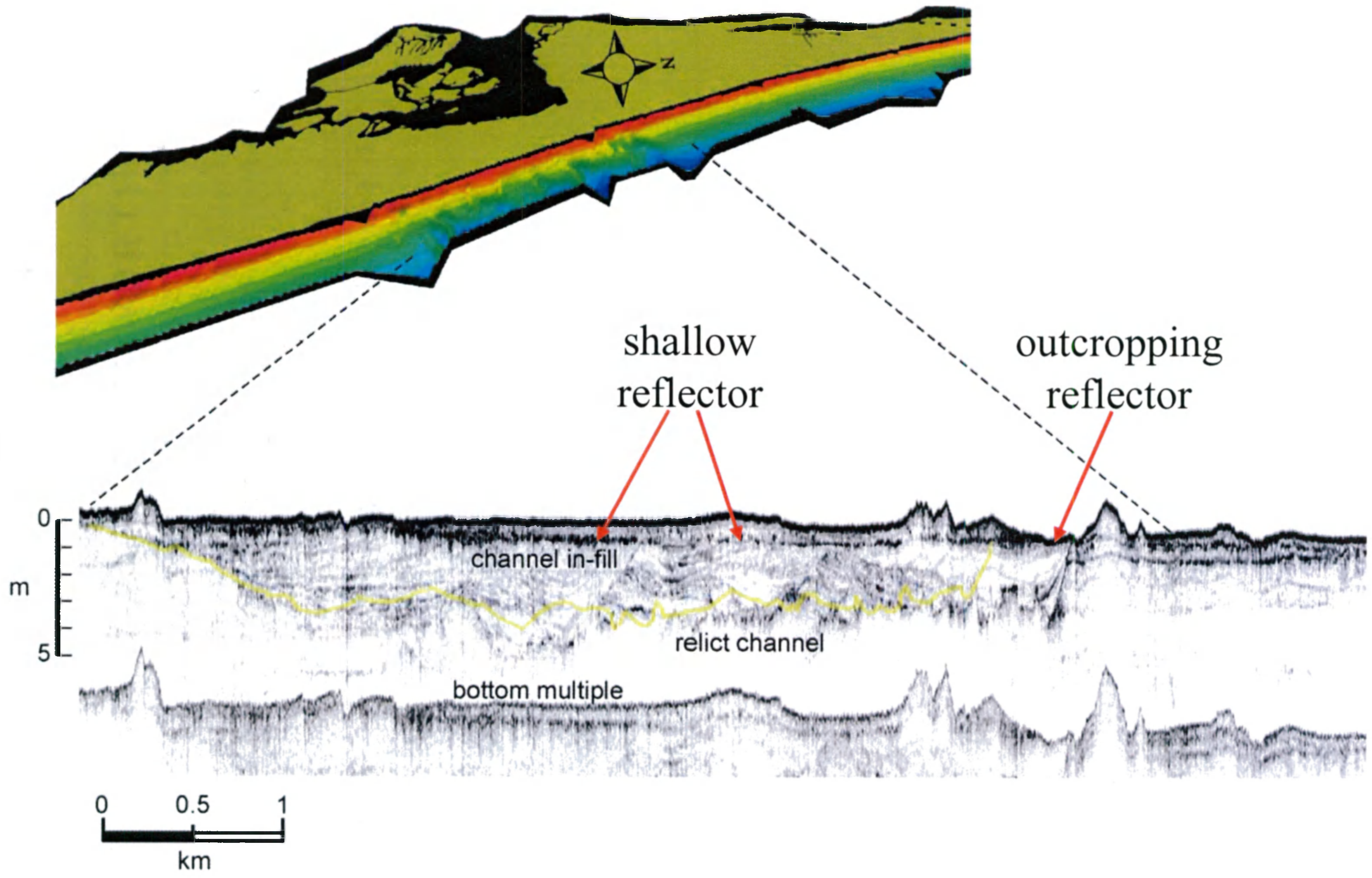


Figure 31. Bathymetry of the northern Outer Banks and the associated chirp sub-bottom profile showing a shallow reflector, an incised channel and subsequent infilling of a large, Pleistocene river (after McNinch, 2004).

LITERATURE CITED

Aubrey, D.G., Twichell, D.C., Pfirman, S.L., 1982. Holocene sedimentation in the shallow nearshore zone off Nauset Inlet, Cape Cod, Massachusetts. Mar. Geol. 47, 243-259.

Beach, R.A., Sternberg, R.W., 1996. Suspended-sediment transport in the surf zone: Response to breaking waves. Continent. Shelf Res. 16 (15), 1989-2003.

Belknap, D.F., Kraft, J.C., 1985. Influence of antecedent geology on stratigraphic preservation potential and evolution of Delaware's barrier systems. Mar. Geol. 63, 235-262.

Birkemeier, W.A., Miller, H.C., Wilhelm, S.D., DeWall, A.E., Gorbics, C.S., 1985. A User's Guide to the Coastal Engineering Research Center's (CERC's) Field Research Facility, Miscellaneous Report CERC-85-1. United States Army Engineer Waterways Experiment Station, Duck, NC, 136 pp.

Boss, S.K., Hoffman, C.W., Cooper, B., 2002. Influence of fluvial processes on the Quaternary geologic framework of the continental shelf, North Carolina USA. Mar. Geol. 183, 45-65.

Browder, A.G., McNinch, J.E., 2003. Correlation of underlying, relict channels with gravel outcrops and shore-oblique sandbars in the nearshore. Eos Trans., AGU 84 (52), Ocean Sci. Meet. Suppl., Abstract OS52C-04.

Caballeria, M., Coco, G., Falques, A., Huntley, D.A., 2002. Self-organization mechanisms for the formation of nearshore crescentic and transverse sand bars. J. Fluid Mechanics 465, 379-410.

Cacchione, D.A., Grant, W.D., Tate, G.B., 1984. Rippled scour depressions on the inner continental shelf off central California. J. Sediment. Petrol. 54, 1280-1291.

Carter, R.W., Woodroffe, C.D., 1994. Coastal evolution: an introduction, in: Carter, R.W. (Ed.), Coastal evolution: Late Quaternary Shoreline Morphodynamics. Cambridge University Press, Cambridge, pp. 1-31.

Dean, R.G., Liotta, R., Simon, G., 1999. Erosional Hot Spots, Prepared for: FL Dept of Environmental Protection, Office of Beaches and Coastal Systems, UFL/COEL-99/021. Coastal and Oceanographic Engineering Program, University of Florida, Gainesville, 60 pp.

Dolan, R., Hayden, B., Heywood, J., Vincent, L. 1977. Shoreline Forms and Shoreline Dynamics. Science 197, 49-51.

Dolan, R., Fenster, M.S., Holme, S.J. 1991. Temporal analysis of shoreline recession and accretion. J. Coastal Res. 7 (3), 723-744.

Fenster, M.S., Dolan, R., 1993. Historical shoreline trends along the Outer Banks, North Carolina: processes and responses. J. Coastal Res. 9 (1), 172-188.

Fenster, M.S., Dolan, R., 1996. Assessing the impact of tidal inlets on adjacent barrier island shorelines. J. Coastal Res. 12 (1), 294-310.

Fitzgerald, D.M., 1984. Interactions between the ebb-tidal delta and landward shoreline: Price Inlet, South Carolina. J. Coastal Res. 23, 47-71.

Fucella, J.E., Dolan, R., 1996. Magnitude of Subaerial Beach Disturbance During Northeast Storms. J. Coastal Res. 12 (2), 420-429.

Goff, J.A., Mayer, L.A., Traykovski, P., Buynevich, I., Wilkens, R., Raymond, R., Glang, G., Evans, R.L., Olson, H., Jenkins, C., in press. Detailed investigation of sorted bedforms, or "rippled scour depressions," within the Martha's Vineyard Coastal Observatory, Massachusetts. Cont. Shelf Res.

Green, M.O., Vincent, C.E., Trembanis, A.C., 2004. Suspension of coarse and fine sand on a wave-dominated shoreface, with implications for the development of rippled scour depressions. Continental Shelf Res. 24 (3), 317-335.

Gutierrez, B.T., Voulgaris, G., Thieler, E.R., 2005. Exploring the persistence of sorted bedforms on the inner-shelf of Wrightsville Beach, North Carolina. Continental Shelf Res. 25, 65-90.

Hanson, H., 1989. Genesis—A generalized shoreline change numerical model. J. Coastal Res. 5, 1-27.

Hanson, H., Kraus, N.C., 1989. Genesis: Generalized Model for Simulating Shoreline Change. CERC, Technical Report CERC-89-19. U.S. Army Corps of Engineers, Vicksburg, MS, 185 pp.

Hayes, M.O., 1979. Barrier island morphology as a function of tidal and wave regime, in: Leatherman, S.P., (Ed.), Barrier islands from the Gulf of St. Lawrence to the Gulf of Mexico. Academic Press, New York, pp. 1-27.

Hayes, M.O., 1980. General morphology and sediment patterns in tidal inlets. Sed. Geol. 26, 139-156.

Hequette, A., Hill, P.R., 1995. Response of the seabed to storm-generated combined flows on a sandy arctic shoreface, Canadian Beaufort Sea. J. Sediment. Res. A65, 461-471.

Holland, K.T., Puleo, J.A., Kooney, T.N., 2001. Quantification of swash flows using video-based particle image velocimetry. Coastal Eng. 44, 65-77.

Honeycutt, M.G, Krantz, D.E., 2003. Influence of the geologic framework on spatial variability in long-term shoreline change, Cape Henlopen to Rehoboth Beach, Delaware. J. Coastal Res. 38, 147-167.

Hunter, R.E., Dingler, J.R., Anima, R.J., Richmond, B.M., 1988. Coarse-sediment bands on the inner shelf of southern Monterey Bay, California. Mar. Geol. 80(1-2), 81-98.

Inman, D.L., Dolan, R., 1989. The Outer Banks of North Carolina: Budget of Sediment and Inlet Dynamics Along a Migrating Barrier System. J. Coastal Res. 5 (2), 193-237.

Komar, P.D., 1998. Beach Processes and Sedimentation. Prentice-Hall Inc., Upper Saddle River, NJ, 429 pp.

Konicki, K.M., Holman, R.A., 2000. The statistics and kinematics of transverse sand bars on an open coast. Mar. Geol. 169, 69-101.

Kraft, J.C., Allen, E.A., Belknap, D.F., John, C.J., Maurmeyer, E.M., 1979. Processes and morphologic evolution of an estuarine and coastal barrier system, in: Leatherman, S.P., (Ed.), Barrier islands from the Gulf of St. Lawrence to the Gulf of Mexico. Academic Press, New York, pp. 149-183.

Kraus, N.C., Galgano, F.A., 2001. Beach Erosional Hotspots: Types, Causes and Solutions. Coastal & Hydraulics Laboratory Report, ERDC/CHL CHETN-II-44. U.S. Army Corps of Engineers, Vicksburg, MS, 17 pp.

Larson, M., Kraus, N.C., 1989. SBEACH: Numerical Model for Simulating Storm-Induced Beach Change. CERC, Technical Report CERC-89-9. U.S. Army Corps of Engineers, Vicksburg, MS, 256 pp.

Lee, G-H. Nicholls, R.J., Birkemeier, W.A., 1998. Storm-driven variability of the beach-nearshore profile at Duck, NC, USA, 1981-1991. Mar. Geol. 148, 163-177.

Lippman T., Holman, R.A., 1990. The spatial and temporal variability of sandbar morphology. J. Geophys. Res. 95, 11575-11590.

List, J.H., Farris, A.S., 1999. Large-scale shoreline response to storms and fair weather. Proceed. Coastal Sediments '99. Am. Soc. Civ. Eng., Reston, VA, pp. 1324-1338.

List, J.H., Farris, A.S., Sullivan, C., submitted. Shoreline mobility on three U.S. beaches. J. Coastal Res.

McBride, R.A., April 8, 1986. The Virginia/North Carolina Coastal Compartment and Inner Continental Shelf Cape Henry, VA to New River, NC. CADGIS Research Lab, Louisiana State University, Baton Rouge, 1 chart.

McBride, R.A., Moslow, T.F., 1991. Origin, evolution, and distribution of shoreface sand ridges, Atlantic inner shelf, U.S.A. Mar. Geol. 97, 57-85.

McNinch, J.E., 2004. Geologic control in the nearshore: shore-oblique sandbars and shoreline erosional hotspots, Mid-Atlantic Bight, USA. Mar. Geol. 211, 121-141.

Miselis, J.L., McNinch, J.E., 2002. The relationship between shoreline change, surf zone sand thickness, and the topography of the sub-bottom reflector. EOS Trans. AGU, 83(47), Fall Meet. Suppl., Abstract OS71B-0278.

Murray, A.B., Thieler, E.R., 2004. A new hypothesis for the formation of large-scale inner-shelf sediment sorting and rippled scour depressions. Cont. Shelf Res. 24, 295-315.

North Carolina State University (NCSU), 2003. 1998 Shoreline / Transect Intersection Points. Vector digital data "Shoreline_1998_Points" available online at http://www.nccoastalmanagement.net.

Niedoroda, A.W., Tanner, W.F., 1970. Preliminary study of transverse bars. Mar. Geol. 9, 41-62.

Niedoroda, A.W., Swift, D.J., Figueiredo Jr., A.G., Freeland, G.L., 1985. Barrier island evolution, middle Atlantic shelf, U.S.A. Part II: Evidence from the shelf floor. Mar. Geol. 63, 331-361.

Pajak, M.J., Leatherman, S., 2002. The high water line as shoreline indicator. J. Coastal Res.18 (2), 329-337.

Pearson, D.K., 1979. Surface and shallow subsurface sediment regime of the nearshore inner continental shelf, Nags Head and Wilmington areas, North Carolina. M.S. Thesis, East Carolina University, 120 pp.

Plant, N.G., Holman, R.A., 1996. Interannual Shoreline Variations at Duck, NC, USA. Proc. of the 25th Int. Conf. Coastal Eng., pp. 3521-3533.

Plant, N.G., Freilich, M.H., Holman, R.A., 2001. Role of morphologic feedback in surf zone sandbar response. J. Geophys. Res. 106 (C1), 973-989.

Riggs, S.R., York, L.L., Wehmiller, J.F., Snyder, S.W. 1992. Depositional patterns resulting from high-frequency Quaternary sea-level fluctuations in northeastern North Carolina, in: Fletcher, C.H., Wehmiller, J.F. (Eds.), Quaternary Coasts of the United States Marine and Lacustrine Systems. Soc. Econ. Paleontol. Mineral. Spec. Publ. 48, 141-153.

Riggs, S.R., Cleary, W.J., Snyder, S.W., 1995. Influence of inherited geologic framework on barrier shoreface morphology and dynamics. Mar. Geol. 126, 213-234.

Riggs, S.R., Snyder, S.W., Hine, A.C., Mearns, D.L., 1996. Hardbottom morphology and relationship to the geologic framework: Mid-Atlantic continental shelf. J. Sed. Res. 66 (4), 830-846.

Schupp, C.A., McNinch, J.E., List, J.H., Farris, A.S., 2002. Relationship of hotspots to the distribution of surficial surf-zone sediments along the Outer Banks of North Carolina. EOS Trans. AGU, 83(47), Fall Meet. Suppl., Abstract OS71B-0279.

Schwab, W.C., Thieler, E.R., Allen, J.R., Foster, D.S., Swift, B.A., Denny, J.F., 2000. Influence of inner-continental shelf geologic framework on the evolution and behavior of the barrier-island system between Fire Island Inlet and Shinnecock Inlet, Long Island, New York. J. Coastal Res. 16 (2), 408-422.

Schwartz, R.K., Hobson, R., Musialowski, F.R. 1981. Subsurface facies of a modern barrier island shoreface and relationship to the active nearshore profile. Northeast. Geol. 3, 283-296.

Snedecor, G.W., Cochran, W.G., 1967. Statistical Methods. Iowa State Univ. Press, Ames, IA, p. 557.

Snyder, S.W., 1993. North Carolina Outer Banks beach nourishment sand resource study, first interim report: shallow, high-resolution seismic survey, offshore Nags Head area, North Carolina Geological Survey Open-File Report 93-38. NCGS, Raleigh, 47 pp.

Stubblefield, W.L., Swift, D.J.P., 1976. Ridge development as revealed by sub-bottom profiles on the central New Jersey shelf. Mar. Geol. 20, 315-334.

Swift, D.J.P., Holliday, B.W., Avignone, N.F., Shideler, G.I., 1972. Anatomy of a shoreface ridge system, False Cape, Virginia. Mar. Geol. 12, 59-84.

Swift, D.J.P., Field, M.E., 1981. Evolution of a classic sand ridge field: Maryland sector, North American inner shelf. Sedimentology 28, 461-482.

Swift, D.J.P., Niederoda, A.W., Vincent, C.E., Hopkins, T.S., 1985. Barrier island evolution, middle Atlantic shelf, U.S.A. Part I: Shoreface dynamics. Mar. Geol. 63, 331-361.

Thieler, E.R., Brill, A.L., Cleary, W.J., Hobbs III, C.H., Gammisch, R.A., 1995. Geology of the Wrightsville Beach, North Carolina shoreface: Implications for the concept of shoreface profile of equilibrium. Mar. Geol. 126, 271-287.

Thieler, E.R., Pilkey Jr., O.H., Young, R.S., Bush, D.M., Chai, F., 2000. The use of mathematical models to predict beach behavior for U.S. coastal engineering: a critical review. J. Coastal Res. 16 (1), 48-70.

Thieler, E.R., O'Connell, J.F., Schupp, C. A., 2001a. The Massachusetts Shoreline Change Project: 1800s to 1994. U.S. Geological Survey Administrative Report. USGS, Woods Hole, 39 pp., 76 map sheets at 1:10,000.

Thieler, E.R., Pilkey, O.H., Cleary, W.J., Schwab, W.C., 2001b. Modern sedimentation of the shoreface and inner continental shelf at Wrightsville Beach, North Carolina, U.S.A. J. Sediment. Res. 71 (6), 958-970.

Thieler, E. R., Martin, D., Ergul, A., 2003. The Digital Shoreline Analysis System, version 2.0: Shoreline change measurement software extension for ArcView, U.S. Geological Survey Open-File Report 03-076. USGS, Woods Hole, 1 CD-ROM.

Trembanis, A.C., Wright, L.D., Friedrichs, C.T., Green, M.O., Hume, T., 2004. The effects of spatially complex inner shelf roughness on boundary layer turbulence and current and wave friction: Tairua embayment, New Zealand. Cont. Shelf Res. 24 (13-14), 1549-1571.

Williams, G.F., Thieler, E.R., Cross, V.A., Foster, D.S., Irwin, B.J., Nichols, D.R., O'Brien, T.F., Polloni, C., 2000. Archive of sidescan-sonar collected off the North Carolina coast during USGS cruise ATSV99045 7-27 October 1999, U.S. Geological Survey Open-File Report 00-177. USGS, Woods Hole, 25 CD-ROMs.

Wright, L.D., Short, A.D., 1984. Morphodynamic variability of surf zones and beaches: a synthesis. Mar. Geol. 56, 93-118.

Young, R.S., Pilkey, O.H., Bush, D.M., Thieler, E.R., 1995. A discussion of the Generalized Model for Simulating Shoreline Change (GENESIS). J. Coastal Res. 11 (3), 875-886.

Zar, J.H., 1999. Biostatistical Analysis. Prentice Hall, Upper Saddle River, NJ, p. App12.

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